SMALL WIND / PHOTOVOLTAIC HYBRID RENEWABLE ENERGY SYSTEM OPTIMIZATION

by

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ABSTRACT

This thesis presents an optimization model to design a hybrid renewable energy systems consisting of wind turbines, photovoltaic modules, batteries, controllers and inverters. To use this model, a data bank is required where detailed specifications and cost of the equipments must be available. It must also include the wind speed and solar radiation data for the desired site. Using the proposed optimization model with the data bank, the optimal configuration of necessary equipment required for the project to supply energy demand at the lowest possible cost is determined. To evaluate if the project is a good investment, an economic analysis is performed to calculate the net present value of the project over a period of 20 years. For the island of Puerto Rico we created a database of published wind speed and solar radiation. We applied the optimization procedure to residential loads at three different locations on the island. The results show that renewable energy projects are a good investment for Puerto Rico as long as the renewable system is connected to the utility grid benefiting from a net metering program, and is designed to supply the exact energy demand of the residential load. For systems not connected to the utility grid, places like the coast of Fajardo, where wind is abundant, the system is cost effective. But in parts of the island where wind speed is less, the system required the use of photovoltaic solar panels increasing the system cost. These systems have a payback period greater than 20 years.

RESUMEN

Este tesis presenta un modelo de optimización para diseñar un sistema de energía renovable compuesto de molinos de viento, paneles fotovoltaicos, baterías, controladores e inversores. Para usar este modelo se necesita un banco de datos en donde se detalle las especificaciones y costos de los equipos. También debe incluir los recursos de viento y sol para el área de estudio. Utilizando el modelo de optimización con la base de datos, se puede determinar la configuración óptima de equipos necesarios para suplir la demanda de energía, a los costos más bajos posibles. Para evaluar si el proyecto es una buena inversión, un análisis económico es realizado en donde se busca el costo presente del proyecto, en un periodo de 20 años. Una base de datos con valores publicados de velocidades de viento y radiación solar fue creada para la isla de Puerto Rico. Se aplico el procedimiento de optimización a cargas residenciales de tres diferentes lugares en la isla. Los resultados muestran que los proyectos de energía renovable son una buena inversión para Puerto Rico, siempre y cuando el sistema renovable esté conectado a la red de energía mediante un programa de medición neta, y esté diseñado para suministrar exactamente la demanda de energía de la carga residencial. Para los sistemas no conectados a la red de energía, lugares como la costa de Fajardo, donde el viento es abundante, el sistema es costo efectivo. Pero en partes de la isla, donde la velocidad del viento es menor, el sistema requiere el uso de paneles solares fotovoltaicos aumentándole el costo del sistema. Estos sistemas tienen un periodo de recuperación superior a 20 años.

DEDICATION

This thesis is dedicated to my parents Miguel Ríos González and Ana Iris Rivera; my sister, Cristina Ríos; and my grandparents Miguel Ríos Vélez, Ana Lidia González, Ildefonso Rivera and Ángela Aguirre for their endless support in every one of my endeavors. The enrollment and pursuance of graduate studies would have been impossible without their continuous encouragement and motivation throughout the years. Thanks for supporting me in this journey.

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During the development of my graduate studies at the University of Puerto Rico several persons collaborated directly and indirectly with my research. It would have been impossible for me to finish my work without their support. In this section I want to recognize their support.

I want to start by expressing my appreciation to my advisor, Dr Agustin Irizarry because he gave me the opportunity to perform research under him guidance and supervision. I received motivation encouragement and support from him during all my studies. I also want to thank the motivation, inspiration and support I received from Dr José R. Cedeño Maldonado. Thanks to him I began my graduate studies. Special thanks to Dr Erick E. Aponte, for his help, support and guidance during the completion of my work.

Finally but most important, I would like to thank my family, for their unconditional support, inspiration and love.

Table of Contents

Table List

Tables **Page**

Figure List

Figures **Page**

1 INTRODUCTION

The growth of the world's human population has created several problems. One of them is global warming caused by the abundance of CO_2 in the atmosphere. Many of these gases are produced from electrical plants burning fossil fuel all over the world. To reduce these emanations out into the atmosphere alternative sources of energy must be used. In the last two decades solar energy and wind energy has become an alternative to traditional energy sources. These alternative energy sources are non-polluting, free in their availability and renewable. But high capital cost, especially for photovoltaic, made its growth a slow one. In recent years advance materials, the capacity to be interconnected with the utility throw net-metering programs and better manufacturing processes have decreased their capital costs making them more attractive. Another way to attempt to decrease the cost of these systems is by making use of hybrid designs that uses both wind/photovoltaic. The question is which configuration will be the most cost effective while supplying demand. This thesis present an optimization procedure capable to design hybrid removable energy systems using integer linear programming in order to find the most effective way to use wind and solar energy at the lowest cost possible. Then economic analyses were made over a period of 20 years, to determine the project viability. We present examples from the island of Puerto Rico, located in the Caribbean. The island's energy resources of wind speed and solar radiation are favorable for this type of analysis.

1.1 Objectives of the Thesis

The thesis main objective is the sizing of hybrid energy system using photovoltaic modules and wind turbines technologies in an economic manner for the island of Puerto Rico. While trying to achieve this main objective, we will attempt to fulfill the following goals:

- Develop a data base of published data on wind speed and solar radiation in the island of P.R.
- Select a set of photovoltaic modules and small wind turbines suitable to generate electricity using the wind and solar resource available in Puerto Rico.
- Propose an optimization procedure to determine the amount and type of PV modules and wind turbines needed, under grid connected and stand alone conditions, to satisfy a predetermined demand at minimum cost. We will use integer linear programming to develop this optimization [Sucha et al. 2006].
- We will study three locations in Puerto Rico; Fajardo where the wind speed is predominant, Gurabo where the solar radiation is predominant and San Juan where both resource are available but less abundant.
- Perform an economic analysis to compute the net present value of the renewable energy systems proposed.

To do all this we will write a program in Matlab® using integer linear programming and using the database of wind speed and solar radiation to compute the most economic choice of PV technology and wind turbines needed to satisfy the desired.

1.2 Literature Review

In [Borowy and Salameh 1994] and [Borowy and Salameh 2006] the authors propose a method to calculate the optimum size of a battery bank and the PV array for a stand alone hybrid Wind/PV system. Their Pascal algorithm calculated the number of PV and batteries required for these systems. They use one manufacture of wind turbine and PV and only vary the number of PV units used.

In [Kellogg et al. 1998] the authors utilized an optimization method to calculate the components for a stand-alone hybrid system, and determine the optimum generation capacity and storing needed. They used one type of wind turbine, one type of solar module and one type of battery power, and varied the number of units to be used. Also they calculated the minimum distance between the nearest existing distribution line that would justify the cost of installing a standalone generating system as opposed to constructing a line extension and supplying the load with conventional utility.

In [Daming et at. 2005] the authors used a genetic algorithm to optimize the sizing of a standalone hybrid wind/PV power system. The objective was to minimize the total capital cost, subject to the constraint of supplying the power to the system. They proved that genetic algorithms converge very well and the methodology proposed is feasible for optimally sizing stand alone hybrid power system. They noted that using a genetic algorithm provides a number of potential solutions to any given problem and the choice of a final solution is left to the user. One limitation of their approch is that they only used one type of wind turbine when in the market there are many types of wind turbines at different prices and capacities.

In [NREL 2007] they developed a program called Homer. This program simplifies the task of evaluating design of stand alone and grid-connected power system using optimization algorithms. Homer's optimization and sensitivity algorithm can calculate how many and what size of each components should be used for the hybrid system at the lowest cost possible. One limitation of the program is that only two types of wind turbine and one type of solar module can be used for the analysis. Nevertheless it is a useful program, if the user knows exactly what type of wind turbine and solar module he/she will be using for the hybrid system.

1.3 Structure of the Remaining Chapters

Chapter 2 presents wind energy systems and wind data for PR. Chapter 3 presents PV modules and solar radiation data for PR. Chapter 4 presents auxiliary equipment such as batteries, PV controllers and inverters. Chapter 5 presents background on energy demand structure. Chapter 6 presents the proposed optimization model for grid connected and stand alone renewable hybrid energy systems. Chapter 6 also includes the theory of economic analysis used to evaluate our examples. Chapter 7 presents different simulated scenarios of stand alone and grid connected hybrid systems in Puerto Rico, using the proposed optimization model. Finally conclusions and recommendations for future work are presented in Chapter 8.

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

Wind has always been an energy source used by several civilizations many years ago. 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, as made small wind turbines increasingly be 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.

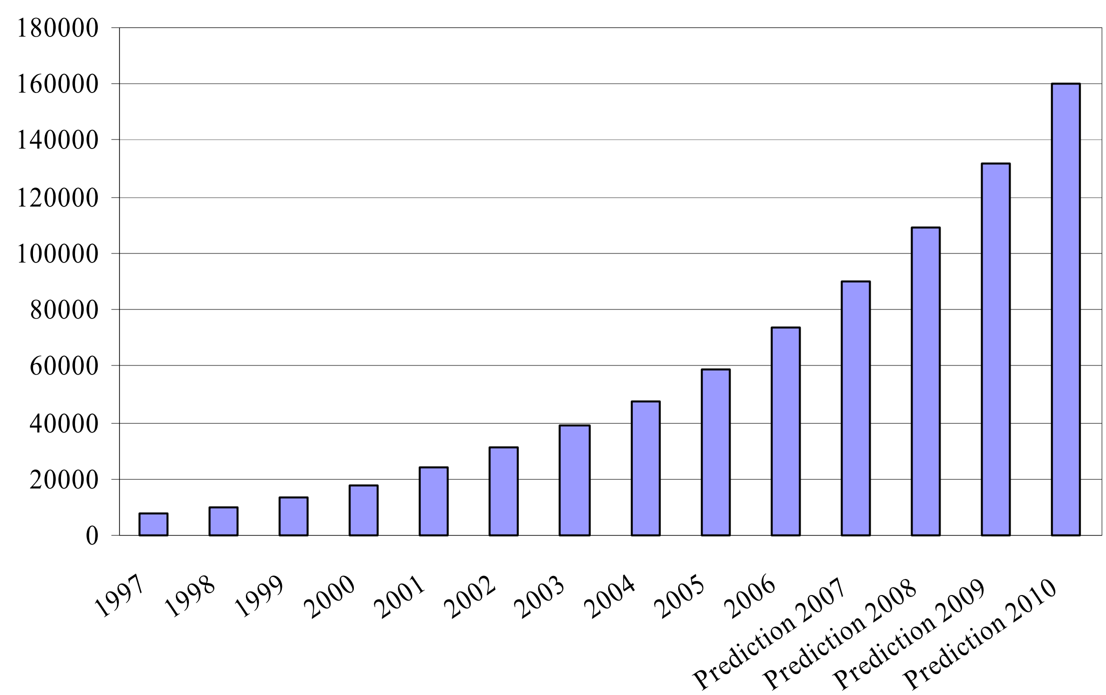

Figure 2-1 World Wind Energy - Total Installed Capacity (MW) [World Wind Energy 2007]

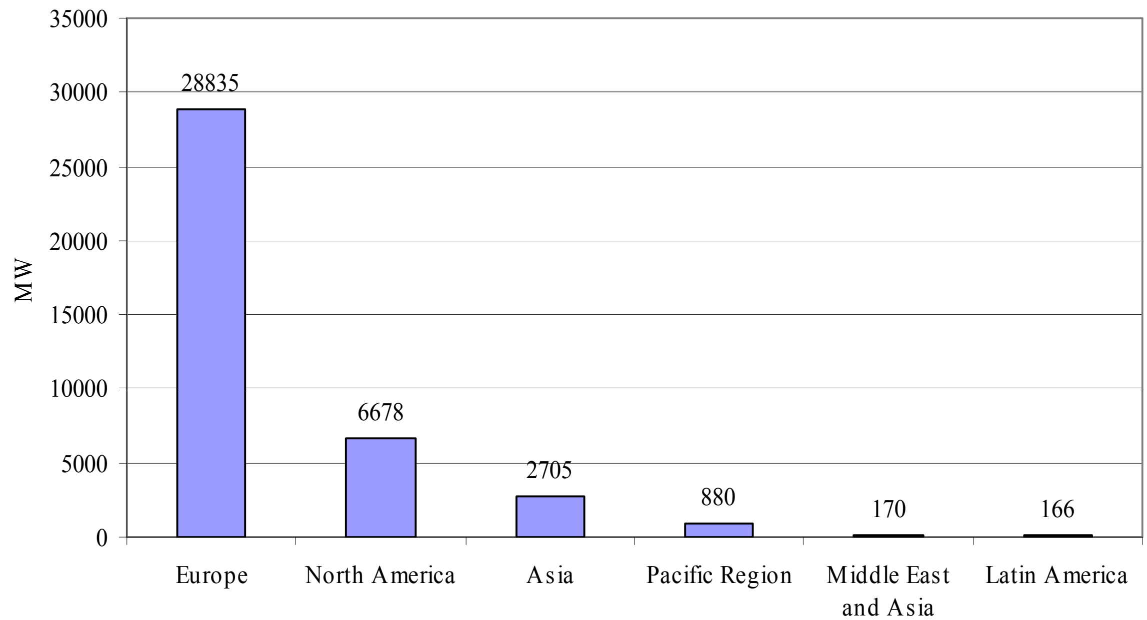

Figure 2-2 Installed Wind Energy Capacity (MW) in Different Regions [The wind indicator 2005]

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 HAWT [Creative Commons 2004] and VAWT [Archiba 2001].

Figure 2-3 Horizontal Axis Wind Turbines HAWT [Creative Commons 2004] and Vertical Axis Wind Turbines VAWT [Archiba 2001]

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. The turbines that will be used for optimization purpose in this thesis are the small horizontal axis with two or three blades, which are usually made of a composite material such as fiberglass.

2.4.1 Small Wind Turbines Components

The basic components for small horizontal axis wind turbine are shown on figure 2.4.

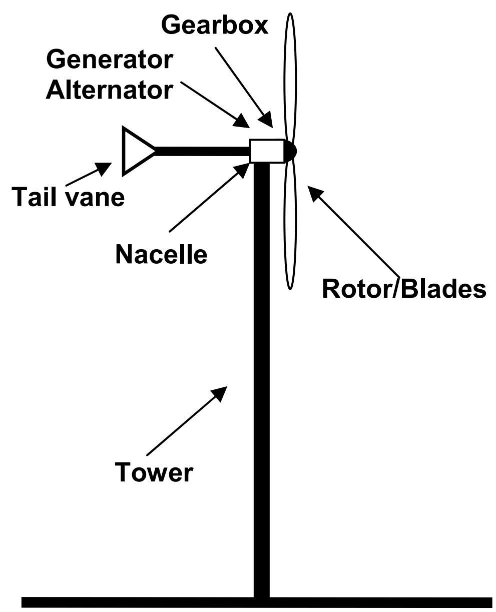

Figure 2-4 Components of a Wind Turbine

- 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.

- o 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.
- o Guyed tilt-up towers, which can be raised and lowered for easy maintenance and repair.
- o 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.

2.4.2 Noise of a Small Wind Turbines

The noise of a small wind turbine varies depending on the side and the height of the tower. The manufacture must specify the sound level in (dB) of the turbine at a given distance. An average sound level of a small wind turbine between 30-300kW is of 45dB at a height of 100 meters [Gipe 1993]. Figure 2-5 offers a comparison of dB. This shows how a sound level of 45dB is like the noise produced in a home or office. Most small wind turbines make less noise than a residential air conditioner. Before install one check that the noise level of the small turbine does not violate local regulations.

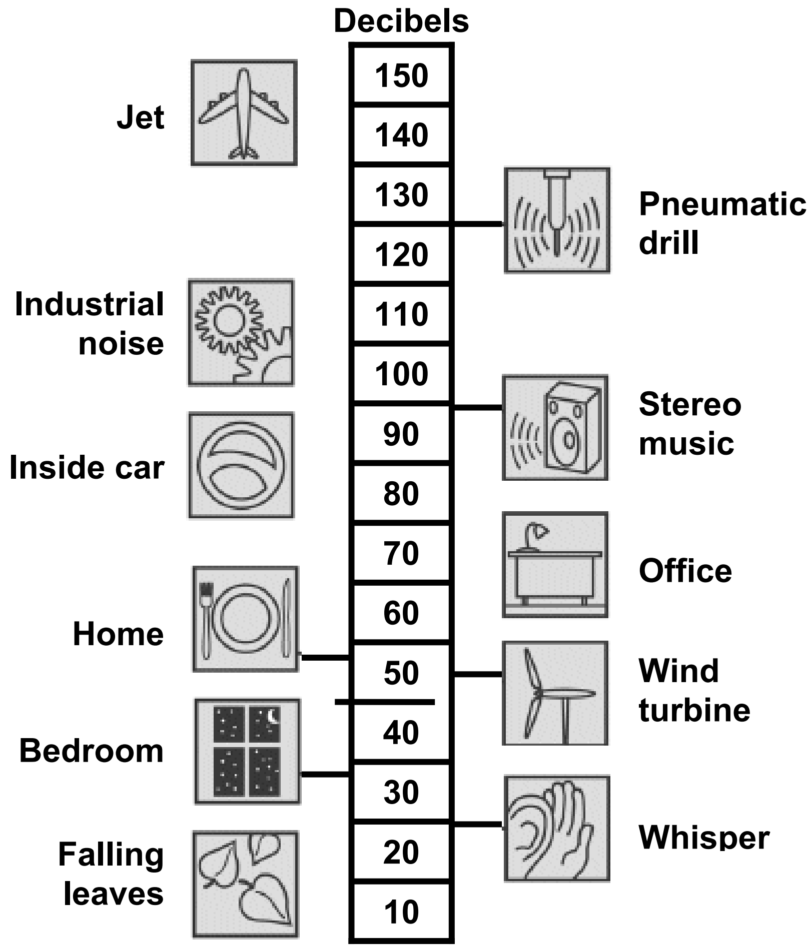

Figure 2-5 Comparison of Decibel Levels from a Hypothetical Wind Turbine (Source: American Wind Energy Association)

2.4.3 Small Wind Turbines Manufactures

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. These are the ones that will be used in this thesis for the analysis. 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

Product:	Watt at 28mph:	Turbine MSRP:	Price Tower 25m	MSRP with tower:	US$/Watt:	US$/Area:	Watt/Area:
SouthWest (Air X)	400	$600.00	$804.86	$1,404.86	$3.51	1376	392
SouthWest (Whisper 100)	900	$2,085.00	$804.86	$2,889.86	$3.21	834	260
SouthWest (Whisper 200)	1000	$2,400.00	$804.86	$3,204.86	$3.20	453	141
SouthWest (Whisper 500)	3000	$7,095.00	$1,157.19	$8,252.19	$2.75	497	181
SouthWest (Skystream 3.7)	1800	$5,400.00	$1,157.19	$6,557.19	$3.64	603	166
Aeromax Engineering (Lakota S, SC)	800	$1,591.00	$804.00	$2,395.00	$2.99	698	233
Bergey (BWC 1500)	1500	$4,700	$1,968.00	$6,668.00	$4.45	943	212
Bergey (BWC XL.1)	1000	$2,590.00	$1,968.00	$4,558.00	$4.56	929	204
Bergey (BWC Excel-R)	8100	$23,000.00	$2,396.00	$25,396.00	$3.14	720	230
Bornay (Inclin 250)	250	$2,151.00	$1,157.00	$3,308.00	$13.23	2149	162
Bornay (Inclin 600)	600	$2,726.00	$1,157.00	$3,883.00	$6.47	1236	191
Bornay (Inclin 1500)	1500	$3,973.00	$1,157.00	$5,130.00	$3.42	896	262
Bornay (Inclin 3000)	3000	$6,028.00	$1,968.00	$7,996.00	$2.67	744	279
Bornay (Inclin 6000)	6000	$10,070.00	$1,968.00	$12,038.00	$2.01	1120	558
Abundant Renewable Energy (ARE110)	2500	$11,500.00	$1,968.00	$13,468.00	$5.39	1323	246
Abundant Renewable Energy (ARE442)	10000	$36,000.00	$2,396.00	$38,396.00	$3.84	943	246
Kestrel Wind (600)	600	$1,296.00	$804.00	$2,100.00	$3.50	1188	340
Kestrel Wind (800)	800	$1,995.00	$804.00	$2,799.00	$3.50	808	231
Kestrel Wind (1000)	1000	$2,950.00	$1,157.00	$4,107.00	$4.11	581	141
Kestrel Wind (3000)	3000	$8,400.00	$1,968.00	$10,368.00	$3.46	914	265
Solacity (Eoltec)	6000	$25,200.00	$1,968.00	$27,168.00	$4.53	1103	244

TABLE 2-2 Small Wind Turbines

Product:	Rotor Diameter (m):	Rotor Area (m^2):	Weigh lb:	Voltage:	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 230Vac	Gaiam
SouthWest (Whisper 500)	4.6	16.62	155	12, 24, 48 Vdc 230Vac	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, 120VDC	Alter System
Bergey (BWC XL.1)	2.5	4.91	75	24, 48Vdc	Alter System
Bergey (BWC Excel-R)	6.7	35.26	1050	48Vdc 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

2.4.4 Small 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 the power curve.

A power curve is a graph that represents the turbine power output at different wind speeds values. The advantage of a power curve is that it includes the wind turbines efficiency. The power curve is normally provided by the turbine's manufacture. Figure 2.6 presents an example of a wind turbine power curve. Note that at speeds from 0 to 3.5m/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.

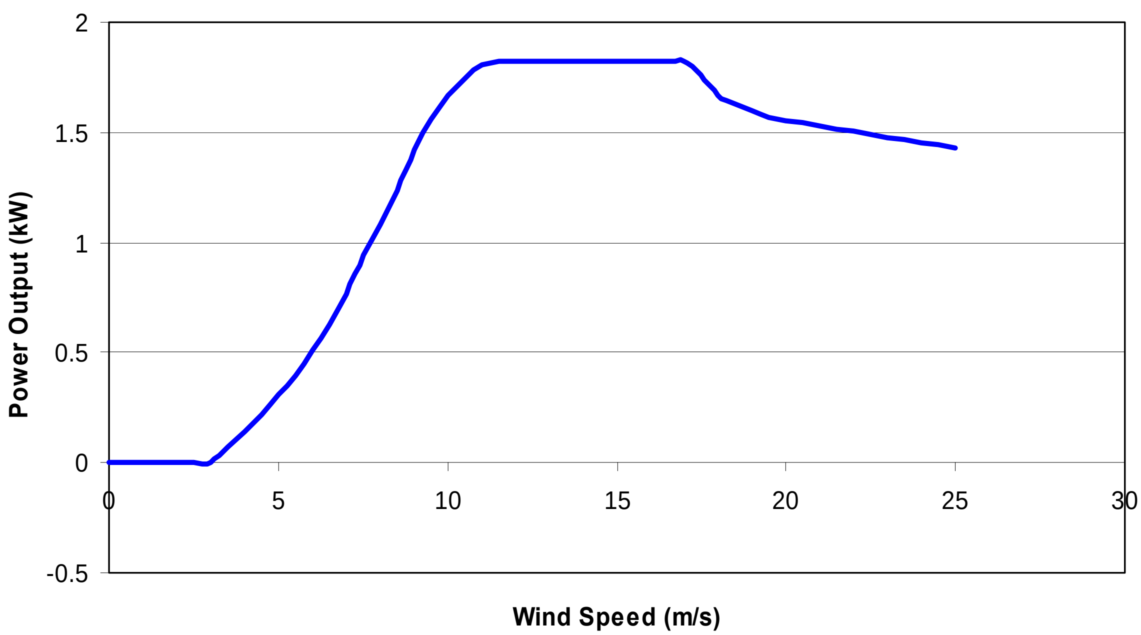

Figure 2-6 Power Curve for Wind Turbine "Sky Stream 3.7" of South West Company

You may also receive or show the power curve information in a table format. Some manufactures provide the exact values of power at different wind speed and present this in a table. The power curve is then obtained by plotting the table values. Table 2.3 presents the power curve data for different wind turbines. The turbines presented in table 2.1 and table 2.2 are the same shown in table 2.3, together these tables provide a complete set of specification data for these turbines

TABLE 2-3 Power Curve Values in kW for Different Wind Turbines

Power Curve Values in KW for Different Wind Turbines																						
	SouthWest					Aeromax Engineering	Bergey			Bornay					Abundant Renewable Energy		Kestrel Wind				Solacity
Wind Speed m/s	Air X	Whisper 100	Whisper 200	Whisper 500	Skystream 3.7	Lakota S, SC	BWC 1500	BWC XL.1	BWC Excel-R	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	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	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	0.15	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	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	0.02	0.02	0.05	0.27	0.14	0.03	0.08	0.06	0.25	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	0.03	0.06	0.15	0.55	0.31	0.07	0.15	0.12	0.70	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	0.04	0.12	0.28	0.88	0.51	0.11	0.30	0.23	1.38	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	0.07	0.19	0.44	1.26	0.77	0.28	0.45	0.38	2.18	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	0.09	0.28	0.63	1.70	1.08	0.34	0.60	0.54	3.11	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	0.13	0.39	0.78	2.18	1.42	0.41	0.80	0.70	4.26	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	0.16	0.52	0.89	2.67	1.67	0.53	1.15	0.89	5.37	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	0.20	0.66	0.96	3.07	1.80	0.64	1.30	1.06	6.63	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	0.28	0.80	0.99	3.28	1.82	0.75	1.50	1.21	7.45	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	0.35	0.90	1.00	3.33	1.82	0.90	1.60	1.24	8.09	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	0.41	0.92	1.00	3.26	1.82	1.16	1.70	1.20	8.05	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	0.44	0.91	0.99	3.13	1.82	1.28	1.60	1.15	7.92	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	0.45	0.88	0.96	2.96	1.82	1.30	0.35	1.10	7.75	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	0.35	0.85	0.93	2.77	1.82	1.25	0.35	1.05	7.51	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	0.15	0.81	0.90	2.56	1.67	1.20	0.40	0.99	7.28	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	0.15	0.77	0.85	2.33	1.60	1.10	0.40	0.94	7.11	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	0.15	0.73	0.81	2.08	1.55	1.00	0.40	0.90	6.96	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	0.15	0.69	0.77	1.76	1.53	0.98	0.40	0.85	6.73	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	0.15	0.64	0.72	1.45	1.50	0.93	0.40	0.85	6.49	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	0.15	0.60	0.68	1.13	1.48	0.90	0.40	0.85	6.26	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	0.15	0.56	0.63	0.82	1.45	0.90	0.40	0.85	6.03	0.26	0.54	1.66	3.40	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00

2.5 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, time of day, elevation above ground, and form of terrain. Proper location in windy sites, away from large obstructions, improves wind turbine's performance.

2.5.1 Anemometer

The 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].

2.5.2 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 2.1, [Burton et al. 2001].

$$\frac{v(z_2)}{v(z_1)} = \left(\frac{z_2}{z_1}\right)^{\alpha} \qquad \textbf{2-1}$$

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, and 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 use is one-seventh (1/7).

2.5.3 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]. [NREL 2008] developed an annual average wind power map for Puerto Rico shown in figure 2.7. The map shows that most of Puerto Rico's coasts at a height of 30m, have wind speed from 4.5 m/s to 6.5m/s.

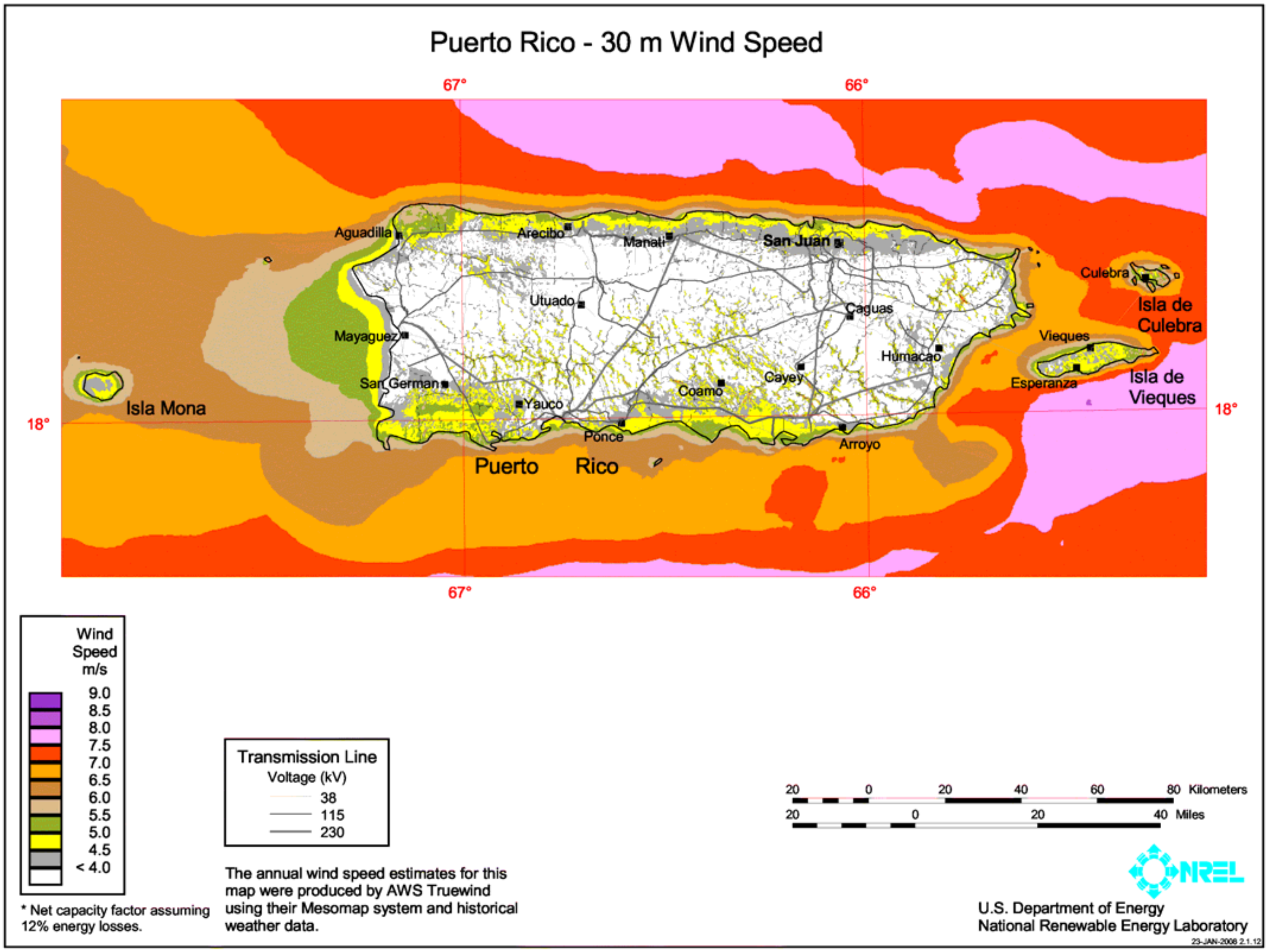

Figure 2-7 Puerto Rico 30m height Wind Map: Annual Average Wind, [NREL 2008]

In addition to this map from NREL there is another one available from a private company [AWS 2008] show in figure 2-5. Both maps seem to have the same wind speed values for the island. Using these maps, we can have an initial idea of what places have a greater wind speed resource.

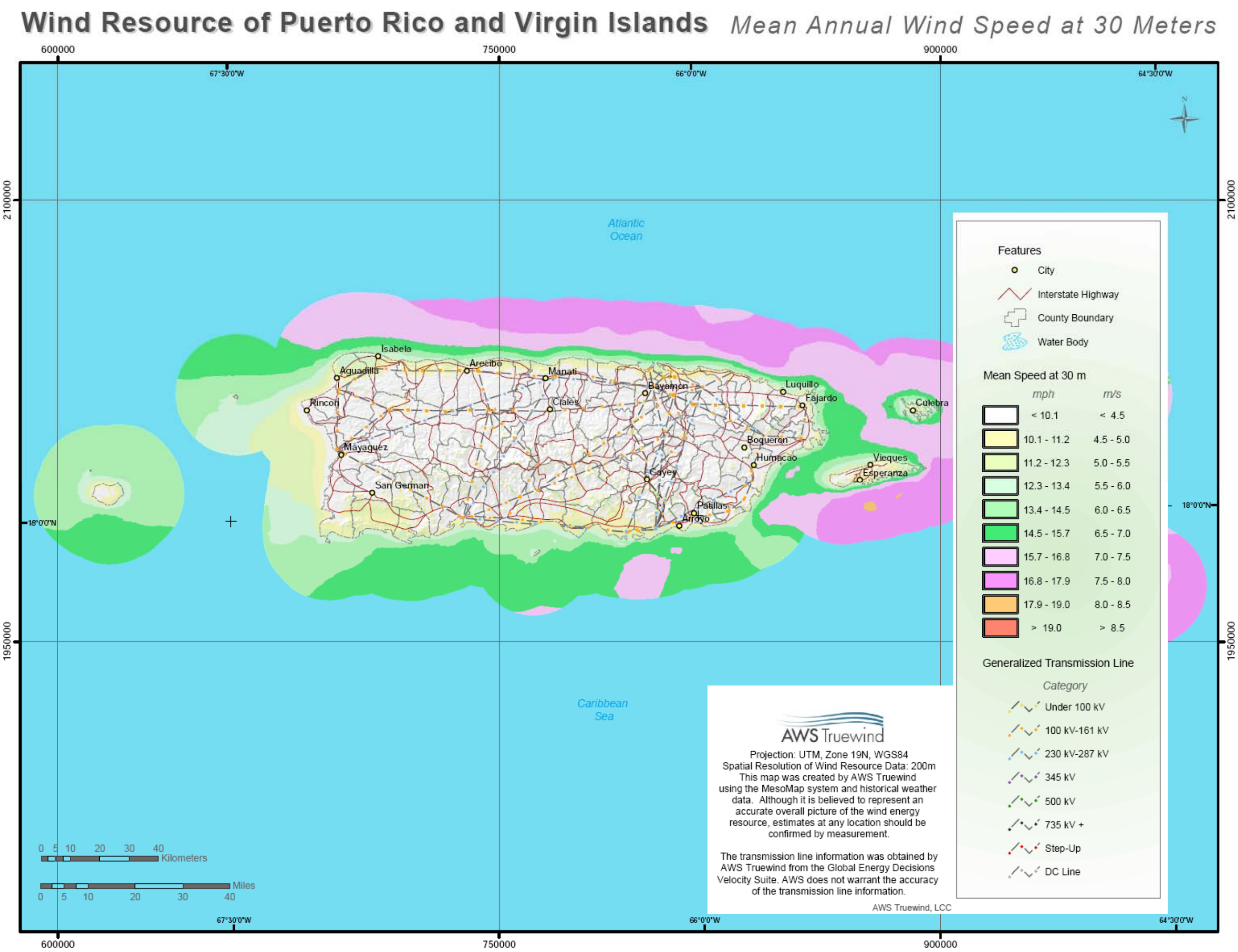

Figure 2-8 Puerto Rico Wind Map: Annual Average Wind [AWS 2008]

These maps are estimates of wind speed. The only way to make sure wind speed presented in the maps is correct for a given location is to use an anemometer to measure wind speed at the site. There are many studies that have measure wind speed in Puerto Rico. Table 2-4 presents the diurnal distribution of mean wind velocity in (m/s) and table 2-5 presents monthly distribution of mean wind velocity in (m/s) for several sites in Puerto Rico. All the data has been adjusted to a height of 25 meters from the ground.

TABLE 2-4 Diurnal Distribution of Mean Wind Velocity in (m/s) at meters

	Place\Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
[USDA Forest Service 1966]	Cape San Juan	6.35	6.11	6.45	6.11	6.06	6.11	6.25	6.06	6.11	6.20	6.11	6.20	6.35	6.35	6.50	6.59	6.59	6.45	6.54	6.50	6.54	6.35	6.59	6.54
	Yunque	6.25	6.20	6.20	6.30	6.25	6.25	6.45	6.35	6.06	5.87	5.82	5.72	5.67	5.77	5.87	5.91	5.77	6.01	6.11	6.25	6.30	6.35	6.30	5.91
	Gurabo Town	1.21	1.26	0.92	1.11	0.97	1.16	1.07	1.02	1.11	1.89	2.62	3.20	3.34	3.44	3.44	3.10	2.67	2.08	1.41	1.21	1.31	0.97	1.11	0.87
	Viejo San Juan	2.42	2.18	2.13	2.08	1.99	2.04	1.94	2.52	3.64	4.99	5.87	6.30	6.69	6.64	6.30	6.11	5.67	5.04	4.17	3.88	3.10	3.01	2.62	2.47
	Buchanan	1.45	1.36	1.45	1.45	1.41	1.31	1.16	1.31	1.70	2.38	3.01	3.30	3.49	3.59	3.49	3.20	3.10	2.76	2.28	1.79	1.41	1.36	1.26	1.21
	Rio Blanco	0.68	0.68	0.63	0.63	0.68	0.63	0.63	0.68	0.78	1.07	1.21	1.31	1.41	1.45	1.26	1.16	1.02	0.73	0.63	0.63	0.58	0.63	0.58	0.58
	Roosvelt Roads	4.70	4.60	3.97	4.02	4.07	4.02	4.02	4.85	5.62	6.16	6.45	6.69	6.59	6.79	6.59	6.45	6.01	5.14	4.65	4.41	4.31	4.22	4.27	4.17
	Fajardo City	0.63	0.63	0.63	0.58	0.58	0.63	0.63	0.78	1.16	1.60	1.74	1.89	2.18	2.13	2.08	2.13	1.70	1.41	0.78	0.63	0.68	0.63	0.78	0.68
	Catalina	1.02	1.07	0.97	1.02	1.02	1.11	1.31	1.41	1.45	1.55	1.60	1.89	1.89	1.89	1.94	1.79	1.50	1.31	1.11	1.02	0.97	1.02	0.97	1.02
[Soderstrom 1989]	Aguirre	2.28	2.18	2.29	2.28	2.13	2.16	2.19	2.29	3.00	4.37	5.47	6.06	6.53	6.69	6.63	6.38	5.89	5.30	4.38	3.32	2.80	2.58	2.52	2.46
	Cuyon	5.97	5.86	5.79	5.59	5.61	5.59	5.61	5.61	5.42	5.10	4.83	4.61	4.58	4.67	4.69	4.72	4.62	4.70	4.94	5.23	5.66	5.94	6.15	6.11
	Croem	4.61	4.51	4.28	4.43	4.14	4.09	3.98	3.83	3.55	3.70	4.18	4.44	4.83	4.99	4.89	4.75	4.43	4.21	4.25	4.30	4.51	4.41	4.55	4.59
	Cape San Juan	6.68	6.52	6.47	6.43	6.35	6.20	6.17	6.27	6.26	6.26	6.33	6.39	6.47	6.49	6.56	6.53	6.56	6.49	6.81	6.95	6.93	6.96	6.93	6.71
	Aguadilla Airport	3.89	3.54	3.16	2.97	2.85	2.85	2.56	2.66	2.59	2.64	2.94	4.02	5.04	6.00	6.53	6.97	7.03	7.10	7.06	6.66	6.28	5.46	4.96	4.59
	Aes	2.96	2.87	2.73	2.72	2.65	2.65	2.60	2.77	3.02	3.47	3.85	4.17	4.42	4.56	4.53	4.44	4.18	3.86	3.54	3.34	3.22	3.10	3.06	2.96

TABLE 2-5 Monthly Distribution of Mean Wind Velocity in (m/s) at 25 meters

	Place\Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
[USDA Forest Service 1966]	Cape San Juan	5.50	5.40	6.30	8.36	7.76	6.83	8.85	7.59	4.19	6.08	3.13	6.01
	Yunque	6.16	5.21	2.13	5.43	7.05	8.97	7.66	6.45	6.52	7.13	5.19	5.09
	Gurabo Town	1.43	1.70	1.94	2.04	1.94	2.40	2.11	2.01	1.09	1.77	1.16	1.67
	Viejo San Juan	3.20	4.44	4.70	3.95	1.94	4.58	4.85	5.26	3.73	3.20	3.05	4.00
	Buchanan	2.40	2.52	1.74	2.59	0.87	2.62	2.64	1.62	2.18	2.11	1.87	1.94
	Rio Blanco	1.07	1.04	0.99	0.92	0.58	0.80	0.80	0.92	0.70	0.70	0.70	0.90
	Roosevelt Roads	4.85	5.65	5.74	5.91	5.60	5.87	6.45	5.94	3.71	4.00	3.64	4.05
	Fajardo City	1.45	1.41	1.53	1.43	0.95	0.58	0.90	1.26	0.63	1.38	1.07	1.07
	Catalina	1.04	1.91	1.96	1.58	1.19	0.97	1.87	1.41	1.38	0.92	0.92	0.78
[Soderstrom 1989]	Aguirre	3.72	3.76	3.86	3.29	3.81	2.95	4.69	4.72	4.37	4.45	3.36	3.11
	Cuyon	5.42	4.76	5.50	4.06	5.05	5.40	6.72	6.35	4.76	4.33	5.61	5.84
	Croem	3.65	5.04	4.89	4.89	4.38	3.57	3.16	4.20	3.54	3.42	5.74	5.74
	Cape San Juan	6.40	6.11	6.13	6.34	5.68	4.90	7.11	5.76	6.76	6.76	7.76	7.01
	Aguadilla Airport	3.30	5.19	5.97	4.45	4.64	6.11	5.59	4.49	3.48	3.05	4.14	4.77
	Aes	3.81	3.98	3.91	3.98	3.76	4.08	4.32	4.07	3.54	3.74	3.74	4.08
	Isla Verde	3.64	3.95	4.16	3.95	3.64	3.95	4.26	3.85	3.33	3.02	3.33	3.64

2.6 Wind Power

The power (P) in the wind is a function of air density (ρ), the area intercepting the wind (A), and the instantaneous wind velocity (V), or the speed. Increasing these factors will increase the power available from wind. Equation 2-2 shows the relationship between these parameters, [Burton et al. 2001, Gipe 2004, Ramos 2005, Patel 2006].

$$P = \frac{1}{2}\rho A V^3 \qquad \textbf{2-2}$$

Where P is the power output in (watts), ρ is the air density in (kg/m^3), A is the area where wind is passing (m^2) and V is the wind speed in (m/s).

2.6.1 Air Density

The air density (ρ) changes slightly with air temperature and with elevation. Warm air in the summer is less dense than cold air in the winter. However at higher elevation the air is less dense than lower elevation. A density correction should be made for higher elevations and cooler weather. The density of the air in kg/m^2 can be calculated using the following equation 2-3.

$$\rho = \frac{p}{RT} \qquad \textbf{2-3}$$

Where *P* is the air pressure in Pa, T is the temperature in Kelvin and R is the gas constant (287J/kgK). Change in temperature produce a smaller effect on air density than elevation. If the density of the air has to be adjusted to another height the following equation 2-4 can be used.

$$\rho = \frac{353.05}{T} e^{-0.034\left(\frac{z}{T}\right)} \qquad \textbf{2-4}$$

Where z is the height measured with respect to sea level, and T is the temperature at height z. For purpose of this thesis we will use the air density at sea level, 1.225 kg/m^3 at 1atm and 60ºF.

2.6.2 Swept Area

As shown in equation 2-2, the output power is also related to the area intercepting the wind, that is, the area swept by the wind turbines rotor. Double this area and you double the power available. For the horizontal axis turbine, the rotor swept area is the area of a circle:

$$A = \frac{\pi}{4} D^2 \qquad \textbf{2-5}$$

Where D is the rotor diameter in meters. The relationship between the rotor's diameter and the energy capture is fundamental to understanding wind turbine design. Relatively small increases in blade length or in rotor diameter produce a correspondingly bigger increase in the swept area, and therefore, in power. Nothing tells you more about a wind turbines potential than rotor diameter. The wind turbine with the larger rotor will almost invariably generate more electricity than a turbine with a smaller rotor, not considering generator ratings, [Gipe, 2004].

2.6.3 Wind Speed

No other factor is more important to the amount of wind power available to a wind turbine than the speed of the wind. Because the power in the wind is a cubic function of wind speed, changes in speed produce a profound effect on power. Doubling the wind speed does not double the power available it increases a whopping eight times. [Patel 2006]

Using the average annual wind speed alone in the power equation would not give us the right results; our calculation would differ from the actual power in the wind by a factor of two or more. To understand why, remember that wind speeds vary over time. The average speed is composed of winds above and below the average. The cube of the average wind speed will always be less than the average of the cube of wind speed. In other words the average of the cube of wind speed is greater than the cube of the average wind speed. The reason for this paradox is the single number representing the average speed ignores the amount of wind above as well below the average. It's the wind speed above the average that contributes most of the power, [Ramos, 2005].

2.6.4 Wind Speed Distribution

Having a cubic relation with the power, wind speed is the most critical data needed to appraise the power potential of a potential site. The wind is never steady at any site. It is influenced by weather system, the local land terrain, and its height above the ground surface. Wind speed varies by the minute, hour, day, season, and even by year. Since wind velocity varies it is necessary to capture this variation in the model used to predict energy production. This is usually done using probability functions to describe wind velocity over a period of time, [Ramos, 2005].

2.6.4.1 Weibull Probability Density Function

The variation in wind speed is best described by a probably density function (pdf). A probability density function is used to model the wind velocity variation. The pdf provides the probability that an event will occur between two end points. The area under the curve between any two speeds greater than zero will equal the probability that wind will blow somewhere between those two speeds. It is important to understand that actual height and shape of a pdf curve are determined such that the area under the curve from 0 to infinity is exactly 1. Physically, this means that there is a 100% chance that the wind will blow at some speed between 0 m/s and infinite m/s.

The Weibull probability distribution has been found to be a very accurate model to describe wind velocity variation. This distribution is often used in wind energy engineering, as it conforms well to the observed long-term distribution of mean wind speeds for a range of sites, [RETSCREEN]. The Weibull pdf is found in the literature using different notations. In this thesis the Weibull probability density function is defined as, [Montgomery and Runger 1998, Jangamshetti and Guruprasada 1999, Ramos 2005, RETSCREEN],

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} e^{-\left(\frac{x}{\eta}\right)^{\beta}} \quad where\ 0 \leq x,\ \beta > 1,\ \eta > 0 \qquad \textbf{2-6}$$

Where β is the shape factor, η is the scale factor and x represent in this case the wind speed. In some literature the parameter (β) is called (k) parameter and the parameter (η) is called (c) parameter. For a given average wind speed, a smaller shape factor indicates a relatively wide distribution of wind speeds around the average while a larger shape factor indicates a relatively narrow distribution of wind speeds around the average. A smaller shape factor will normally lead to a higher energy production for a given average wind speed [RETSCREEN]. A pdf with a large shape factor has a bell shape. The scale (η) factor defines where the bulk of the distribution lies and how stretched out the distribution is. Figures 2.9 and 2.10 show an example of a weibull probability distribution function with variable scale and shape parameters.

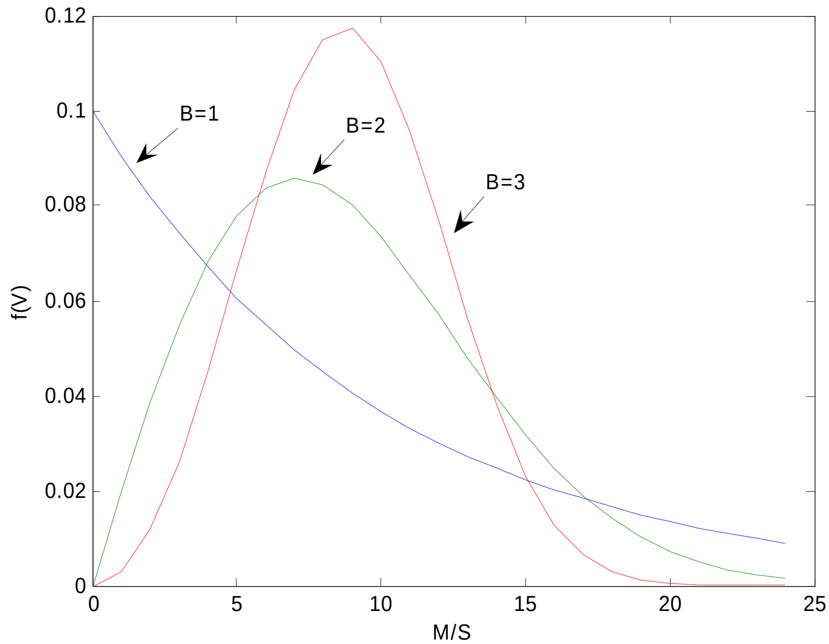

Figure 2-9 Weibull Probability Distribution Function with Scale Parameter η = 10 and Shape Parameter β = 1, 2, and 3

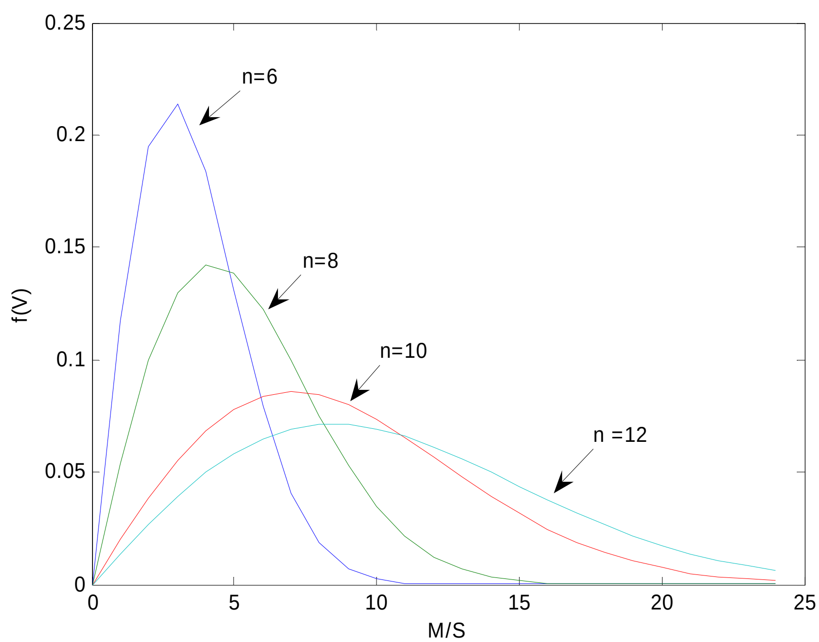

Figure 2-10 Weibull Probability Distribution Function with Shape Parameter β = 2 and Scale Parameter η = 6, 8, 10, and 12.

2.6.4.2 Weibull Parameter Estimation

There are a lot of ways to calculate the Weibull parameter. Some technique use to calculate the Weibull parameters are: probability plots, least square parameter estimation, Maximum likelihood estimators, typical shape factors values, Justus Approximation, and the Quick Method, [Ramos 2005]. For purpose of this thesis, we will use the Maximum likelihood and the typical shape factors.

The maximum likelihood estimation (MLE) method, from a statistical point of view, is considered to be the most robust of the parameter estimation techniques [Reliasoft 2000]. Maximum likelihood estimation works by developing a likelihood function based on the available data and finding the values of the parameter estimates that maximize the likelihood function. The basic concept is to obtain the most likely values of the distribution parameters that best describe a given data set. This can be achieved by using iterative methods to determine the parameter estimate values that maximize the likelihood function, but this can be rather difficult and time-consuming. Another method of finding the parameter estimates involves taking the partial derivatives of the likelihood function with respect to the parameters, setting the resulting equations equal to zero, and solving simultaneously to determine the values of the parameter estimates, [Reliasoft 2000, Montgomery and Runger 1998, Ramos 2005].

The software MATLAB [Matlab] has a built-in function that easily calculates the Weibull pdf parameters using maximum likelihood estimation. The function name is (wblfit) and estimates the parameters (β) and (η) for a given input data vector. The Input data usually are values of wind speed per hour in a year. Standard year has 8760 hours meaning you could have 8760 values of wind speed. In other cases the only value available is the average wind speed per year or the averages wind speed per month. In those cases using the maximum likelihood estimation will result in a bad approximation due to insufficient data points. An alternative is to use typical shape factors values. The shape factor will normally range from 1 to 3. These typical values are known from experience and multiple observations of sites where wind speed measurements have been taken. These wind types are categorized as inland, coastal, and trade wind (off-shore) sites. Table 2-6 shows typical values for the shape factor. [RETSCREEN]

TABLE 2-6 Typical Shape Factor Values

Type of Wind	Shape Factor (β=k)
Inland Winds	1.5 to 2.5
Coastal Winds	2.5 to 3.5
Trade Winds	3 to 4

The scale factor (η) can be calculated using the following equation 2.7, [Jangamshetti and Gruruprasada 1999]:

$$\eta = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{\beta}\right)} \qquad \textbf{2-7}$$

Where $\bar{v}$ is the average wind speed value and Γ is the gamma function, [Arfken and Weber 1985]. The average wind speed can be estimated using the equation 2-8:

$$\bar{v} = \left(\frac{1}{N}\sum_{i=1}^{N} v_i^n\right)^{\frac{1}{n}} \qquad \textbf{2-8}$$

Where $\bar{v}$ is the actual wind speed measurement at interval i, N is the total number of wind speed measurements, and n = 1 for arithmetic mean, n = 2 for root mean square, and n = 3 for cubic root cube.

In summary we use typical shape factor when the only data available are average wind speed. If the available data you have has sufficient wind speed values then we use the maximum likelihood method [Ramos 2005].

2.6.5 Calculating the Mean Wind Speed Using the Weibull PDF

2.6.5.1 Arithmetic Mean Wind Speed

The arithmetic mean wind speed is what is normally known as the average wind speed. The arithmetic mean (average) wind velocity in meters per second is given by

$$V_{avg} = \int_{0}^{\infty} f(v)v\,dv = \int_{v\min}^{v\max} f(v)v\,dv \qquad \textbf{2-9}$$

Where $f(v)$ is the Weibull pdf, v is the measured wind speed data vector, $v\min$ is the minimum wind speed measured and $v\max$ is the maximum wind speed measured. [Ramos 2005]

2.6.5.2 Cubic Root Cube Wind Speed

The use of arithmetic mean tends to underestimate the electric energy production. A case study made in Kappadaguda, India, [Jangamshetti and Guruprasada 1999, Patel 2006], suggests that the Cubic Root Cube (CRC) wind speed produces a better estimate of actual energy production.

To find the cubic root cube average speed the wind speed data vector is elevated to the cube and multiplied by the pdf. The function is integrated between $v\min$ and $v\max$, and then it is elevated to the one third (cubic root). The result is the cubic root cube (CRC) average speed in meters per second. The CRC average wind speed is defined as,

$$V_{CRC} = \sqrt[3]{\int_{v\min}^{v\max} f(v) v^3 dv} \qquad \textbf{2-10}$$

Where $f(v)$ is the Weibull pdf, v is the measured wind speed data vector, $v\min$ is the minimum wind speed measured and $v\max$ is the maximum wind speed measured.

2.6.6 Calculating the Wind Energy

Energy is power over some unit of time. It's is energy that we're after. Its energy in kilowatt-hours (kWh) that we store in the batteries of an off-the-grid hybrid system, or energy in kWh that we sellback to the utility by net-metering. There are many methods to calculate the energy available from the wind, [Ramos 2005]. For the purpose of this thesis the method we will use to calculate energy in the wind is the energy probability function (epf). Energy probability function (epf) per unit area is defined as,

$$\frac{e(v)}{A} = \frac{1}{2} \rho V^3 f(v)(hours)(days) \qquad \textbf{2-11}$$

Where $e(v)$ is the epf, ρ is the air density in (kg/m^3), A is the area where wind is passing (m^2), V is the wind speed in (m/s), $f(v)$ is the Weibull pdf, and the product hours-days represents the number of hours in the period of analysis. The period of analysis can be a month or a year. The units of $e(v)$ are (Wh). The epf can be plotted and numerically integrated.

After plotting the epf the next step is to integrate the expression, as shown in Equation 2.12 in order to obtain the total energy for the given period. The Limits of integration are the minimum wind speed and the maximum wind speed measured.

$$\frac{E}{A} = \int_{v\min}^{v\max} \frac{e(v)}{A} dv \qquad \textbf{2-12}$$

A fast way for calculate the energy in the wind is using the average wind speed value. The energy production can be calculated substituting the average (arithmetic or crc) wind speed value in the power equation, Equation 2.2. Then multiplying the power equation by the hours of the period the energy is available as shown in Equation 2.13.

$$E = \frac{1}{2} \rho A V^3 (hours)(days) \qquad \textbf{2-13}$$

Where E is the total energy in (Wh) and the area is a constant. The variable V can be either the arithmetic mean wind speed or the cubic root cube wind speed, but using the crc wind speed the results from Equation 2.12 are similar to the results from Equation 2.10. This shows in principle that the crc wind speed is a better estimation of the average wind speed than the arithmetic mean wind speed. Remember this is only the energy in the wind. To calculate the energy generated in a small wind turbine the equation must be multiplied by the efficiency of the turbine and the area must be equal to the rotor swept area. For purpose of this thesis we won't use this equation to calculate the power in the turbine. In the next section we explain the method we used to calculate the expected energy that can be produced using the power curve of wind turbines.

2.7 Energy Available in Small Wind Turbines

To calculate the kWh generated in a year by a wind turbine, the wind speed distribution (pdf) for the site is required, then using the wind turbine power curve the annual energy output is estimated. A power curve is a graph give by the manufacture that specifies the power that the wind turbine will produce for any wind speed data, (See section 2.4.4). The energy available for a wind turbine at a specific site is

$$E_{WT} = (days)(hours)\sum_{v=1}^{25} P_c f(v,\beta,\eta) \qquad \textbf{2-14}$$

Where E_{WT} is the expected wind turbine energy production in kWh of the site, the product of days and hours gives the total hours in the period of analysis, P_c is the turbine power output at wind speed v, and $f(v)$ is the Weibull probability density function for wind speed v, shape parameter β and scale parameter η.

Essentially you match the speed distribution with the power curve to find the number of hours per year the wind turbine will be generating at various power levels.

2.8 Example for Calculating the Power Available in Small Wind Turbines

Assume for the purpose of this example a site that have a Weibull probability distribution function with shape parameter β = 2 and scale parameter η = 6, as shown in figure 2.11. For this probability density function the average wind speed is of 5.3 m/s. Then we must select a wind turbine. For this example let's use the Sky Stream wind turbine and its' power curve shown in figure 2.12. Finally the estimated annual energy output for the wind turbine can be calculated using equation 2.13.

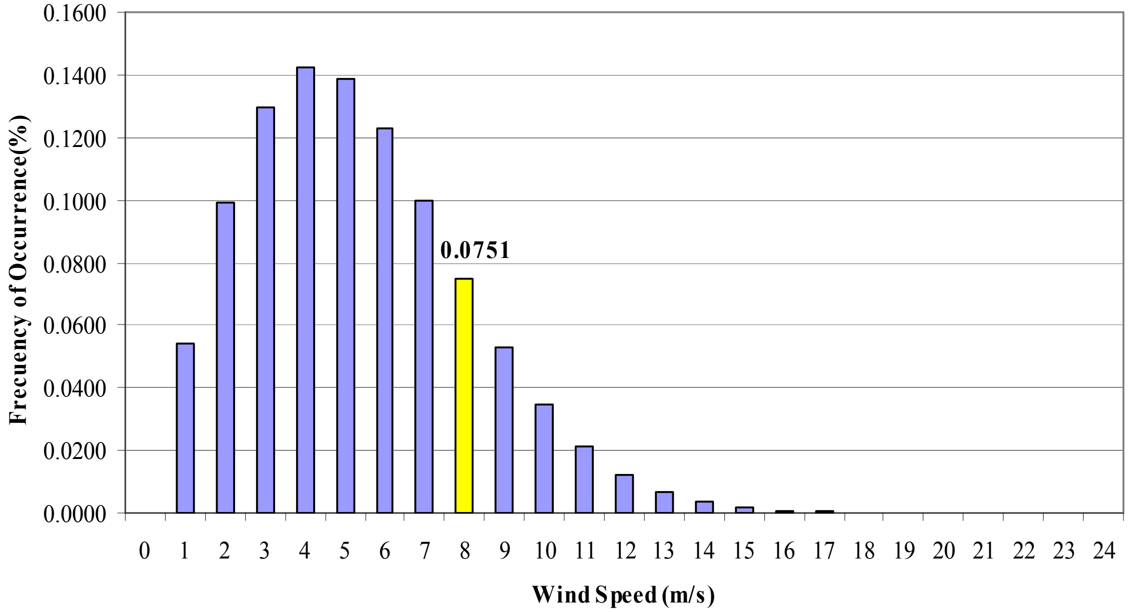

Figure 2-11 Weibull Probability Distribution Function with Scale Parameter η = 6 and Shape Parameter β = 2.

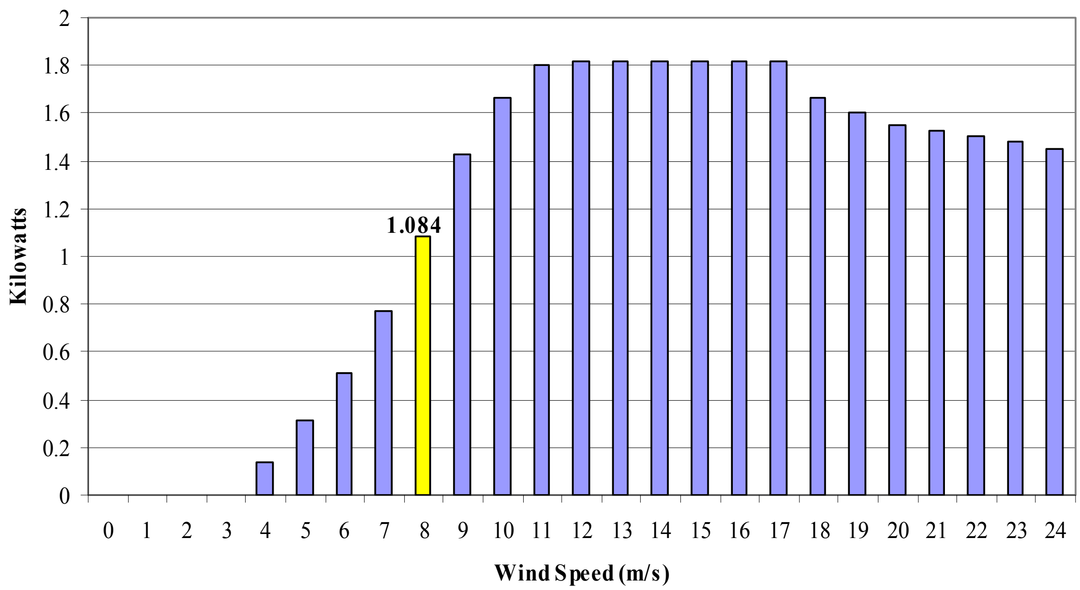

Figure 2-12 Sky Stream Wind Turbine Power Curve

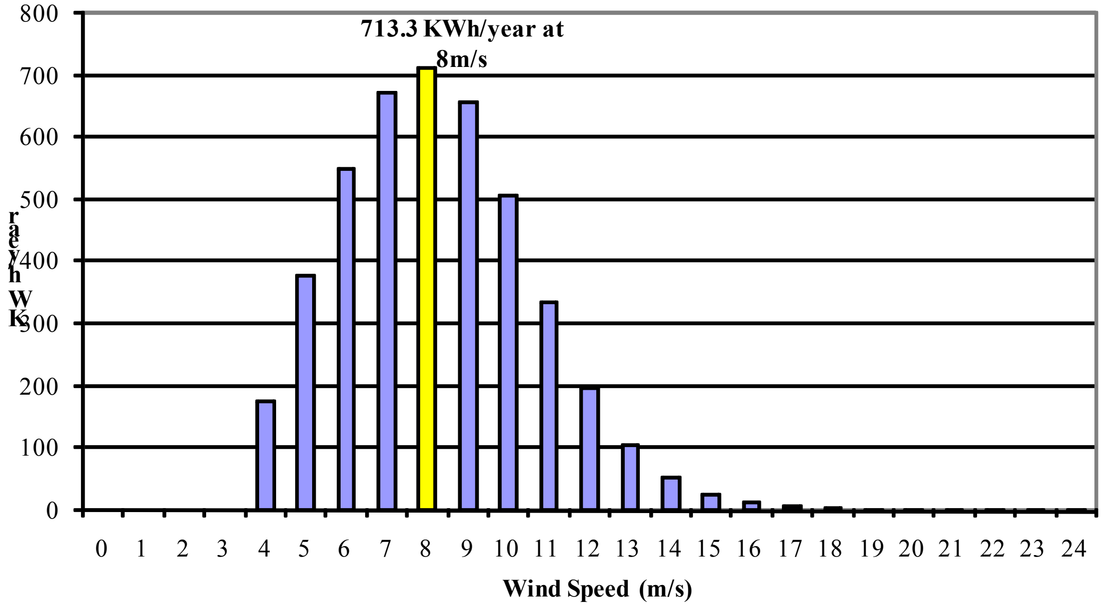

Figure 2-13 Estimated Annual Energy Output using Sky Stream Power Curve

For example, at a wind speed of 8 m/s the Sky Stream wind turbine will produce 1.084 kW. Wind occurs at this speed about 0.0751% year. A year has 8760 hours, thus (0.0751)*(8760) = (657.8 hours) the wind is at 8m/s. Then we can estimate the annual energy output multiplying (1.084kW)*(657.8hours) = (713 kWh/year at 8m/s). See figure 2.13. To calculate the total energy output in a year you only need to integrate the curve in figure 2.13. For this example the total energy in a year that can be generated is 4379 kWh/year.

3 PHOTOVOLTAIC POWER SYSTEMS

3.1 Introduction

Photovoltaic (PV) solar cells made of semiconductors materials generates electrical power, measured in Watts or Kilowatts, when they are illuminated by photons. Many PV have been in continuous outdoor operation on Earth or in space for over 30 years [Luque et al. 2003].

3.2 History

The photovoltaic history starts in 1839 when a French physicist Alexander Edmond Becquerel discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes. When the cells were exposed to light the generation of electricity increased [USDE 2004]. In 1954 Bell Laboratories produced the first silicon cell. It soon found applications in U.S. space programs for its high power-generation capacity per unit weight. Since then it has been extensively used to convert sunlight into electricity for earth-orbiting satellites. Having matured in space applications, PV technology is now spreading into terrestrial applications ranging from powering remotes sites to feeding utility grids around the world. Economically speaking in the past the PV cost was very high. For that reason, PV applications have been limited to remote locations not connected to utility lines. But with the declining prices in PV, the market of solar modules has been growing at 25 to 30% annually during the last 5 yr [Patel 2006]. Table 3.1 shows the total cumulative installed capacity of PV modules installed in different part of the world. Figure 3.1 shows the growth in PV cumulative total capacity from 1993 to 2006. This growth is attributed to decrease in PV prices and the high cost of fossil fuels.

TABLE 3-1 Cumulative Installed PV Power, [IEA 2007]

[redacted]

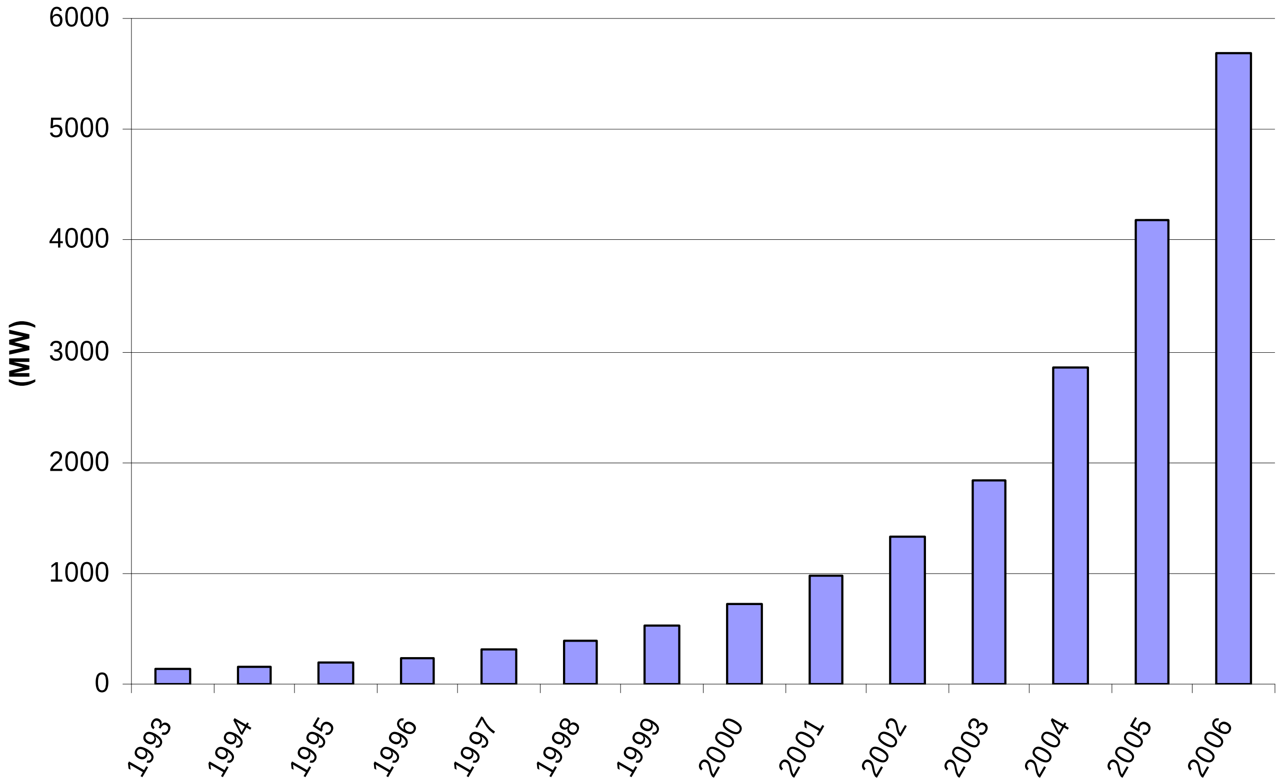

Figure 3-1 Cumulative Installed PV Power [IEA 2007]

3.3 Photovoltaic

The solar cells that are used on calculators and satellites are photovoltaic cells or modules. This PV module consists of many PV cells wired in parallel order to increase current and in series to produce a higher voltage. Use of 36 cell modules are the industry standard for large power production. When we speak of a PV panel it means any number of PV modules and when we speak of array it means any number of PV panels. See figure 3.2.

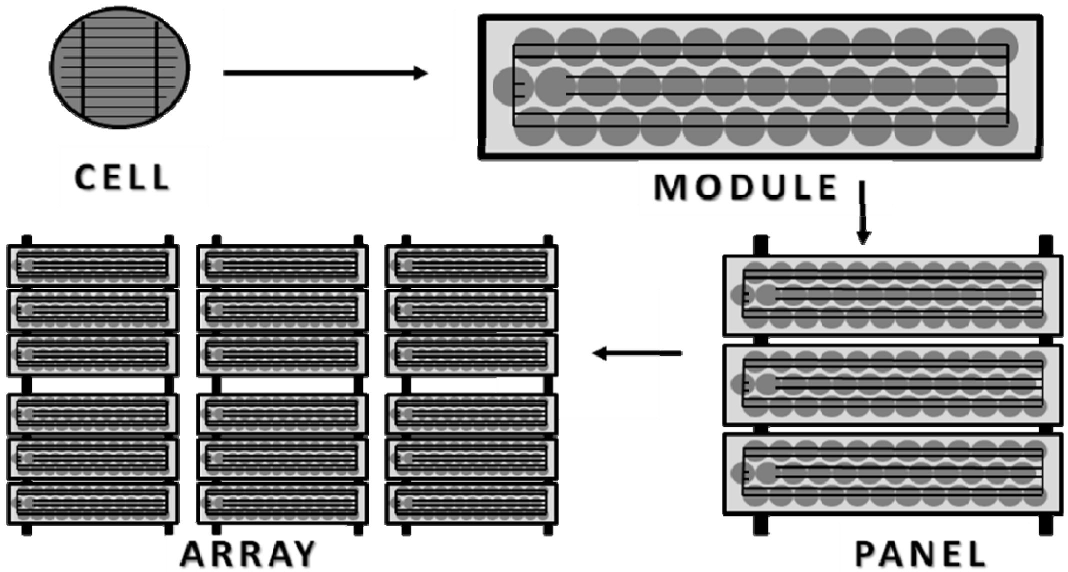

Figure 3-2 PV Diagram

3.3.1 Photovoltaic Cells and Efficiencies

PV cells are made up of semiconductor material, such as silicon, which is currently the most commonly used. Basically, when light strikes the cell, a certain portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely. PV cells have one or more electric fields that act to force electrons that are freed by light absorption to flow in a certain direction. This flowing of electrons is a current and by placing metal contacts on the top and bottom of the PV cell we can draw that current off to be used externally. For example, the current can power a calculator. This current, together with the cell's voltage, which is a result of its built-in electric field or fields, defines the power in watts that the solar cell can produce [Patel, 2006].

There are currently five commercial production technologies for PV cells:

- Single Crystalline Silicon: This is the oldest and more expensive production technique, but it's also the most efficient sunlight conversion technology available. Cells efficiency averages between 11% and 16%
- Polycrystalline or Multi-crystalline Silicon: This has a slightly lower conversion efficiency compared to single crystalline and manufacturing costs are also lower. Cells efficiency averages between 10% and 13%
- String Ribbon: This is a refinement of polycrystalline silicon production. There is less work in its production so costs are even lower. Cells efficiency averages 8% to 10%
- Thin Film “copper-indium-diselenide”: This is a promising alternative to silicon cells. They are much more resistant to effect of shade and high temperatures, and offer the promise of much lower cost. Cells efficiency averages 6% to 8%
- Amorphous: Made when silicon material is vaporized and deposited on glass or stainless steel. The cost is lower than any other method. Cells efficiency averages 4% to 7%

Cells efficiency decreases with increases in temperature. Crystalline cells are more sensitive to heat than thin films cells. The output of a crystalline cell decreases approximately 0.5% with every increase of one degree Celsius in cell temperature. For this reason modules should be kept as cool as possible, and in very hot condition amorphous silicon cells may be preferred because their output decreases by approximately 0.2% per degree Celsius increase. [Antony et al. 2007]

3.3.2 Photovoltaic Modules

A PV module is composed of interconnected photovoltaic cells encapsulated between a weather-proof covering (usually glass) and back plate (usually a plastic laminate). It will also have one or more protective by-pass diodes. The output terminals, either in a junction box or in a form of output cables, will be on the back. Most have frames. Those without frames are called laminates. In some, the back plate is also glass, which gives a higher fire rating, but almost doubles the weight [Antony et al. 2007].

The cells in the modules are connected together in a configuration designed to deliver a useful voltage and current at the output terminals. Cells connected in series increases the voltage output while cells connected in parallel increases the current. A group of several PV modules are connected together are called a solar array.

3.3.2.1 Photovoltaic Power

In this thesis, the power production of PV array will be calculated using two methods. In [Ortiz 2006] a photovoltaic module model based on the electrical characteristics provided by the manufacturer is presented. The model predicts power production by the photovoltaic module for different temperatures and irradiance levels. Equations 3-1 - 3-4 show the model:

$$I(V) = \frac{Ix}{1-\exp\left(\frac{-1}{b}\right)} \cdot \left[1-\exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)\right] \quad \textbf{3-1}$$

$$\begin{aligned} Vx = s \cdot \frac{\mathrm{E_i}}{\mathrm{E_{iN}}} \cdot TCV \cdot (T - T_N) + s \cdot V_{\max} \\ - s \cdot (V_{\max} - V_{\min}) \cdot \exp\left(\frac{E_i}{E_{iN}} \cdot \ln\left(\frac{V_{\max} - V_{oc}}{V_{\max} - V_{\min}}\right)\right) \end{aligned} \quad \textbf{3-2}$$

$$Ix = p \cdot \frac{\mathrm{E_i}}{\mathrm{E_{iN}}} \cdot \left[I_{sc} + TCi \cdot (T - T_N)\right] \quad \textbf{3-3}$$

$$P(V) = \frac{V \cdot Ix}{1-\exp\left(\frac{-1}{b}\right)} \cdot \left[1-\exp\left(\frac{V}{b \cdot Vx} - \frac{1}{b}\right)\right] \quad \textbf{3-4}$$

Where:

$P = Output\ power\ of\ the\ photovoltaic\ panel\ (I(V) \cdot V)$

$I(V) = Output\ current\ of\ the\ photovoltaic\ panel$

$V = Output\ voltage\ of\ the\ photovoltaic\ panel$

$I_{sc} = Short-circuit\ current\ at\ 25°C\ and\ 1000W/m^2$

$V_{oc} = Open-circuit\ voltage\ at\ 25°C\ and\ 1000W/m^2$

$V_{\max} = Open-circuit\ voltage\ at\ 25°C\ and\ 1200W/m^2$

$(ussually, V_{\max}\ is\ close\ to\ 1.03 \cdot V_{oc})$

$V_{\min} = Open-circuit\ voltage\ at\ 25°C\ and\ 200W/m^2$

$(ussually, V_{\max}\ is\ close\ to\ 0.85 \cdot V_{oc})$

$T = Solar\ panel\ temperature\ in\ °C$

$E_i = Effective\ solar\ irradiation\ impinging\ the\ cell\ in\ W/m^2$

$T_N = 25°C\ Sta\ dard\ Test\ Condition\ (STC)$

$E_{iN} = 1000W/m^2\ Sta\ dard\ Test\ Condition\ (STC)$

$TC_i = Temperature\ coefficient\ of\ I_{SC}\ in\ A/°C$

$TCV = Temperature\ coefficient\ of\ V_{OC}\ in\ V/°C$

$Ix = Short\ circuit\ current\ at\ any\ given\ E_i\ and\ T$

$Vx = Open\ circuit\ voltage\ at\ any\ given\ E_i\ and\ T$

$s = Photovoltaic\ panel\ in\ series$

$p = Photovoltaic\ panel\ in\ parallel$

$b = Characteristic\ consta\ nt\ based\ on\ the\ I-V\ Curve$

The characteristic constant, b, is obtained using Equitation 3-5 following an iterative procedure. Usually b range from 0.01 to 0.18.

$$b_{n+1} = \frac{V_{op} - V_{oc}}{V_{oc} \cdot \ln\left(1 - \frac{I_{op}}{Isc} \cdot \left(1 - \exp\left(\frac{-1}{b_n}\right)\right)\right)} \qquad \textbf{3-5}$$

A simpler method to calculate the power produced by a solar module is using the photo conversion efficiency formulas [Patel, 2006], as shown in Equation 3-6 – 3-7.

$$\eta = \frac{P_{STC}}{E_{iN}} \qquad \textbf{3-6}$$

$$P_{out} = \eta \cdot E_i \cdot C_f \quad \textbf{3-7}$$

$Where:$
$\eta = Photoconversion\ efficiency$
$P_{STC} = Power\ at\ 25°C\ and\ 1000W/m^2$
$E_{iN} = 1000\ W/m^2\ Standard\ Test\ Condition\ (STC)$
$P_{out} = Power\ Output$
$E_i = Effective\ solar\ irradiation\ impinging\ the\ cell\ in\ W/m^2$
$C_f = Correction\ factor\ for\ \eta$

This method quicker and only need the power produced by the PV module at 1000 W/m² and the irradiance level reaching the module. The method assumes that the efficiency of the solar module is constant at any irradiance level. In theory is not the same, the efficiency is lower at low irradiance levels, but the change is practically constant over a wide range of radiation. Figure 3-3 presents photo conversion efficiency vs. solar radiation of a solar module Kyocera KC200. We see from the graph that a change in radiation from 600W/m² to 1000W/m² only produce an efficiency change of 5%. This suggests a correction factor of 95% while using the quick estimate method.

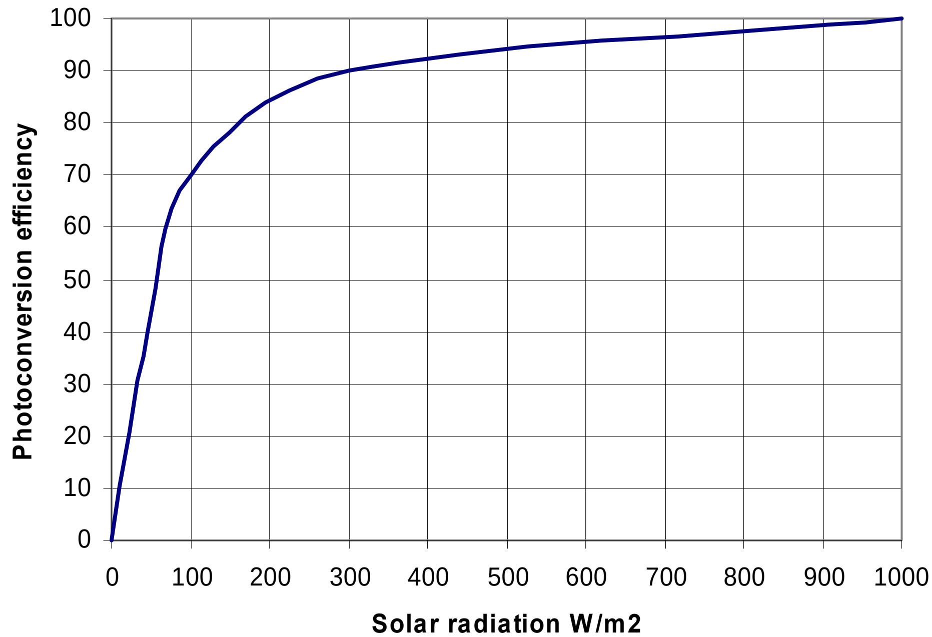

Figure 3-3 Photo Conversion Efficiency vs. Solar Radiation

3.3.2.2 Photovoltaic Energy

To calculate the kWh generated in a year at a specific site we use hourly average solar radiation values for one year at a given site. Normally there are average daily solar radiation values for each month of the year. Calculate the hourly average and then using the formula 3-4 or 3-7 calculates the power generated hourly by the solar module. Then for calculate the energy available for a PV module at a specific site:

$$E_{PV} = P_{out}(E_x) \cdot (SolarWindow) \cdot (365) \qquad \textbf{3-8}$$

Where E_{PV} is the yearly expected photovoltaic energy production in kWh of the site, the solar window is the time of hours the sun hit the PV module at a average hourly solar irradiation, the product of 365 is to change form daily to yearly quantities; $P_{out}(E_x)$ is the PV module power output at a average hourly solar irradiation (E_x).

3.3.3 Photovoltaic Manufactures

Photovoltaic's modules are available in a range of sizes. Those used in grid tied or stand alone systems range from 80W to 300W. The performance of PV modules and arrays are generally rated according to their maximum DC power output (watts) under the Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25ºC (77 F), an incident solar irradiant level of 1000 W/m² and under Air Mass 1.5 spectral distribution. Since these conditions are not always present PV modules and arrays operate in the field with performance of 85 to 90 percent of the STC rating. Tables 3-2 and 3-3 present the PV modules specification used in this thesis. All the data was taken from the manufacture's data sheet. Price of each module where obtained in January 2008 from the vendors.

TABLE 3-2 Solar Module Power at STC Rating and Price

Solar Module Brand	Photoconversion efficiency	Watt at 1000W/m²	US$/Unit	US$/Watt	Solar Panel Vendor
Kyocera Solar (KC200)	0.20	200	$800.00	**$4.00**	www.advancepower.net
BP Solar (SX 170B)	0.17	170	$728.97	**$4.29**	www.thesolarbiz.com
Evergreen (Spruce ES-170)	0.17	170	$731.00	**$4.30**	www.beyondoilsolar.com
Evergreen (Spruce ES-180)	0.18	180	$774.00	**$4.30**	www.beyondoilsolar.com
Evergreen (Spruce ES-190)	0.19	190	$817.00	**$4.30**	www.beyondoilsolar.com
Solar World (SW-165)	0.17	165	$709.97	**$4.30**	www.thesolarbiz.com
Mitsubishi (PV-MF155EB3)	0.16	155	$669.97	**$4.32**	www.thesolarbiz.com
Sharp (ND-208U1)	0.21	208	$898.56	**$4.32**	www.beyondoilsolar.com
Sharp (NE-170U1)	0.17	170	$739.50	**$4.35**	www.beyondoilsolar.com
Mitsubishi (PV-MF165EB4)	0.17	165	$719.97	**$4.36**	www.thesolarbiz.com
Sunwize (SW150)	0.15	150	$668.31	**$4.46**	www.infinigi.com
Kyocera (KC175GT)	0.18	175	$799.00	**$4.57**	www.affordable-solar.com
Kyocera (KC175GT)	0.18	175	$799.00	**$4.57**	www.affordable-solar.com

TABLE 3-3 Solar Module Data Sheet Specification at STC Rating

[redacted]

Today's photovoltaic modules are extremely safe and reliable products, with minimal failure rates and projected service lifetimes of 20 to 30 years. Most major manufacturers offer warranties of twenty or more years maintaining a high percentage of the initial rated power output.

3.4 Solar Resources

Solar radiation provides a huge amount of energy to the earth. The total amount of energy, which is irradiated from the sun to the earth's surface, equals approximately 10,000 times the annual global energy consumption. On average, 1,700 kWh per square meter is insolated every year [Patel 2006].

The light of the sun, which reaches the surface of the earth, consists mainly of two components: direct sunlight and indirect or diffuse sunlight, which is the light that has been scattered by dust and water particles in the atmosphere. Photovoltaic cells not only use the direct component of the light, but also produce electricity when the sky is overcast. To determine the PV electricity generation potential for a particular site, it is important to assess the average total solar energy received over the year, rather than to refer to instantaneous irradiance. Some example of this average is the NREL annual solar radiation for United States and U.S. territories [NREL]. The annual daily solar radiation per month is shown in figure 3-4.

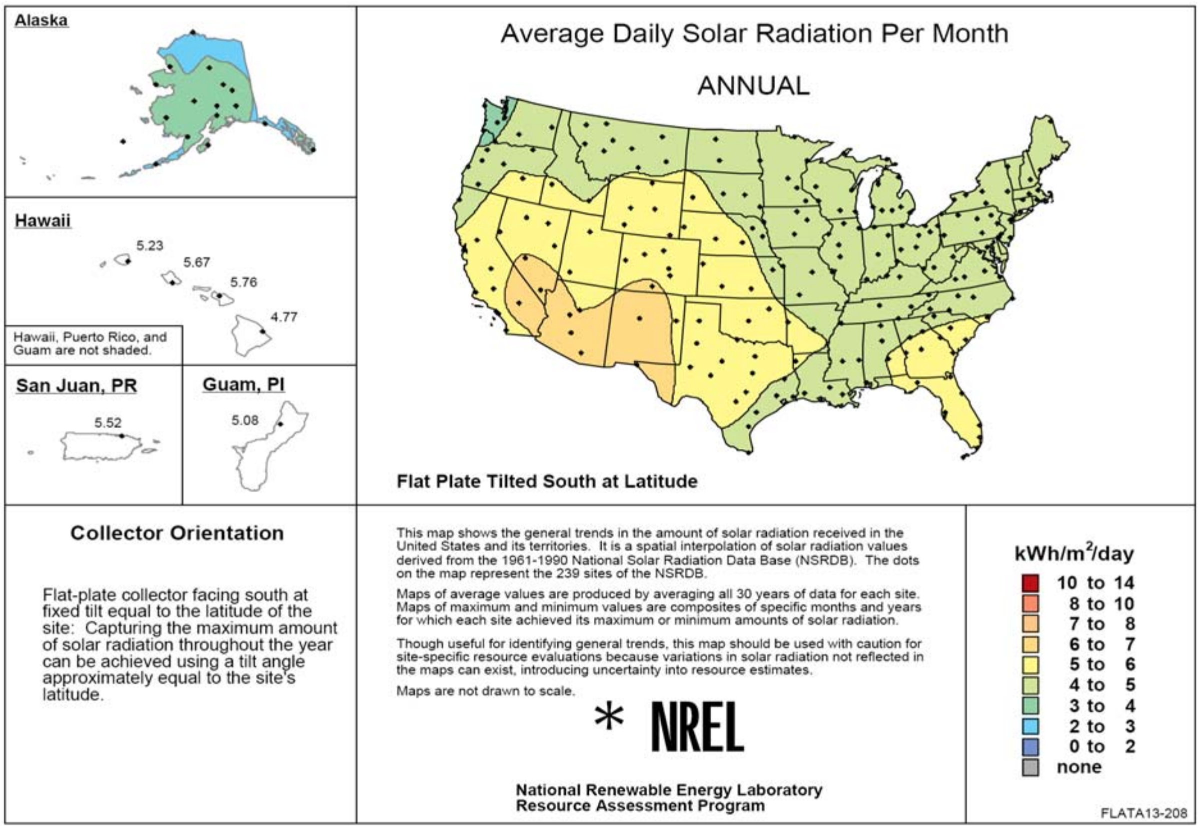

Figure 3-4 Annual Daily Solar Radiation per Month [NREL]

When using photovoltaic cells, this radiation can be used to generate electricity. When sunlight strikes a photovoltaic cell a direct current DC is generated. By putting an electric load across the cell this current can be collected. Not all of the light can be converted into electricity since PV cells use mainly visible light. A lot of the sun's energy is in IR- or warmth- and UV radiation, which explains why theoretical conversion efficiencies are as low as 20-30%. Practical deficiencies such as impurities may decrease the performance of a photovoltaic cell even further.

The amount of useful electricity generated by a PV module is directly generated to the intensity of light energy, which falls onto the conversion area. In other words, the greater the available solar resource, the greater the electricity generation potential. The tropics, for instance, offer a better resource for generating electricity than what is available at high latitudes. It also follows that a PV system will not generate electricity at night, and it is important that modules are not shaded. If electricity is required outside daylight hours, or if extended periods of bad weather are anticipated, some form of storage system is essential.

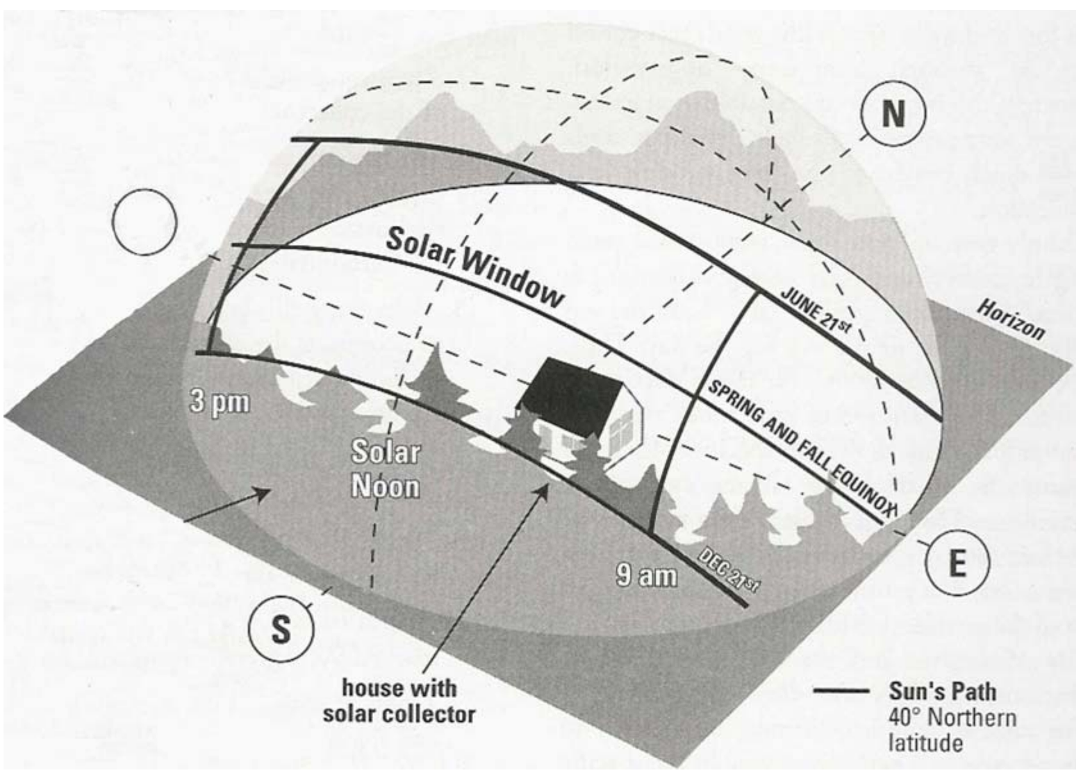

Figure 3-5 The Solar Window [PVDI 2004]

In order to capture as much solar energy as possible, the photovoltaic cell must be oriented towards the sun. If the photovoltaic cells have a fixed position, their orientation with respect to the south (northern hemisphere), and tilt angle, with respect to the horizontal plane, should be optimized. For grid-connected PV systems in Western Europe, the optimum tilt angle is about 35 degrees. For regions nearer to the equator, this tilt angle will be smaller, for regions nearer to the poles it will be larger. A deviation of the tilt angle from the optimum angle, will lead to less power to be capture by the photovoltaic system.

For example Puerto Rico is located at the Latitude 18º 15' N and longitude 66º 30' W, meaning that the tilt angle for the island should be 18º 15' N.

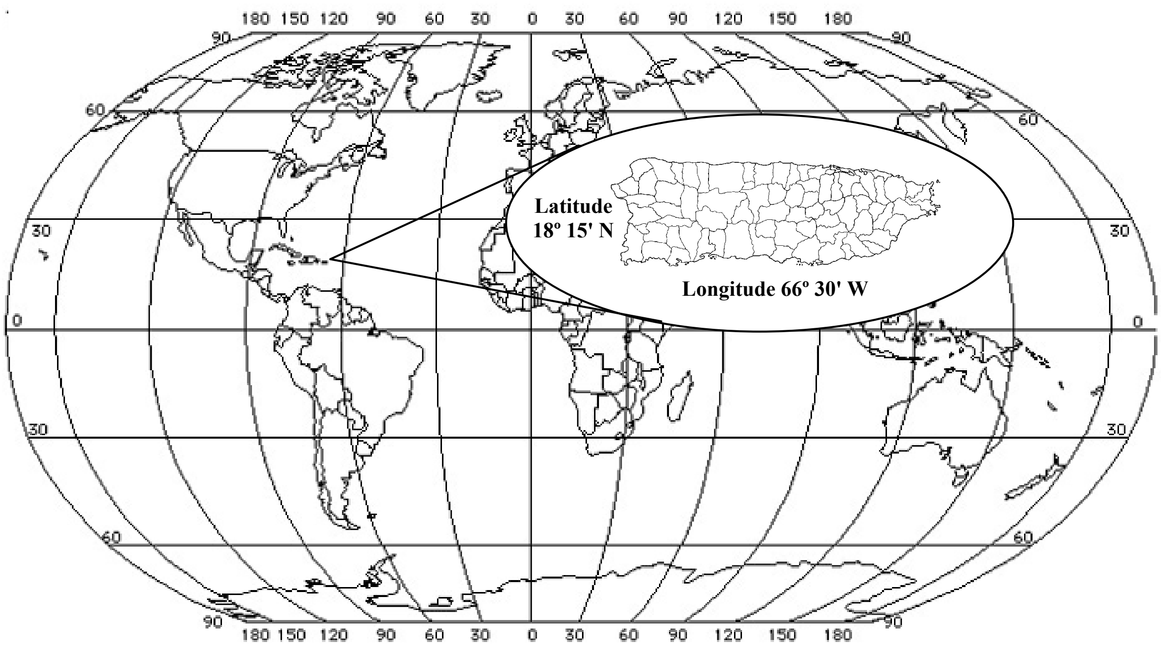

Figure 3-6 Puerto Rico Latitude and Longitude

PV modules are actually more efficient at lower temperatures, so to ensure that they do not overheat, it is essential that they are mounted in such a way as to allow air to move freely around them. This is an important consideration in locations that are prone to extremely hot midday temperatures. The ideal PV generating conditions are cold, bright, sunny days. [IEA 2006]

3.4.1 Puerto Rico Solar Resources

Solar resources is an important factor for know how many power can be generated by a photovoltaic system. In the past many studies have bean done for Puerto Rico. Table 3-4 presents a summary of published solar radiation at different places in Puerto Rico. The table shows monthly averages in kWh/m². It can be noted from the table that Cabo Rojo, Juana Diaz and Ponce has the highest solar radiation values and Rio Grande (El Yunque Mountains) has the lowest. For purpose of this thesis the average day temperature for the island will be 32.5ºC. This is the average temperature day light hours in Puerto Rico, [Soderstrom, 1989].

TABLE 3-4 Daily Averages Solar Energy in kWh/m²

	[Soderstrom, 1989]						[Briscoe, 1966]			[Zapata]			[NREL]	
	Mayaguez	San Juan	Ponce	Cabo Rojo	Cataño	Manatí	Fajardo	Rio Grande	Gurabo	Juana Diaz	Isabela	Lajas	Aguadilla	Ceiba
JAN	3.99	4.11	4.57	4.58	4.44	4.22	4.41	2.77	4.72	4.97	4.58	3.78	4.10	3.67
FEB	4.29	4.50	5.21	5.31	6.17	4.58	5.56	3.35	5.42	5.69	5.36	4.75	4.78	4.25
MAR	4.76	5.34	5.86	6.17	5.28	6.03	5.73	3.81	3.73	6.50	5.86	5.89	5.33	5.06
APR	5.00	5.23	6.03	5.39	5.64	6.11	5.50	2.52	5.95	5.83	4.33	5.61	5.11	4.48
MAY	4.31	4.25	5.33	6.42	4.61	5.31	7.00	3.36	6.21	6.28	6.44	5.53	5.72	5.10
JUN	4.87	5.12	5.55	6.56	4.67	6.53	3.51	3.35	5.91	5.81	5.83	5.33	5.51	4.76
JUL	4.54	5.65	6.22	6.19	6.83	5.78	6.76	3.49	5.44	5.86	6.03	5.36	5.81	5.08
AUG	4.77	5.25	6.11	5.69	5.83	5.28	3.19	3.84	5.15	5.11	5.64	5.67	5.43	4.86
SEP	4.62	4.55	5.65	6.03	4.97	4.92	5.87	3.68	3.76	5.81	5.08	5.19	5.32	4.65
OCT	4.23	4.44	5.06	5.25	4.72	4.83	2.45	2.86	3.27	5.42	5.14	5.14	4.72	4.27
NOV	4.08	4.06	4.75	4.92	4.47	4.53	4.76	1.72	2.80	5.00	4.94	4.72	4.03	3.58
DEC	3.65	3.61	4.11	3.94	4.11	3.78	3.54	1.78	3.49	4.22	4.39	4.33	3.75	3.43
Monthly Average	4.43	4.68	5.37	5.54	5.15	5.16	4.86	3.04	4.66	5.54	5.30	5.11	4.97	4.43

3.5 Example to Calculated the Power Generated by a Solar Module

Lets calculates how many module are needed to supply a load of 4000W in the city of San Juan, Puerto Rico. First we need the solar resource at the site. For example the solar radiation during the month of January in San Juan, from Table 3-4, is 4.11kWh/m² a day. If we assume a solar window of 6 hours, we obtain (4.11kWh/m²)/(6h) = 685 W/m² per hour of solar radiation during 6 hours. Assume a temperature of 32.5ºC for the example and the Kyocera Solar (KC200) module which produce 200W at 1000W/m² and 25ºC.

Using the formulas 3-1 to 3-4 of [Ortiz 2006] we can compute the power generated by the photovoltaic module. Figures 3-7 and 3-8 show graphically the power vs. voltage "P-V" curve and current vs. voltage "I-V" curve obtained by applying Ortiz formula. Note in the P-V curve that at 1000W/m² the module generated the same power that the manufacture specifies 200W. Then changing the radiation level to 685W/m², the power of the photovoltaic module drop to 132W. We can see in the I-V curve that the current drops 30% when the radiation level is change to 685W/m².

Now for calculate the number of solar module that need the system using the Ortiz model, take the load power of 4000W and divide it by the power generated from the solar module (4000W)/(132) = 30.3 meaning we need 31 Kyocera solar module to generate the enough power for a load of 4000W.

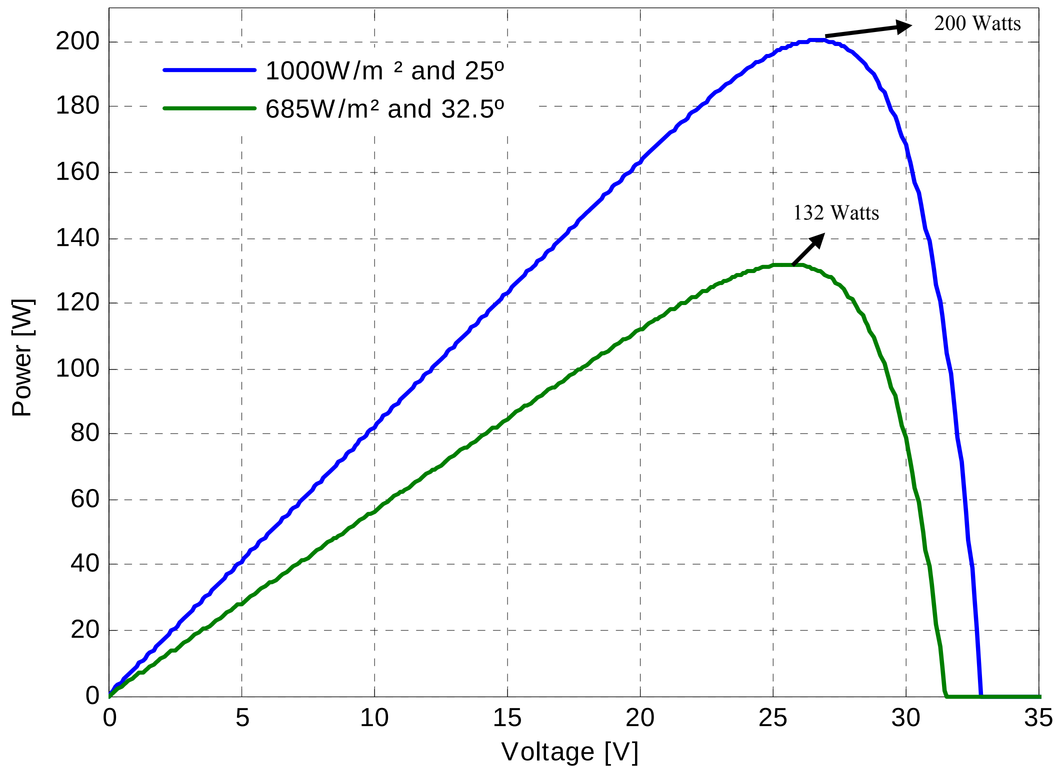

Figure 3-7 P-V Curve for the Kyocera Module at 1000W/m² and 685W/m²

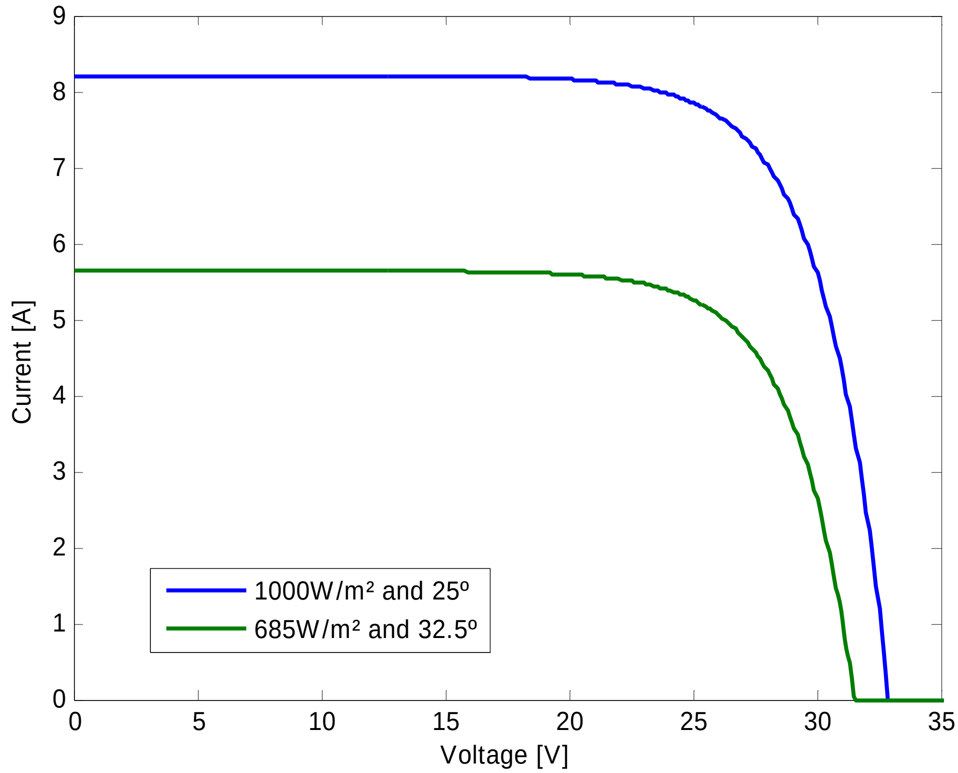

Figure 3-8 I-V Curve for the Kyocera Module at 1000W/m² and 685W/m²

Now let's use the second, quick method to calculate the power of the Kyocera photovoltaic module and compare it with the first method. Using the formula 3-6 we calculate the photo conversion efficiency by dividing (200)/(1000) = (0.2). Now using the formula 3-7 we can calculate the power by multiplying (685)*(.95)*(02) = 130W. The .95 is the correction factor. We can conclude that both methods find the same power generation value with a percent different of 1.5%.

Now for calculate the number of solar module that need the system using the quick method, take the load power of 4000W and divide it by the power generated from the solar module (4000W)/(130) = 30.7 meaning we need 31 Kyocera solar module to generate the enough power for a load of 4000W.

4 BATTERIES, PV CONTROLLER AND INVERTERS

4.1 Introduction

A battery is a device that stores Direct Current (DC) electrical energy in electrochemical form for later use. The amount of energy that will be storage or deliver from the battery is managed by the controller or the inverter. The inverter converts the DC electrical energy to Alternative Current (AC) electrical energy, which is the energy that most residential homes use.

4.2 Batteries

Electrical energy is stored in a battery in electrochemical form and is the most widely used device for energy store in a variety of application. The conversion efficiency of batteries is not perfect. Energy is lost as heat and in the chemical reaction, during charging or recharging. Because not all battery's can be recharged they are divided in two groups. The first group is the primary batteries which only converts chemical energy to electrical energy and cannot be recharged. The second group is rechargeable batteries. Rechargeable batteries are used for hybrid wind / PV system.

The internal component of a typical electrochemical cell has positive and negative electrodes plates with insulating separators and a chemical electrolyte in between. The cells store electrochemical energy at a low electrical potential, typically a few volts. The cell capacity, denoted by C, is measured in ampere-hours (Ah), meaning it can deliver C A for one hour or C/n A for n hours, [Luque et al. 2003].

4.2.1 Battery Manufacturers

Many types of batteries are available today like for example: Lead-acid, Nickel-cadmium, Nickel-metal, Lithium-ion, Lithium-polymer and Zinc air. Lead-acid rechargeable batteries continue to be the most used in energy storage applications because of its maturity and high performance over cost ratio, even though it has the least energy density by weight and volume. These lead acid batteries come in many versions. The shallow- cycle version is the one use in automobiles, in which a short burst of energy is drawn from the battery to start the engine. The deep-cycle version, on the other hand, is suitable for repeated full charge and discharge cycles. Most energy store applications require deep-cycle batteries, [Patel 2006]. Table 4-1 show the lead acid batteries used in this thesis. These specifications are taken from manufactures data sheet and the prices were obtained in January 2008.

TABLE 4-1 Lead-Acid Batteries Information

Flooded Lead-Acid Batteries	Price ($)	Volt	Capacity C/100 (Ah)	Capacity C/72 (Ah)	Capacity C/20 (Ah)	Dimensions (mm) With	Length	Height	Weith (lbs)	Supplier
MK 8L16	288.77	6	420.0		370	11.8	6.0	17.3	113.0	Alternative Energy Store
Surrette 12-Cs-11Ps	1118.96	12	503.0	475	357	11.0	22.0	18.0	272.0	Alternative Energy Store
Surrette 2Ks33Ps	874.9	2	2480.0	2349	1765	8.5	15.5	24.3	208.0	Alternative Energy Store
Surrette 4-CS-17PS	604.23	4	770.0	726	546	8.25	14.375	18.25	128.0	Alternative Energy Store
Surrette 4-Ks-21Ps	1110.44	4	1557.0	1468	1104	9.375	15.75	24.75	267.0	Alternative Energy Store
Surrette 4-Ks-25Ps	1386.85	4	1900.0	1800	1350	10.625	15.75	24.75	315.0	Alternative Energy Store
Surrette 6-Cs-17Ps	906.31	6	770	726	546	8.25	22	18.25	221	Alternative Energy Store
Surrette 6-Cs-21Ps	1075.01	6	963	908	683	9.75	22	18.25	271	Alternative Energy Store
Surrette 6-Cs-25Ps	1241.37	6	1156	1091	820	11.25	22	18.25	318	Alternative Energy Store
Surrette 8-Cs-17Ps	1256.21	8	770.0	726	546	8.3	28.3	18.3	294.0	Alternative Energy Store
Surrette 8-Cs-25Ps	1654.76	8	1156	1091	820	11.25	28.25	18.25	424	Alternative Energy Store
Surrette S-460	324.93	6	460.0	441	350	7.1	12.3	16.8	117.0	Alternative Energy Store
Surrette S-530	370.65	6	530.0	504	400	7.1	12.3	16.8	127.0	Alternative Energy Store
Trojan L16H	357	6			420	7.0	11.6	16.8	121.0	Alternative Energy Store
Trojan T-105	138	6			225	7.2	10.4	10.8	62	Alternative Energy Store
US Battery US185	216.58	12			195	7.1	15.5	14.25	111	Alternative Energy Store
US Battery Us2200	127.99	6			225	7.2	10.25	11.2	63	Alternative Energy Store
US Battery US250	126.35	6			250	7.2	11.7	11.7	72	Alternative Energy Store
Surrette S-460	357.36	6	460	441	350	7.125	12.25	16.75	117	Infinigi
Surrette S-530 6V	406.09	6	530	504	400	7.125	12.25	16.75	127	Infinigi
Surrette 4-CS-17PS	770.45	4	770	726	546	8.25	14.375	18.25	128	Infinigi
Surrette 4-Ks-21Ps	1206	4	1557	1468	1104	9.375	15.75	24.75	267	Infinigi
Surrette 4-Ks-25Ps	1508.83	4	1900	1800	1350	10.625	15.75	24.75	315	Infinigi
Surrette 6-Cs-17Ps	932.31	6	770	726	546	8.25	22	18.25	221	Infinigi
Surrette 6-Cs-21Ps	1164	6	963	908	683	9.75	22	18.25	271	Infinigi
Surrette 6-Cs-25Ps	1349.45	6	1156	1091	820	11.25	22	18.25	318	Infinigi
Surrette 8-Cs-17Ps	1795.71	8	1156	1091	820	11.25	28.25	18.25	424	Infinigi

4.2.2 Battery Sizing

Battery sizing consists in calculating the number of batteries needed for a hybrid renewable energy system. This mainly depends on the days of autonomy desired. Days of autonomy are the number of days a battery system will supply a given load without being recharged by a PV array, wind turbine or another source. If the load being supplied is not critical then 2 to 3 autonomy day are commonly used. For critical loads 5 days of autonomy are recommended. A critical load is a load that must be used all the time.

Another important factor is maximum depth of discharge of the battery. The depth of discharge refers to how much capacity will be use from the battery. Most systems are designed for regular discharges of up to 40 to 80 percent. Battery life is directly related to how deep the battery is cycled. For example, if a battery is discharged to 50 percent every day, it will last about twice long as if is cycled to 80 percent, [PVDI 2007].

Atmospheric temperature also affects the performance of batteries. Manufacturers generally rate their batteries at 25ºC. The battery's capacity will decrease at lower temperatures and increase at higher temperature. The battery's life increases at lower temperature and decreases at higher. It is recommended to keep the battery's storage system at 25 ºC. At 25 ºC the derate factor is one.

The following procedure shows how to calculate the number of batteries needed for a hybrid energy system, [Sandia 2004]. Equation 4-1 shows how to calculate the required battery bank capacity for a hybrid renewable energy system

$$B_R = \frac{L_{Ah/Day} \cdot D_{ST}}{M_{DD} \cdot D_f} \qquad \textbf{4-1}$$

Where $L_{Ah/Day}$ is the Amp-hour consume by the load in a day (Ah/Day), D_{ST} is the number of autonomy days, M_{DD} is the maximum depth of discharge, D_f is the derate factor and B_R is the required battery bank capacity in (Ah).

Equation 4-2 presents how to calculate the number of batteries to be connected in parallel to reach the Amp hours required by the system.

$$B_P = \frac{B_R}{B_C} \qquad \textbf{4-2}$$

Where B_R is the required battery bank capacity in (Ah). B_C is the capacity of the selected battery in (Ah) and B_P is the number of batteries that needs to be in parallel.

Equation 4-3 presents how to calculate the number of batteries to be connected in series to reach the voltage required by the system.

$$B_S = \frac{V_N}{V_B} \qquad \textbf{4-3}$$

Where V_N is the DC system voltage (Volt), V_B is the battery voltage (Volt) and B_S is the number of battery that needs to be in series.

The total number of batteries needed is obtained multiplying the total number of batteries in series and the total number of batteries in parallel as shown in equation 4-4.

$$N_B = B_S \cdot B_P \qquad \textbf{4-4}$$

Where B_S is the number of batteries in series. B_P is the number of batteries in parallel. N_B is the total number of batteries needed.

To obtain the total cost of the battery bank multiply the total number needed of batteries by the cost of a single battery.

$$C_{Bbank} = N_B \cdot C_B \qquad \textbf{4-5}$$

Where C_{Bbank} is the cost of the battery bank, N_B is the total number of batteries required and C_B is the retail cost of the battery.

4.2.3 Battery Sizing Example

We will now size a battery system to supply 4000Wh per day to a DC electrical load. The DC voltage of the battery system will be 48-volt. The number of autonomy days will be 3 days. The maximum depth of discharge will be 50 percent. Assume the batteries are kept at a temperature of 25ºC, thus the derate factor is 1. From Table 4-1 we select Lead-Acid Battery model Surrette 12-Cs-11Ps. It has 357 Ah at 12Volts. The cost of this battery is $1,118.98 per battery.

The Amp-hour load of the system, take 4000Wh/day and divide it by 48V, is 83.3Ah/day. Then using equation 4-1 to 4-4 we calculate the batteries required by this system.

$$\text{Required Battery Capacity} = \frac{L_{Ah/Day} \cdot D_{ST}}{M_{DD} \cdot D_f} = \frac{(83.3)\cdot(3)}{(0.5)\cdot(1)} = 499.8Ah$$

$$\text{Batteries in Parallel} = \frac{B_R}{B_C} = \frac{(499.8)}{(357)} = 1.5 \rightarrow 2$$

$$\text{Batteries in Series} = \frac{V_N}{V_B} = \frac{48}{12} = 4$$

$$\text{Total Number of Batteries} = B_S \cdot B_P = (2)\cdot(4) = 8$$

$$\text{Total Cost of the Battery Bank} = C_{Bbank} = N_B \cdot C_B = (8)\cdot(\$1{,}118.98) = \$\ 8{,}951.84$$

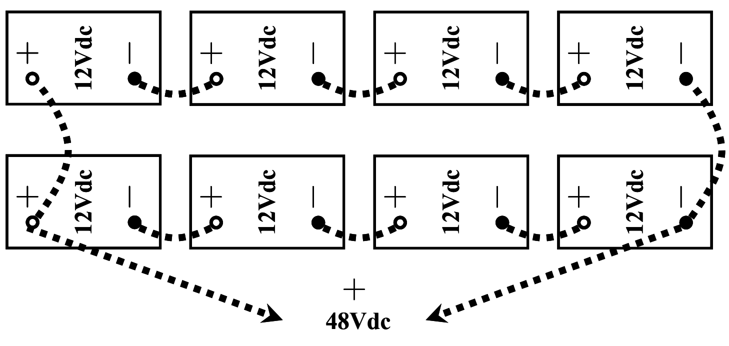

Figure 4-1 Battery Example Configuration

4.3 PV Controllers

The photovoltaic controller works as a voltage regulator. The primary function of a controller is to prevent the battery from being overcharged by a photovoltaic array system. A charge controller constantly monitors the battery's voltage. When the batteries are fully charged, the controller will stop or decrease the amount of current flowing from the photovoltaic array into the battery. The controllers average efficiencies range from 95% to

98%. For this thesis the efficiency that will be use for the analysis will be 95%, [Luque et al. 2003].

Charge controllers for PV system come in many sizes, typically from just a few amps to as much as 80 amps. If high current are required, two or more controllers can be used. When using more than one controller, it is necessary to divide the array into sub-arrays. Each sub-array will be wired into the same battery bank. There are five different types of PV controllers: shunt controller, single-stage series controllers, diversion controller, pulse width modulation (PWM) controller and the maximum power point tracking controllers (MPPT). See [PVDI 2007] for more information on these controllers. The one we will be using in this thesis are the MPPT controllers.

4.3.1 MPPT Charge Controllers

The Maximum Power Point Tracking (MPPT) charge controllers are the best of today's PV systems. As the names implies, this feature allows the controller to track the maximum power point of the array throughout the day in order to deliver the maximum available solar energy to the batteries or the system. The result is additional 15-30% more power out of an array versus a PWM controller. Before MPPT was available as an option in controllers, the array voltage would be pulled down to just slightly above the battery voltage while charging battery. For example, in a 12V battery charging system, an array’s peak power point voltage is around 17-18V. Without MPPT, the array would be forced to operate around the voltage of the battery. This results in a loss of the power coming from the array. Table 4-2 present the MPPT PV controllers be used in this work.

TABLE 4-2 MPPT Charge Controllers Manufactures

MPPT Charge Controllers			Max Output	Nom. Battery	Max PV Open Circuit	
Manufacture	Model	Price ($)	Current (A)	Voltage (V)	Voltage Allowed (VOC)	Store
Blue Sky Solar (Solar Boost 3048)	Solar Boost 3048	$486.25	30	48	140	Alternative Energy Store
Outback (Flexmax 80)	Flexmax 80	$671.10	80	12, 24, 36, 48, 60	150	Alternative Energy Store
Outback (Mx60)	Mx60	$497.76	60	12, 24, 48	125	Alternative Energy Store
Outback (Mx60-Es)	Mx60-Es	$498.43	60	12, 24, 48	125	Alternative Energy Store

4.3.2 MPPT Controller Sizing

MPPT controller sizing consist in calculating the number of MPPT controllers needed for the PV system. In small PV system one controller may be enough to supply the demand but for larger PV system more controllers may be needed for supply the demand. When you select a controller you must be sure it has an output voltage rating equal to the nominal battery voltage. Also the Maximum PV voltage should be less than the maximum controller voltage rating.

$$Maximum\,Controller\,Voltage > Maximum\,PV\,Voltage \quad \textbf{4-6}$$

You can calculate the maximum PV voltage using Equation 4-7:

$$Maximum\,PV\,Voltage = (Module\ Voc)\cdot(n\,Number\,of\ Modules\,in\,Series) \quad \textbf{4-7}$$

Where Voc is the module open circuit voltage and the n represent the number of modules connected in series. When PV modules are connected in series the voltage increases.

The number of controllers needed for a PV array system, [PVDI 2007] is calculated using:

$$Photovoltaic\,Maximun\,Power\,STC = P_{PVSTC}\cdot N_{PV} \quad \textbf{4-8}$$

$$Controller\ Maximun\,Power = V_{BatteryBank}\cdot I_{Controller} \quad \textbf{4-9}$$

$$Number\,of\ Controller\ required = \frac{Photovoltaic\,Maximun\,Power\,STC}{Controller\,Maximun\,Power} \quad \textbf{4-10}$$

Where P_{PVSTC} represent the STC rating power of the photovoltaic module you choose. The N_{PV} variable represents the number of PV module in your system. $V_{BatteryBank}$ is the voltage of the battery bank. $I_{controller}$ is the max current the controller can handle from the PV system to the battery bank.

4.3.3 Controller Sizing Example

Let's calculate the number of controllers needed for a system that have a DC load of 4000W connected to a battery bank with a voltage of 48V. The power will be generated by a Kyocera solar module (KC200). Example 3.5, in page 61 of this thesis, shows that using Kyocera solar module KC200 we will need 31 modules to generated 4000W. Remember that the KC200 have a Voc of 32.9V and a STC power output rating of 200Watts. All the modules will be connected in parallel and divided in sub arrays if the design needs it.

Let choose for this example the Outback Flaxman 80 controller which have a maximum output current of 80Amps and a maximum controller voltage of 150V. Now using the Equations 4-10, the number of controller needed for the system can be compute.

$$Number\ of\ Controller\ Required = \frac{P_{PVSTC} \cdot N_{PV}}{V_{BatteryBank} \cdot I_{Controller}} = \frac{(200)\cdot(31)}{(48)\cdot(80)} = 1.6 \rightarrow 2$$

The total number of controllers needed is two. If we have 31 PV modules, one sub arrays of 16 PV modules and one sub-array of 15 PV modules should be configured and connected in parallel to each one of the controllers. Another restriction is that Maximum PV voltage must be less than the maximum controller voltage rating. The Voc of the Kyocera KC200 is 32.9, making it lower voltage than the maximum controller voltage of 150V. If you like to connect two or three modules in series, it can be done. It depends how you want to configure it. For this example the modules are in parallel.

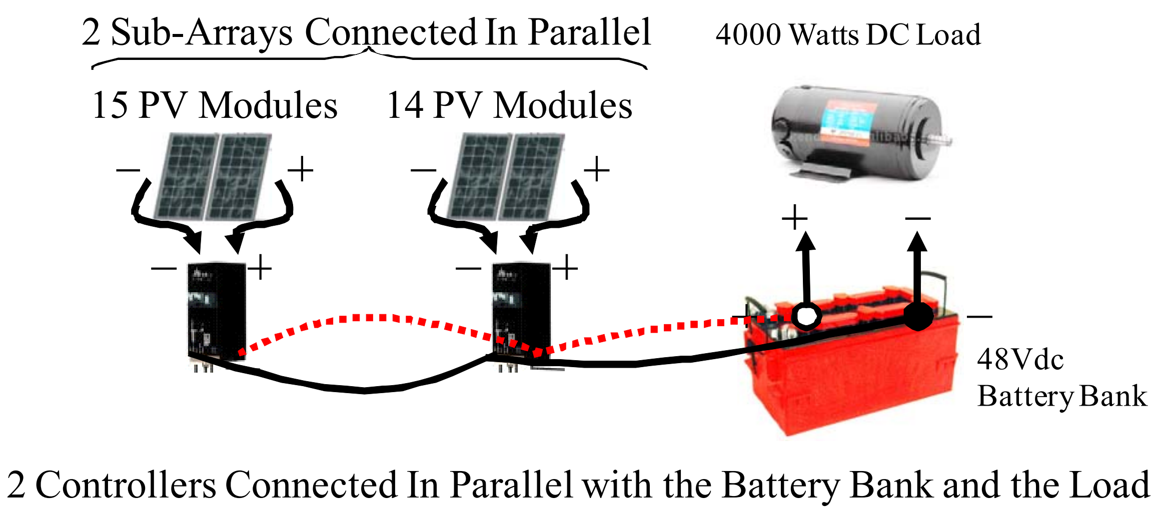

Figure 4-2 DC Example Configuration

4.4 Inverters

An inverter converts the direct current (DC) electricity from sources such as batteries, solar modules, or wind turbine to alternative current (AC) electricity. The electricity can then be used to operate AC equipment like the ones that are plugged in to most house hold electrical outlets. The normal output AC waveform of an inverters is a sine wave with a frequency of 60Hz (for the United States and Puerto Rico).

Inverters are available in three different categories: grid-tied battery less, grid tied with battery back-up and stand-alone. The grid tied battery less are the most popular inverters today. These inverters connect directly to the public utility, using the utility power as a storage battery. When the sun is shining or the wind is blowing, the electricity comes from the PV or Wind turbine via the inverter. If the PV array or the Wind turbine is making more power than is being used, the excess is sold to the utility power company through the electric meter. If you use more power than the PV or Wind Turbine can supply, the utility provides up the difference, [PVDI 2007].

The grid-tied with battery backup are more complex than battery less grid-tied inverters because they need to sell power to the grid, supply power to backed-up loads during outages, and charge batteries from the grid, PV or Wind Turbine after an outage. These inverters need to have features similar to both a battery less grid-tied inverter when selling power to the utility, and to a stand alone inverter when it is feeding the backed-up loads during outages. Also these inverters must have a high surge capacity meaning that they must be able to exceed their rated wattage for limited periods of times. This is important because power motor can draw up to seven times their rated wattage during startup, [Pate, 2006].

The stand alone inverters are designed for independent utility-free power system and are appropriated for remote hybrid system installation. These inverters supply power to the loads using the energy coming from the PV or wind Turbine and when there’s no wind or sun the power will come from the battery bank. These inverters must have battery charge capability to maintain the battery bank charge so when it is needed it could supply power to the loads. Also these inverters must have a high surge capacity.

The efficiency of converting the direct current to alternative current of most inverters today is 90 percent or more. Many inverters claim to have higher efficiencies but for this thesis the efficiency that will be used is 90%.

Table 4-3 presents inverters used in this thesis. All the inverters have output voltage of 120V and produce a sine wave AC output signal of 60Hz. All the inverters are grid-tied with battery backup. Meaning can do the work as stand alone inverters or grid tied inverters.

TABLE 4-3 Inverters Manufactures

Inverter Manufacture	Model	Price ($)	Power (W)	DC Input Voltage (VDC)	AC Output Voltage (VAC)	Nominal Frequency (Hz)	Store
Xantrex (XW6048)	XW6048	$3,597.75	6000	48	120	60	Alternative Energy Store
Xantrex (XW4548)	XW4548	$2,878.20	4500	48	120	60	Alternative Energy Store
Xantrex (SW5548)	SW5548	$2,735.85	5500	48	120	60	Alternative Energy Store
Xantrex (SW4048)	SW4048	$2,178.96	4000	48	120	60	Alternative Energy Store
Outback (GTFX3048)	GTFX3048	$1,760.00	3000	48	120	60	Alternative Energy Store
Outback (GVFX3648)	GVFX3648	$1,913.00	3600	48	120	60	Alternative Energy Store
Sunny Island (SI4248U)	SI4248U	$4,228.00	4200	48	120	60	Alternative Energy Store
Sunny Island (SI5048U)	SI5048U	$6,535.00	5000	48	120	60	Alternative Energy Store

4.4.1 Inverter Sizing

Inverter sizing consists in calculating the number of inverters needed for the PV and wind turbine system. In small hybrid systems one inverter will be enough to supply the power but for a larger hybrid system more inverters may be needed. When you select an inverter you must have a DC voltage equal to your inverter DC voltage and have an AC voltage and frequency equal to your home and utility values.

Equation 4-11 shows how to calculate the number of inverters needed for a stand alone hybrid system.

$$Number\ of\ Inverters\ required = \frac{P_{LOAD}}{P_{INVERTER}} \qquad \textbf{4-11}$$

Where P_{LOAD} represent the maximum continues power load your home consumes. $P_{INVERTER}$ is the maximum power that can be supplied by the inverter. If the system is grid connected use equation 4-12.

$$Number\ of\ Inverters\ required = \frac{P_{GENERATED}}{P_{INVERTER}} \qquad \textbf{4-12}$$

Where $P_{GENERATED}$ represent the maximum power generated by your hybrid system. $P_{INVERTER}$ is the maximum power that can be supply by the inverter.

4.4.2 Example Inverter Sizing

Let's calculate the number of inverters needed for a stand alone system that have an AC load of 3600W. Using table 4-3 we choose an inverter with an output power of 3600W or more. The Xantrex XW4048 has and output of 4000W at 120V. Using equation 4-12:

$$Number\ of\ Inverters\ Required = \frac{P_{LOAD}}{P_{INVERTER}} = \frac{3600}{4000} = 0.9 \rightarrow 1$$

The total number of inverters needed is one. To calculate the input power to the inverter, divide the power of the load by the efficiency of the inverter. Assuming the efficiency of the inverter is 0.9, the total input power to the inverter in the DC side needed to supply the load in the AC side is 4000Watts. (3600/.9)

5 ENERGY CONSUMPTION

5.1 Introduction

Energy consumption is the electrical power your loads consume in a period of time. It is measured in kWh. Loads are usually the largest single influence on the size and cost of a PV and wind turbine system. In order to reduce the cost of the PV and wind turbine system it is necessary to use more efficient, lower demand appliance and to eliminate, partially or completely, the use of other loads.

5.2 Loads Power Consumption

Normally you can find the power consumption (or “wattage”) of most appliances printed on the bottom or back of the appliance. This power consumption is the maximum power the appliance may use. Since many appliances have a range of settings, as for example, the volume on a home theater, the actual amount of power consumed depends on the setting used at any one time, [PVDI 2007].

If the power consumption is not printed on the appliance, you can still estimate it by measuring the current draw (in amperes) and multiplying it by the rated voltage of the appliance. Most appliances in the United States are rated at 120 volts. Larger appliances, such as clothes dryers and electric cook tops, are rated at 240 volts.

Many appliances continue to draw a small amount of power when they are switched off. These phantom loads occur in many appliances such as VCRs, televisions, stereos, computers, and kitchen appliances. Most phantom loads will increase the appliance's energy consumption a few watt-hours. These loads can be avoided by unplugging the appliance or using a power strip and using the switch on the power strip to cut all power to the appliance.

Table 5-1 shows examples of power consumption for various household appliances, [NREL 2007].

TABLE 5-1 Typical Appliances Wattages

Appliance	Watt		Appliance	Watt
Aquarium	50-1210		Personal computer	
Clock radio	10		CPU awake/asleep	120/30 or less
Coffee maker	900-1200		Monitor awake/asleep	150/30 or less
Clothes washer	350-500		Laptop	50
Clothes dryer	1800-5000		Radio (Stereo)	70-400
Dishwasher	1200-2400		Energy Star Refrigerator (16 cubic feet)	127
Dehumidifier	785		Televisions (color)	
Electric blanket	60-100		19"	65-110
Fans			27"	113
Ceiling	65-175		36"	133
Window	55-250		53"-61" Projection	170
Furnace	750		Flat screen 36"	120
Whole house	240-750		Toaster	800-1400
Hair dryer	1200-1875		Toaster oven	1225
Heater (portable)	750-1500		VCR/DVD	17-21/20-25
Clothes iron	1000-1800		Vacuum cleaner	1000-1440
Microwave oven	750-1100		Water heater (40 gallon)	4500-5500
Compact fluorescent			Water pump (deep well)	250-1100
40 watt equiv	11		Water bed (with heater, no cover)	120-380
60 watt equiv	16			
75 watt equiv	20			
100 watt equiv	30			

5.3 Energy Consumption Estimate

To estimated energy consumption we need to calculate the average daily electrical energy use in watt-hours as well as the total power demand in watts. The system will be more economical if high efficient, low power consumption loads are used.

Once the power consumption per appliance is known or estimated we use equation 5-1 to calculate the kWh that a type of load consumes in a day, [PVDI 2007].

$$KWh/Day = \frac{n \cdot P_{LOAD} \cdot H_{DAY} \cdot D_{WEEK}}{7} \qquad \textbf{5-1}$$

Where n represent the quantity of that type of load, P_{LOAD} is the power consumption of the type of load, H_{DAY} is the number of hours the load is consuming power and D_{WEEK} is the number of days the load is used during a week. Total kWh/day of all the loads is obtained by adding individual load consumption as in equation 5-2.

$$Total\ KWh/Day = \sum_i KWh/Day_i \qquad \textbf{5-2}$$

Where Total kWh/Day is the sum of the individual i load consumption in kWh/Day. For calculate the yearly load use the next formula:

$$YearlyLoad = (Total\ KWh/Day) \cdot 365 \qquad \textbf{5-3}$$

If you want to calculate the total wattage installed or in other word the maximum power wattage sum all the P_{LOAD} of all the loads i.

$$Maximum\ Power\ Wattage\ KW = \sum_i P_{LOAD\,i} \qquad \textbf{5-4}$$

The next example will present more easily how to do this.

5.4 Example Energy Consumption Estimation

Let's estimate the energy consumption of a hypothetical house located in the city of Fajardo, Puerto Rico. The house has two bedrooms, two bathrooms, a living room, an office room and a kitchen. The kitchen oven and the clothes dryer will use propane gas as the power source. The house hot water will come from a solar thermal water heater. Table 5-2 shows the electrical loads and total Watt and kWh that the home consumes.

TABLE 5-2 Example of Energy Consumption Estimation

Individual Loads (Appliances)	Qty X	Volts X	Amps =	Watts X AC	Use X hrs/day	Use / days/wk	7 = days	Watt AC
Refrigerator (16 cubic feet)	1	120	1.06	127	9.00	7	7	1145
Microwave oven	1	120	9.00	1080	0.08	7	7	90
Toaster	1	120	8.00	960	0.04	7	7	38
Coffee maker	1	120	8.33	1000	0.08	7	7	80
Ceiling Fans	3	120	1.25	450	8.00	7	7	3600
Cellular Charger	2	120	0.11	26	4.00	7	7	106
Laptop Computer	2	120	0.42	101	8.00	7	7	806
TV Flat screen LCD 46"	2	120	1.89	454	4.00	7	7	1814
Music Home Theater	1	120	3.47	416	4.00	3	7	714
Clothes washer	1	120	2.92	350	1.00	4	7	200
Lights Compact fluorescent	14	120	0.17	286	4.00	7	7	1142
Printer/fax	1	120	0.90	108	0.20	7	7	22
Cable Modem	1	120	0.08	10	12.00	7	7	115
Wireless	1	120	0.08	10	12.00	7	7	115
Cable box	2	120	0.08	20	4.00	7	7	80
Clock radio	2	120	0.08	19	24.00	7	7	461
Hair dryer	1	120	10.00	1200	0.25	7	7	300
Air Conditioner	1	120	9.41	1129	6.00	7	7	6775
AC Total Connected Watts =				7746	AC Average Daily Load =			17604 Wh/Day
Total System kWh/Day = (AC Average Daily Load)/(1000) = (17604)/(1000) =								17.6 kWh/Day
Total System kWh/Yearly = (365 Days)*(Total System kWh/Day) =								6425 kWh/Yearly
Total System kWh/Monthly = (Total System kWh/Yearly) / (12) =								535 kWh/Monthly

Total AC power consumption in the house is 7746W and the average AC daily load is 17.6kWh.

6 HYBRID ENERGY SYSTEM

6.1 Introduction

With advances in solar and wind technology, and if you have both resources available, it does not make any sense to design a stand alone system or a grid connected system, to use only wind or solar energy. Hybrid, wind turbine and photovoltaic modules, offer greater reliability than any one of them alone because the energy supply does not depend entirely on any one source. For example, on a cloudy stormy day when PV generation is low there's likely enough wind energy available to make up for the loss in solar electricity, [Pate, 2006].

Wind and solar hybrids also permit use of smaller, less costly components than would otherwise be needed if the system depended on only one power source. This can substantially lower the cost of a remote power system. In a hybrid system the designer doesn't need to weigh the components for worst-case conditions by specifying a larger wind turbine and battery bank than is necessary, [Pate, 2006].

Despite advances by hybrid power systems in improving reliability and reducing the overall size of the power system, initial costs remain relatively high. It heaves the potential user to reduce demand as much as possible to keep costs down. Advances in energy efficiency permits users to meet their energy needs from smaller, less expensive power systems than once was possible. The development of compact fluorescent lights and energy-efficient appliances now makes this possible with little sacrifice in lifestyle [Gipe 2004].

6.2 Stand Alone Hybrid System

The stand-alone hybrid power system is used primarily in remote areas where utility lines are uneconomical to install due to the terrains right-of-way difficulties, or environmental concerns. Building new transmission lines is expensive even without these constraints. A 230-kV line costs more than $1 million per mile, [Patel 2006]. A stand-alone system would be more economical for remote villages that are farther than a couple of miles from the nearest transmission line.

Solar and wind power outputs can fluctuate on an hourly or daily basis. The stand-alone system, therefore, must have some means of storing excess energy on a sunny day or a windy day for use on a rainy day or without wind. Alternatively, wind turbines and PV modules can be used in a hybrid configuration with a Diesel engine generator in remote areas or with a fuel cell in urban areas. For this thesis we only focus on PV modules and wind turbine configurations.

According to the World Bank, more than 2 billion people live in villages that are not yet connected to utility lines, [Patel 2006]. These villages are the largest potential market for stand-alone hybrid systems using wind turbines and PV modules for meeting their energy needs. Additionally, wind turbines and PV modules systems create more jobs per dollar invested than many other industries. On top of this fact they are bringing much needed electricity to rural areas and helps minimize migration to already strained cities in most countries, [Patel 2006].

The stand-alone hybrid system is technically more challenging and expensive to design than the grid-connected system because the use of battery increases the initial cost.

6.2.1 Typical Stand Alone Hybrid Components and Efficiencies

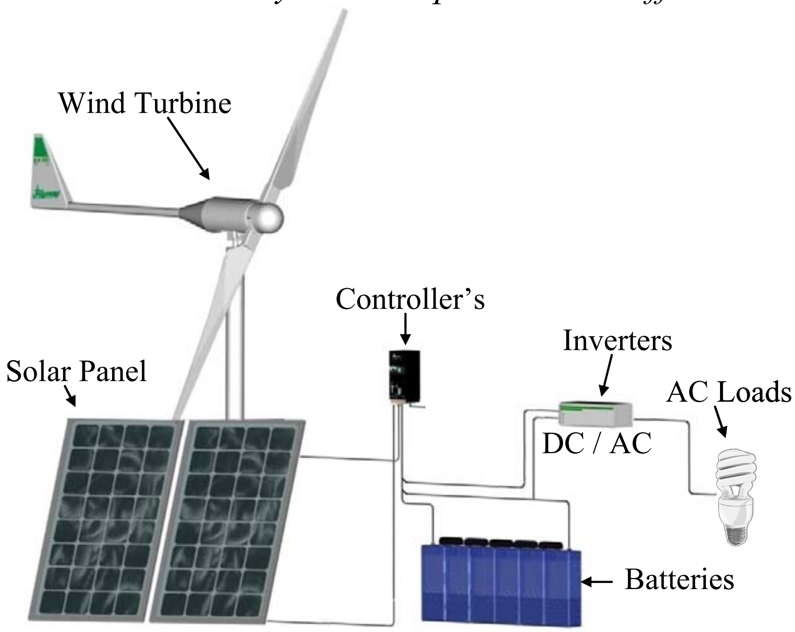

Figure 6-1 PV Stand Alone System

Typical components for a stand alone hybrid system are:

- Wind Turbine: Provides energy from the wind.
- Solar modules: Provide energy from solar radiation.
- Inverters: it is an electronic circuit use to convert direct current (DC) to alternating current (AC). Its average efficiency is 90%.
- Controllers (MPPT): Keep the batteries from overcharging and maintain the solar module at the maximum power point output. Its average efficiency is 95%
- Batteries: Supply energy to the system when is needed and store it when is not needed. Its average efficiency is 90%
- Wires: Electrically connect equipment together. Their average efficiency is 98%.
- Loads: Consume the power generated by the wind turbine and photovoltaic modules.

Since the subsystem, or the components, are sequential regarding the energy flow the overall efficiency of the system is the product of individual components efficiency.

$$\eta_{SA} = (InverterEfficiency)\cdot(ControllerEfficiency)\cdot(WiresEfficiency)\cdot(BatteryEfficiency) \quad \textbf{6-1}$$

Where η_{SA} is the total stand alone system efficiency. Table 6-1 shows the average efficiency for inverter, controllers, batteries and wires used in this work.

TABLE 6-1 Average Efficiency of hybrid system components

Inverter	0.90
Controller	0.95
Wires	0.98
Battery	0.90

Using the values from table 6-1 above and equation 6-1, the total stand alone system efficiency is:

$$\eta_{SA} = (0.90)\cdot(0.95)\cdot(0.98)\cdot(0.90) \approx 0.75$$

The total efficiency of the system is approximately 75%. This means that 75% of all the electricity produced is delivered to the loads and 25% is consumed by the wires and the internal components, inverters, controllers and batteries.

6.2.2 Proposed Stand Alone Sizing Optimization Procedure

We now formulate the stand alone hybrid sizing optimization problem procedure. We will use linear optimization with constraints to solve the problem.

Minimize

$$Equipment\,Cost(X) = \sum_i C_{PV_i} N_{PV_i} + \sum_j C_{WT_j} N_{WT_j} + \sum_h C_{Bbank_h} N_{Bbank_h} + \sum_g C_{IN_g} N_{IN_g} + \sum_k C_{CT_k} N_{CT_k} \quad \textbf{6-2}$$

subject to constraints

$$\frac{Yearly\,Load}{\eta_{SA}} \leq \sum_i E_{PV_i} N_{PV_i} + \sum_j E_{WT_j} N_{WT_j} \qquad \textbf{6-3}$$

$$Maximun\,Power\,Wattage \leq \sum_g P_{IN_g} N_{IN_g} \qquad \textbf{6-4}$$

$$Photovoltaic\,Maximun\,Power\,STC \leq \sum_k P_{CT_k} N_{CT_k} \qquad \textbf{6-5}$$

$$1 = \sum_h N_{Bbank_h} \qquad \textbf{6-6}$$

Where:

N_{PV_i} = Number of photovoltaic modules

N_{WT_j} = Number of wind turbines

N_{Bbank_h} = Number of battery bank to be use. N_{Bbank_h} represent a preselected set of batteries

N_{IN_g} = Number of inverters

N_{CT_k} = Number of controllers

C_{PV_i} = Cost of a photovoltaic module, in U.S dollars ($)

C_{WT_j} = Cost of wind turbine, in U.S dollars ($)

C_{Bbank_h} = Cost of battery bank, in U.S dollars ($)

C_{IN_g} = Cost of inverters, in U.S dollars ($)

C_{CT_k} = Cost of controllers, in U.S dollars ($)

E_{PV_i} = kWh/year generated by photovoltaic module i

E_{WT_j} = kWh/year generated by wind turbine j

P_{IN_g} = Maximum output power of inverter g

P_{CT_k} = Maximum output power of controller k

η_{SA} = Total stand alone system efficiency

The kWh/year consumed by the loads is obtained from equation 5-3. Battery bank cost, C_{Bbank_h} is computed using equation 4-5. The maximum power consumption is calculated using equation 5-4. Photovoltaic maximum power STC is calculated using equation 4-9.

C_{PV_i} C_{WT_j} C_{IN_g} C_{CT_k} and P_{IN_g} P_{CT_k} are cost, and power values found using the specification data sheets for each equipment. We obtain these values from Tables 2-1, 2-2, 3-2, 3-3, 4-1, 4-2 and 4-3. Yearly energy values of PV modules E_{PV_i} are found using equation 3-8 and yearly energy values from wind turbines E_{WT_j} are found using equation 2-14.

Note that the only unknown variables are N_{PV_i} N_{WT_j} N_{Bbank_h} N_{IN_g} N_{CT_k}. These variables represent the number of different equipment the system needs to supply the power to the load at the lowest cost possible. These are the ones that will be optimized using integer liner optimization algorithm explained in the chapters 6-4.

6.3 Grid Connected Hybrid System

Wind and photovoltaic power systems have made a successful transition from small stand-alone sites to large grid-connected systems. The utility interconnection brings a new dimension to the renewable power economy by pooling the temporal excess of the renewable power system with the connecting grid that generates base-load power using conventional fuels. With the grid connected system we do not need to use batteries to store energy. This task is made by the utility, making the initial cost of the system lower.

6.3.1 Typical Grid Connected Components and Efficiencies

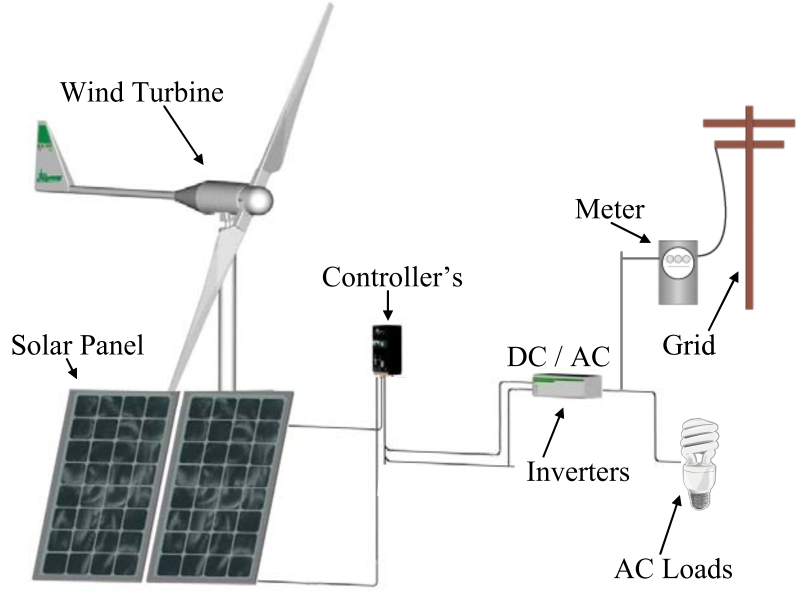

Figure 6-2 Grid Connected System

Typical components for a grid connected system are:

- Wind Turbine: Provides energy from the wind.
- Solar Modules: Provide energy from solar radiation.
- Inverter: An electronic circuit that convert direct current (DC) to alternating current (AC). Its average efficiency is 90%.
- Controllers (MPPT): maintain the solar module at the maximum power output. Its average efficiency is 95%.
- Wires: Electrically connect equipment together. Its average efficiency is 98%.
- Loads: Consume the power generated by the wind turbine and photovoltaic modules.
- Meter: Measure the energy injected into the utility grid or the energy consumed from the grid.

• Grid: supplies power to the loads when needed or absorbs the excess power from the solar module and wind turbines when is available.

The approximate total grid connected system efficiency is:

$$\eta_{NT} = (InverterEfficiency)\cdot(ControllerEfficiency)\cdot(WiresEfficiency) \qquad \textbf{6-7}$$

Where η_{NT} is the total grid connected system efficiency. Using the values from table 6-1 and equation 6-7, the approximate total grid connected system efficiency used in this thesis is:

$$\eta_{NT} = (0.90)\cdot(0.95)\cdot(0.98) \approx 0.84$$

The total grid connected efficiency of the system is 84%, meaning that 84% of all the electricity is delivered to the loads and the rest 16% is consumed by the wires and the internal components of the inverters and controllers.

6.3.2 Proposed Grid Connected Sizing Optimization Procedure

We now formulate the grid connected optimization problem. Again we use linear optimization with constrains to solve this problem.

Minimize

$$Equipment\,Cost(X) = \sum_i C_{PV_i} N_{PV_i} + \sum_j C_{WT_j} N_{WT_j} + \sum_g C_{IN_g} N_{IN_g} + \sum_k C_{CT_k} N_{CT_k} + \sum_U C_U KWh_U \qquad \textbf{6-8}$$

subject to constraints

$$\frac{Yearly\,Load}{\eta_{NT}} \le \sum_i E_{PV_i} N_{PV_i} + \sum_j E_{WT_j} N_{WT_j} + \sum_U KWh_U \qquad \textbf{6-9}$$

$$Maximun\,Generated\,Wattage \le \sum_g P_{IN_g} N_{IN_g} \qquad \textbf{6-10}$$

$$Photovoltaic\,Maximun\,Power\,STC \le \sum_k P_{CT_k} N_{CT_k} \qquad \textbf{6-11}$$

Where:

N_{PV_i} = Number of photovoltaic modules

N_{WT_j} = Number of wind turbines

N_{IN_g} = Number of inverters

N_{CT_k} = Number of controllers

C_{PV_i} = Cost of a photovoltaic module, in U.S dollars ($)

C_{WT_j} = Cost of wind turbine, in U.S dollars ($)

C_{IN_g} = Cost of inverters, in U.S dollars ($)

C_{CT_k} = Cost of controllers, in U.S dollars ($)

C_U = Cost of utility kWh ($)

KWh_U = kWh/year I want to sell or buy from Utility

E_{PV_i} = kWh/year generated by photovoltaic module i

E_{WT_j} = kWh/year generated by wind turbine j

P_{IN_g} = Maximum output power of inverter g

P_{CT_k} = Maximum output power of controller k

η_{NT} = Total grid connected system efficiency

The kWh/year consumed by the loads is obtained from equation 5-3. Battery bank cost, C_{Bbank_h} is computed using equation 4-5. The maximum power consumption is calculated using equation 5-4. Photovoltaic maximum power STC is calculated using equation 4-9.

Unknown variables are N_{PV_i} N_{WT_j} N_{IN_g} N_{CT_k}. Optimization is achieved while selecting the correct value for each variable. These variables represent the number of different equipment the grid connected power system needs to supply the power to the load at the lowest cost possible.

6.4 Optimization Method

The stand alone and grid connected hybrid system optimization problems formulated above are compose of linear objective functions, subject to linear inequality constraints where the solution to the problem must be integer values of the variables. For example, 31 Solar modules and 1 Wind Turbine are integers, 30.6 Solar modules and 1½ wind turbines are not integers. Since the optimization problem is linear, the optimization method to be used is linear programming with integer variables.

We solve this optimization problem using TORSCHE (Time Optimization Resource Scheduling) toolbox for Matlab developed at the Czech Technical University in Prage, [Sucha et al. 2006]. We use the function "ilinprog" in TORSHE. For Stand Alone see Appendix E and for grid connected see Appendix F.

6.4.1 Integer Linear Programming Model Validation

In this section we present a simple example of the use of the method to optimize the hybrid renewable power systems. For the purpose of this example assume a residence consuming 9600kWh/year and will be powered by a grid connected hybrid renewable power systems. We simplify the example ignoring the inverter and controller in this example. We limit the user choices to two wind turbines and two solar modules as shown in table 6-2.

TABLE 6-2 Equipment Specification for Validation Example

	Cost ($):	**kWh/yearly generated:**
Wind Turbine A (WTA)	$8,000.00	8000
Wind Turbine B (WTB)	$9,000.00	9000
Solar Module A (PVA)	$600.00	300
Solar Module B (PVB)	$700.00	300

A simple enumeration of the available options show, the most economic option is to use one Wind Turbine A and two Solar Module B. This configuration can generated the 9600kWh the residence needs at a cost of $10,200 dollars.

We repeat the example using integer liner programming [TORSHE]. The Objective function is:

$$Minimize\,Equipment\,Cost = 8000 \cdot N_{WTA} + 9000 \cdot N_{WTB} + 600 \cdot N_{PVA} + 700 \cdot N_{PVB}$$

Subject to the following constraints:

$$9600 \leq 8000 \cdot N_{WTA} + 9000 \cdot N_{WTB} + 300 \cdot N_{PVA} + 300 \cdot N_{PVB}$$

Where:

$$0 \leq N_{WTA} \leq 1,\ 0 \leq N_{WTB} \leq 1,\ 0 \leq N_{PVA} \leq 30,\ 0 \leq N_{PVB} \leq 30$$

$N_{WTA}, N_{WTB}, N_{PVA}, N_{PVB}$ are integer variables.

and Appendix G shows the complete script used in Matlab to run this example. The result is:

TABLE 6-3 Optimization Results for Validation Example

Equipment	**'Opt'**
Wind Turbine A (WTA)	0
Wind Turbine B (WTB)	1
Solar Module A (PVA)	2
Solar Module B (PVB)	0

Both the program and the enumeration arrive to the same result.

6.5 Economic Analysis

We will use the net present value (NPV) method to calculate the economic feasibility of the hybrid energy system. We seek to determine if the proposed hybrid system pays for itself in a period of 20 years. Our analysis will include the initial project cost, or capita cost, that includes equipment and installation cost. We will calculate net present value, using a one year intervals. The operation & maintenance cost, inflation & insurance will be yearly costs. The electric energy generated by the hybrid system, priced according to the cost of the power purchased from the utility will be the income.

We consider:

- Inflation rate – it reflect the raise in the prices paid for goods and services every year. The Inflation rate affects the operation & maintenance cost and the insurance cost
- Utility rate escalation – it reflect the change in the utility kWh cost every year. We estimate this value based in historical data. Table 6.4 shows the utility rate escalation in Puerto Rico in the last 5 years.

TABLE 6-4 Puerto Rico Increase in kWh Cost in the Last 5 Years

[redacted]

Note the increment in utility rate escalation in the last 5 years. In our work we assume a utility rate escalation increase of 7% to be conservative.

- Interest rate– This rate represents the interest a lender charges on borrowed money. We assume the hybrid system to be paid with a loan, a period equal to the project expected life. We assume an interest rate of 8% for this loan.

Equation 6-12, [Newman et al. 2004] is used to determine the present value of a future amount of money

$$P = F(1+i)^{-n} \qquad \textbf{6-12}$$

Where n is a time interval of one year and i is the interest rate. We transfer the future cash flow, cost and income, to present values and sum them to determine the net present value of the project. If the net present value is positive the hybrid system is a good investment and it produces a profit. If the net present value is negative, the hybrid system results in losses.

Finally we consider in our analysis a replacement of batteries every 10 years in the stand alone option.

7 EXAMPLE AND RESULTS

7.1 Introduction

In this chapter we use all concept, formulas and tables presented in previous chapters to evaluate three examples of hybrid renewable energy system, wind turbine and photovoltaic modules, for the island of Puerto Rico. Three locations where selected for this study; the city of Fajardo where the wind resource is abundant, the city of San Juan with moderate wind speed and solar radiation and the town of Gurabo where the solar resource is abundant. In each location we assume to be serving a residential load of 800kWh per month. This is the average demand for medium class residential home in Puerto Rico. In the economic analysis we use a life time period of 20 years with an inflation rate of 3% and an interest rate on the loan to finance the hybrid system of 8%.

For each location we use solar and wind data, and our optimization procedure to design hybrid renewable power system. We consider a stand alone system and three versions of grid connected system. For the stand alone system we seek to determine the most economic combination of PV modules and wind turbines to serve the residential load. We assume batteries have a life time of 10 years, thus a replacement of batteries is considered at the end of year 10. We assume that every kWh generated has a value of 23.5 cents with a utility rate escalation of 7% per year

For each location, we consider three grid connected possibilities:

1. A grid connected hybrid renewable system benefiting from a Net Metering Program that generates the sufficient energy to supply the load and at the end of

the year the net metering with the utility is be even. No, or almost no electricity is sold to the utility. In the economic analysis we assume the value of every kWh generated 23.5 cents with a utility rate escalation of 7% per year.

2. A grid connected hybrid renewable system, benefiting from a Met Metering Program, capable of generat sufficient energy to supply the load and sell an excess of energy equal to the load. The economic analysis will assume that every kWh generated and used by the residential load there will be priced at 23.5 cents with a utility rate escalation of 7% per year and the excess generation will be sold to the utility at a rate of 10 cents/kWh with no utility rate escalation.
3. A grid connected hybrid renewable system, benefiting from a Net Metering Program, capable of generating sufficient energy to supply the load and sell an excess of energy equal to the load. The economic analysis will assume that every kWh generated and used by the residential load will be priced at 23.5 cents with a utility rate escalation of 7% per year and the rest excess generation will be sold to the utility at a rate of 23.5 cents/kWh with a utility rate escalation of 7% per year

In all cases we will use integer linear programming for the optimization procedure.

7.2 Example 1: A Stand Alone System in Fajardo, P.R.

We now present the procedure to optimize a stand alone hybrid power system for a residential load located in Fajardo Puerto Rico with a monthly demand of 800 kWh. We divided the example in four parts. First we present how to obtain or calculate all the data needed for the optimization. Second we perform optimization to determine the best configuration. Third we present an economic analysis. And finally we discuss the results obtained for this example.

7.2.1 Required Data

We obtain solar radiation and wind speed data for Fajardo Puerto Rico from Tables 2-5 and Table 3-4.

[redacted]

Wind speed is given at a height of 25 meters. If the measurement of wind speed was not made at the wind turbine hub height it is necessary to adjust the wind speed to the hub height using Equation 2.1. In this work all towers will have a height of 25 meters, so there's no need for adjustment. All solar data is given in kWh/m^2.

We calculate the energy generated in a year by the wind turbines and solar modules using the wind speed and solar radiation data. To obtain this energy values two functions where created in Matlab program.

The first one is call WindP (See Appendix B) and can calculated the power generated in a year by any given wind turbine. The function uses the combination of Weibull and power curve explained in Chapter 2. The user must specify the wind turbines power curves, tower height and the wind speed resource at hub height.

The wind turbines used in this example are available in Table 2-1 and Table 2-3. Table 7-1 show the results after applying function WindP.

TABLE 7-1 Wind Turbine Yearly Energy Output at Fajardo Puerto Rico in kWh

Wind Turbine's	
Product:	**Energy Generated (kWh/year)**
SouthWest (Air X)	600
SouthWest (Whisper 100)	1730
SouthWest (Whisper 200)	3443
SouthWest (Whisper 500)	10271
SouthWest (Skystream 3.7)	6286
Aeromax Engineering (Lakota S, SC)	1939
Bergey (BWC 1500)	3790
Bergey (BWC XL.1)	3158
Bergey (BWC Excel-R)	18707
Bornay (Inclin 250)	977
Bornay (Inclin 600)	1927
Bornay (Inclin 1500)	5991
Bornay (Inclin 3000)	11310
Bornay (Inclin 6000)	23706
Abundant Renewable Energy (ARE110)	7286
Abundant Renewable Energy (ARE442)	32305
Kestrel Wind (600)	1305
Kestrel Wind (800)	2201
Kestrel Wind (1000)	4420
Kestrel Wind (3000)	7050
Solacity (Eoltec)	16498

Figure 7-1 shows the power curve for each wind turbine, the weibull probability distribution function and total energy output for each turbine.

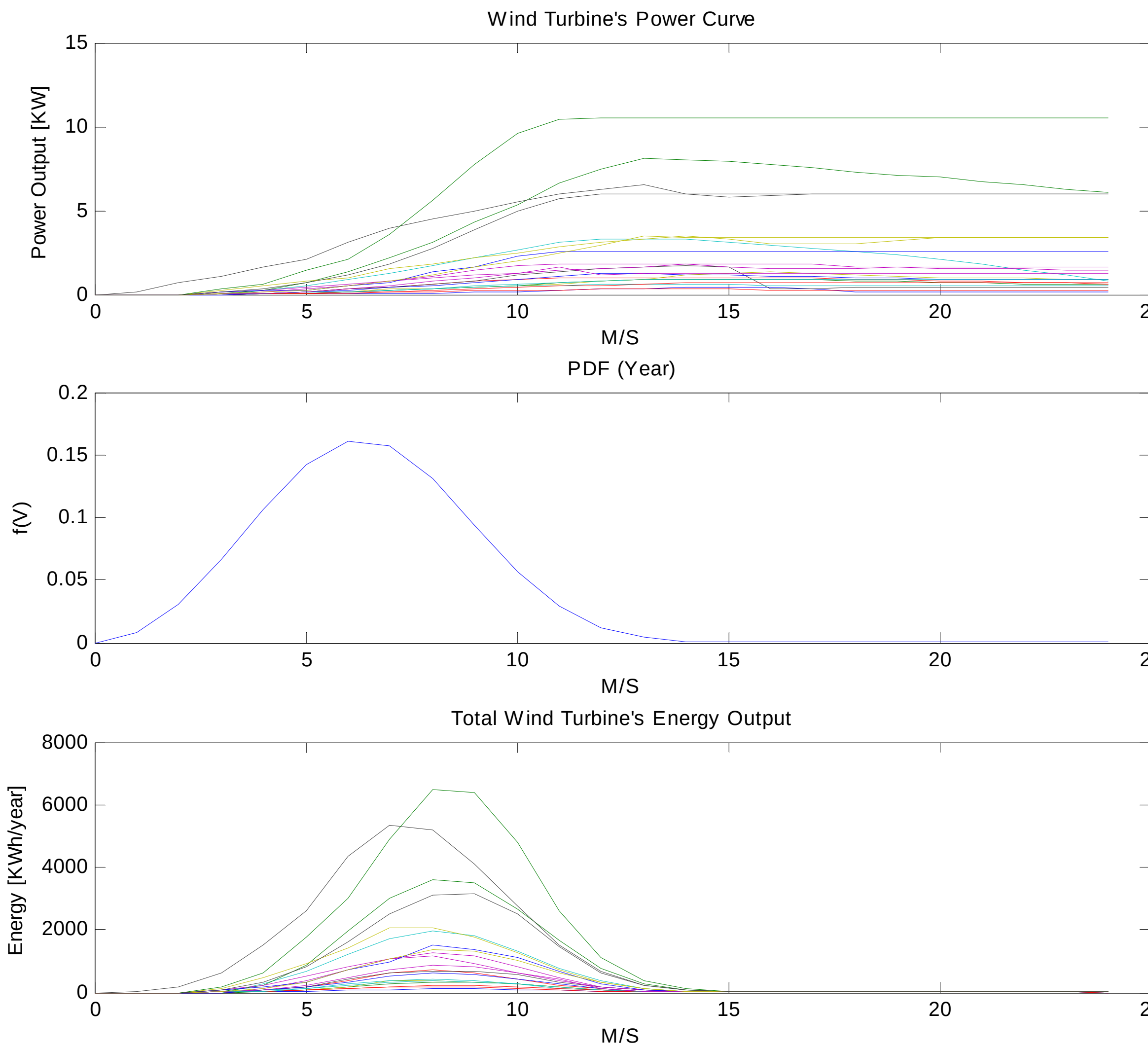

Figure 7-1 Fajardo Wind Turbine Power Curve's, PDF and Energy Output's

The second function is solarP (See appendix C) and it is used to calculate the power generated in a year by a given photovoltaic module. The function uses the method of [Ortiz, 2006] or the method of photo conversion efficiency [Patel, 2006] as explained both in Chapter 3. The user can select the method that want to use.

In this example we use Ortiz method to calculated the energy generated in a year for all the solar modules available in Table 3-4. Table 7-2 presents the results for this example.

TABLE 7-2 Solar Yearly Energy Output for Fajardo Puerto Rico in kWh

Solar Panel's	
Product:	**Energy Generated (kWh/year)**
Kyocera Solar (KC200)	344
BP Solar (SX 170B)	323
Evergreen (Spruce ES-170)	295
Evergreen (Spruce ES-180)	312
Evergreen (Spruce ES-190)	330
Solar World (SW-165)	294
Mitsubishi (PV-MF155EB3)	271
Sharp (ND-208U1)	364
Sharp (NE-170U1)	299
Mitsubishi (PV-MF165EB4)	285
Sunwize (SW150)	263
Kyocera (KC175GT)	301
Kyocera (KC175GT)	301

Figure 7-2 shows the P-V and IV curves for each photovoltaic module adjusted using available solar radiation for this site.

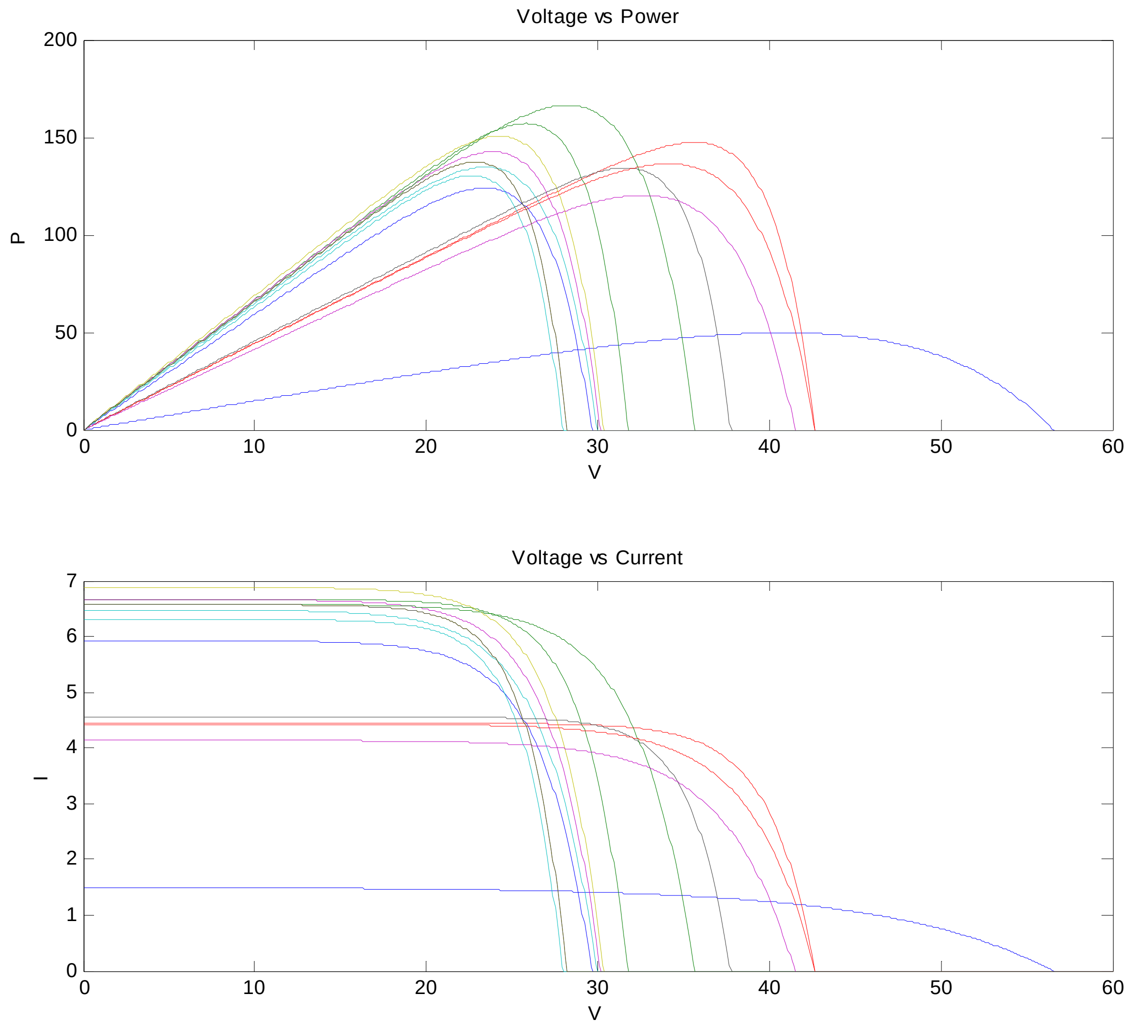

Figure 7-2 Fajardo Photovoltaic Modules P-V and I-V Curve

To obtain the maximum rated power for controllers and inverters use Tables 4-3 and 4-2 where all the specifications for each one are available. Table 7-3 shows the maximum power values for inverters and controllers used in this example:

TABLE 7-3 Inverters and Controllers Maximum Rated Power

	Product:	Power in "Watts"
MPPT Charge Controllers	Blue Sky Solar (Solar Boost 3048)	1440
	Outback (Flexmax 80)	3840
	Outback (Mx60)	2880
	Outback (Mx60-Es)	2880
Inverter's	Xantrex (XW6048)	6000
	Xantrex (XW4548)	4500
	Xantrex (XW4024)	4000
	Xantrex (SW5548)	5500
	Xantrex (SW4048)	4000
	Outback (GTFX3048)	3000
	Outback (GVFX3524)	3500
	Outback (GVFX3648)	3600
	Sunny Island (SI4248U)	4200
	Sunny Island (SI5048U)	5000

We now obtain the price of each wind turbine, PV module, controller and inverter used in the example from Tables 2-1 for wind turbines, Table 3-2 for PV modules, Table 4-2 for controllers and Table 4-3 for inverters. Table 7-4 summarize these costs.

TABLE 7-4 Cost in ($) for Wind Turbines, PV Modules, Controllers and Inverters

Wind Turbine's with 25m heigth tower	
Product:	**Cost ($)**
SouthWest (Air X)	$1,404.86
SouthWest (Whisper 100)	$2,889.86
SouthWest (Whisper 200)	$3,204.86
SouthWest (Whisper 500)	$8,252.19
SouthWest (Skystream 3.7)	$6,557.19
Aeromax Engineering (Lakota S, SC)	$2,395.00
Bergey (BWC 1500)	$6,668.00
Bergey (BWC XL.1)	$4,558.00
Bergey (BWC Excel-R)	$25,396.00
Bornay (Inclin 250)	$3,308.00
Bornay (Inclin 600)	$3,883.00
Bornay (Inclin 1500)	$5,130.00
Bornay (Inclin 3000)	$7,996.00
Bornay (Inclin 6000)	$12,038.00
Abundant Renewable Energy (ARE110)	$13,468.00
Abundant Renewable Energy (ARE442)	$38,396.00
Kestrel Wind (600)	$2,100.00
Kestrel Wind (800)	$2,799.00
Kestrel Wind (1000)	$4,107.00
Kestrel Wind (3000)	$10,368.00
Solacity (Eoltec)	$27,168.00

MPPT Charge Controllers	
Product:	**Cost ($)**
Blue Sky Solar (Solar Boost 3048)	$486.25
Outback (Flexmax 80)	$671.10
Outback (Mx60)	$497.76
Outback (Mx60-Es)	$498.43

Solar Panel's	
Product:	**Cost ($)**
Kyocera Solar (KC200)	$800.00
BP Solar (SX 170B)	$728.97
Evergreen (Spruce ES-170)	$731.00
Evergreen (Spruce ES-180)	$774.00
Evergreen (Spruce ES-190)	$817.00
Solar World (SW-165)	$709.97
Mitsubishi (PV-MF155EB3)	$669.97
Sharp (ND-208U1)	$898.56
Sharp (NE-170U1)	$739.50
Mitsubishi (PV-MF165EB4)	$719.97
Sunwize (SW150)	$668.31
Kyocera (KC175GT)	$799.00
Kyocera (KC175GT)	$799.00

Inverter's	
Product:	**Cost ($)**
Xantrex (XW6048)	$3,597.75
Xantrex (XW4548)	$2,878.20
Xantrex (XW4024)	$2,598.20
Xantrex (SW5548)	$2,735.85
Xantrex (SW4048)	$2,178.96
Outback (GTFX3048)	$1,760.00
Outback (GVFX3524)	$1,913.00
Outback (GVFX3648)	$1,913.00
Sunny Island (SI4248U)	$4,228.00
Sunny Island (SI5048U)	$6,535.00

The cost of the battery bank C_{Bbank_h} to be considered in the optimization is obtain from Equation 4-5. The requirements for battery bank are: 2 days of autonomy for a system that consume 800kWh/month, DC battery bank voltage of 48-volt, maximum depth of discharge of 50 percent and a derate factor of 1. The batteries to be considered in this example are listed in Table 4-1. The cost for each different battery bank is shown in Table 7-5.

TABLE 7-5 Calculated Battery Bank Cost for Different Battery Manufactures

Product:	Cost ($)	Required Number of Battery	Battery Bank Cost ($)
MK (8L16)	$288.77	56	$16,171.12
Surrette (12-Cs-11Ps)	$1,118.96	28	$31,330.88
Surrette (2Ks33Ps)	$874.90	48	$41,995.20
Surrette (4-CS-17PS)	$604.23	60	$36,253.80
Surrette (4-Ks-21Ps)	$1,110.44	36	$39,975.84
Surrette (4-Ks-25Ps)	$1,386.85	24	$33,284.40
Surrette (6-Cs-17Ps)	$906.31	40	$36,252.40
Surrette (6-Cs-21Ps)	$1,075.01	32	$34,400.32
Surrette (6-Cs-25Ps)	$1,241.37	24	$29,792.88
Surrette (8-Cs-17Ps)	$1,256.21	30	$37,686.30
Surrette (8-Cs-25Ps)	$1,654.76	18	$29,785.68
Surrette (S-460)	$324.93	56	$18,196.08
Surrette (S-530)	$370.65	48	$17,791.20
Trojan (L16H)	$357.00	48	$17,136.00
Trojan (T-105)	$138.00	88	$12,144.00
US Battery (US185)	$216.58	52	$11,262.16
US Battery (Us2200)	$127.99	88	$11,263.12
US Battery (US250)	$126.35	80	$10,108.00
Surrette (S-460)	$357.36	56	$20,012.16
Surrette (S-530 6V)	$406.09	48	$19,492.32
Surrette (4-CS-17PS)	$770.45	60	$46,227.00
Surrette (4-Ks-21Ps)	$1,206.00	36	$43,416.00
Surrette (4-Ks-25Ps)	$1,508.83	24	$36,211.92
Surrette (6-Cs-17Ps)	$932.31	40	$37,292.40
Surrette (6-Cs-21Ps)	$1,164.00	32	$37,248.00
Surrette (6-Cs-25Ps)	$1,349.45	24	$32,386.80
Surrette (8-Cs-17Ps)	$1,795.71	18	$32,322.78

With the above data, the optimization can be performed.

7.2.2 Optimization Procedure Example

A Matlab program named SThybrid (see Appendix E) is used to calculate the most economic system for a stand alone configuration. The program follows the procedure explained in Chapter 6 and the function “ilinprog” developed by [Torshe]. The Matlab program reads, as input data, from an MS Excel file all the data calculated or gathered in part one. The user must specify the lower and upper bound that each unknown variable may have.

The unknown variables are N_{PV_i} N_{WT_j} N_{Bbank_h} N_{IN_g} N_{CT_k}. For this example we use from 0 to 1 the wind turbines, from 0 to 60 for solar modules, from 0 to 1 for Battery Bank, from 0 to 5 for controllers and from 0 to 4 for inverters. We also specify the demand in kWh, in this case 800kWh per month.

The solution found by our program is shown in Table 7.6. It shows an optimum combination of equipments needed to supply the energy to the load at the lowest cost possible.

TABLE 7-6 Optimization Results for Fajardo, Stand Alone System

'Wind Turbines'	'Opt'	'Solar Panel'	'Opt'	'Battery'	'Opt'	'Inverter'	'Opt'	'Controller'	'Opt'
'Air X'	0	'Kyocera Solar (KC200)'	0	' MK 8L16'	0	Xantrex (XW6048)	0	**Blue Sky Solar (Solar Boost 3048)**	**1**
'Whisper 100'	0	**'BP Solar (SX 170B)'**	**5**	' Surrette 12-Cs-11Ps'	0	Xantrex (XW4548)	0	Outback (Flexmax 80)	0
'Whisper 200'	0	'Evergreen (Spruce ES-170)'	0	' Surrette 2Ks33Ps'	0	Xantrex (XW4024)	0	Outback (Mx60)	0
'Whisper 500'	0	'Evergreen (Spruce ES-180)'	0	' Surrette 4-CS-17PS'	0	Xantrex (SW5548)	0	Outback (Mx60-Es)	0
'Skystream 3.7'	0	'Evergreen (Spruce ES-190)'	0	' Surrette 4-Ks-21Ps'	0	**Xantrex (SW4048)**	**2**		
'Lakota S, SC'	0	'Solar World (SW-165)'	0	' Surrette 4-Ks-25Ps'	0	Outback (GTFX3048)	0		
'BWC 1500'	0	'Mitsubishi (PV-MF155EB3)'	0	' Surrette 6-Cs-17Ps'	0	Outback (GVFX3524)	0		
'BWC XL.1'	0	'Sharp (ND-208U1)'	0	' Surrette 6-Cs-21Ps'	0	Outback (GVFX3648)	0		
'BWC Excel-R'	0	'Sharp (NE-170U1)'	0	' Surrette 6-Cs-25Ps'	0	Sunny Island (SI4248U)	0		
'Inclin 250'	0	'Mitsubishi (PV-MF165EB4)'	0	' Surrette 8-Cs-17Ps'	0	Sunny Island (SI5048U)	0		
'Inclin 600'	0	'Sunwize (SW150)'	0	' Surrette 8-Cs-25Ps'	0				
'Inclin 1500'	0	'Kyocera (KC175GT)'	0	' Surrette S-460'	0				
'Inclin 3000'	**1**	'Kyocera (KC175GT)'	0	' Surrette S-530'	0				
'Inclin 6000'	0			' Trojan L16H'	0				
'ARE110'	0			' Trojan T-105'	0				
'ARE442'	0			' US Battery US185 '	0				
'Kestrel 600'	0			' US Battery Us2200'	0				
'Kestrel 800'	0			**' US Battery US250'**	**80**				
'Kestrel 1000'	0			' Surrette S-460'	0				
'Kestrel 3000'	0			' Surrette S-530 6V'	0				
'Eoltec'	0			' Surrette 4-CS-17PS'	0				
				' Surrette 4-Ks-21Ps'	0				
				' Surrette 4-Ks-25Ps'	0				
				' Surrette 6-Cs-17Ps'	0				
				' Surrette 6-Cs-21Ps'	0				
				' Surrette 6-Cs-25Ps'	0				
				' Surrette 8-Cs-17Ps'	0				

Results from the Optimization Using Liner Programming				
Type	Manufacture Equipment	Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 3000)	($7,996.00)	1	($7,996.00)
Solar Panel	BP Solar (SX 170B)	($728.97)	5	($3,644.85)
Battery	US Battery US250	($126.35)	80	($10,108.00)
Inverter	Xantrex (SW4048)	($2,178.96)	2	($4,357.92)
Controller	Blue Sky Solar (Solar Boost 3048)	($486.25)	1	($486.25)
			Total Equipment Cost =	($26,593.02)

Total Generated Power					
Type	Manufacture	Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 3000)	3000	11310	1	11310
Solar Panel	BP Solar (SX 170B)	170	323	5	1613
				Total System Annual Energy Generated =	12924

We now perform an economical analysis to determine if the investment is good or not.

7.2.3 Economic Analysis Example

We perform the economic analysis for a time period of 20 years. For calculated the cash flow first we need to know the rates, installation cost, insurance cost, the capital cost and kWh retail price. The following values are assumed for this economic analysis.

- The cost of operation and maintenance will be 1 cent per kilowatt-hour generated as suggested in [Gipe, 2004]. This money is used to service or repairs in the system.
- We assume an installation cost of 10% of the total equipment cost of the system.
- Insurance cost will be 1% of the capital cost.
- The kWh retail price will be 23.5 cents.
- Rates
  - The utility escalation rate will be 7%.
  - The interest rate will be 8%.
  - The inflation rate will be 3%.

The loan period will be 20 years, the lifetime of the project. A replacement of the battery bank in the year 10 is included in the capital cost. Meaning the capital cost include the equipment cost with the battery replacement and the installation cost.

Table 7-7 shows the result of capital cost and net present value using the system selected using our optimization procedure.

TABLE 7-7 Economic Analysis for Fajardo, Stand Alone System

Economic Analysis - Stand Alone Fajardo, P.R.								
Economic Analysis Term	20	yrs	Retail Rate KWh		$0.235	$/kWh		
Utility Rate Escalation	7%		Equipments Cost		($26,593.02)			
Inflation Rate	3%		Installation Cost		($2,659.30)	(10% of Equipment Cost)		
Down Payment	0%		Battery Replacement at Year 10		($13,584.31)	F=P(F/P,i,n)		
Loan Term	20	yrs	Capital Cost		**($42,836.63)**	(Equipment Cost + Installation Cost+Batt Replacement)		
Interest Rate	8%		Annual O&M Cost		($129.24)	($0.01 per KWh Generated [Gipe,2004])		
Insurance	1%		Annual Insurance Cost		($428.37)	(1% of Capital Cost)		
			Annual Saved Money Per Year		$3,037.05	(kWh Rate Cost multiply by kWh/Year Generated)		
Cash Flow	Expenses					Income		
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Cash Flow	Cumulative Cash Flow
0	$0.00						$0.00	$0.00
1		($129.24)	($428.37)	($3,426.93)	($936.07)	$3,037.05	($1,883.55)	($1,883.55)
2		($133.11)	($441.22)	($3,352.04)	($1,010.96)	$3,249.65	($1,687.69)	($3,571.24)
3		($137.11)	($454.45)	($3,271.17)	($1,091.84)	$3,477.12	($1,477.44)	($5,048.68)
4		($141.22)	($468.09)	($3,183.82)	($1,179.18)	$3,720.52	($1,251.79)	($6,300.48)
5		($145.46)	($482.13)	($3,089.49)	($1,273.52)	$3,980.96	($1,009.63)	($7,310.11)
6		($149.82)	($496.59)	($2,987.60)	($1,375.40)	$4,259.63	($749.79)	($8,059.90)
7		($154.31)	($511.49)	($2,877.57)	($1,485.43)	$4,557.80	($471.01)	($8,530.92)
8		($158.94)	($526.84)	($2,758.74)	($1,604.27)	$4,876.85	($171.94)	($8,702.86)
9		($163.71)	($542.64)	($2,630.40)	($1,732.61)	$5,218.22	$148.86	($8,553.99)
10		($168.62)	($558.92)	($2,491.79)	($1,871.22)	$5,583.50	$492.95	($8,061.04)
11		($173.68)	($575.69)	($2,342.09)	($2,020.92)	$5,974.35	$861.97	($7,199.07)
12		($178.89)	($592.96)	($2,180.42)	($2,182.59)	$6,392.55	$1,257.69	($5,941.38)
13		($184.26)	($610.75)	($2,005.81)	($2,357.20)	$6,840.03	$1,682.01	($4,259.37)
14		($189.79)	($629.07)	($1,817.23)	($2,545.77)	$7,318.83	$2,136.97	($2,122.40)
15		($195.48)	($647.94)	($1,613.57)	($2,749.43)	$7,831.15	$2,624.72	$502.32
16		($201.35)	($667.38)	($1,393.62)	($2,969.39)	$8,379.33	$3,147.60	$3,649.91
17		($207.39)	($687.40)	($1,156.07)	($3,206.94)	$8,965.88	$3,708.09	$7,358.00
18		($213.61)	($708.02)	($899.51)	($3,463.49)	$9,593.49	$4,308.86	$11,666.86
19		($220.02)	($729.26)	($622.43)	($3,740.57)	$10,265.04	$4,952.75	$16,619.61
20		($226.62)	($751.14)	($323.19)	($4,039.82)	$10,983.59	$5,642.83	$22,262.43
						Net Present Value =	$1,891.61	

Since the net present value is positive the hybrid systems produces enough energy to supply all demand and make a profit. It is a good investment. Table 7.7 shows that in the year 9 of the project the yearly income is greater than the yearly expenses. The system pays for itself in 15 years.

Much have been said about renewable energy system not been economical. As this example shows they are. Perhaps an interesting question to answer is at which value of retail price per kWh this system becomes economic? This is the same as calculating the price per kWh at which we have a zero Net Present Value, the break even condition. We use the Goldseek function in MS Excel to determine the breakeven point. For this example is obtained a kWh rate of 22.6 cents. Table 7-8 shows the cash flow for this case.

TABLE 7-8 NPV Break Even Point Economic Analysis for Fajardo, Stand Alone System

Economic Analysis - Stand Alone Fajardo, P.R.					
Economic Analysis Term	20	yrs	Retail Rate KWh	$0.226	$/kWh
Utility Rate Escalation	7%		Equipments Cost	($26,593.02)	
Inflation Rate	3%		Installation Cost	($2,659.30)	(10% of Equipment Cost)
Down Payment	0%		Battery Replacement at Year 10	($13,584.31)	F=P(F/P,i,n)
Loan Term	20	yrs	Capital Cost	**($42,836.63)**	(Equipment Cost + Installation Cost+Batt Replacement)
Interest Rate	8%		Annual O&M Cost	($129.24)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($428.37)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,925.63	(kWh Rate Cost multiply by kWh/Year Generated)

Cash Flow	Expenses					Income		
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Cash Flow	Cumulative Cash Flow
0	$0.00						$0.00	$0.00
1		($129.24)	($428.37)	($3,426.93)	($936.07)	$2,925.63	($1,994.98)	($1,994.98)
2		($133.11)	($441.22)	($3,352.04)	($1,010.96)	$3,130.42	($1,806.91)	($3,801.89)
3		($137.11)	($454.45)	($3,271.17)	($1,091.84)	$3,349.55	($1,605.01)	($5,406.90)
4		($141.22)	($468.09)	($3,183.82)	($1,179.18)	$3,584.02	($1,388.29)	($6,795.19)
5		($145.46)	($482.13)	($3,089.49)	($1,273.52)	$3,834.90	($1,155.69)	($7,950.88)
6		($149.82)	($496.59)	($2,987.60)	($1,375.40)	$4,103.35	($906.07)	($8,856.95)
7		($154.31)	($511.49)	($2,877.57)	($1,485.43)	$4,390.58	($638.23)	($9,495.19)
8		($158.94)	($526.84)	($2,758.74)	($1,604.27)	$4,697.92	($350.86)	($9,846.05)
9		($163.71)	($542.64)	($2,630.40)	($1,732.61)	$5,026.78	($42.58)	($9,888.63)
10		($168.62)	($558.92)	($2,491.79)	($1,871.22)	$5,378.65	$288.10	($9,600.53)
11		($173.68)	($575.69)	($2,342.09)	($2,020.92)	$5,755.16	$642.78	($8,957.75)
12		($178.89)	($592.96)	($2,180.42)	($2,182.59)	$6,158.02	$1,023.16	($7,934.59)
13		($184.26)	($610.75)	($2,005.81)	($2,357.20)	$6,589.08	$1,431.07	($6,503.53)
14		($189.79)	($629.07)	($1,817.23)	($2,545.77)	$7,050.31	$1,868.45	($4,635.08)
15		($195.48)	($647.94)	($1,613.57)	($2,749.43)	$7,543.84	$2,337.41	($2,297.67)
16		($201.35)	($667.38)	($1,393.62)	($2,969.39)	$8,071.90	$2,840.17	$542.50
17		($207.39)	($687.40)	($1,156.07)	($3,206.94)	$8,636.94	$3,379.14	$3,921.65
18		($213.61)	($708.02)	($899.51)	($3,463.49)	$9,241.52	$3,956.89	$7,878.53
19		($220.02)	($729.26)	($622.43)	($3,740.57)	$9,888.43	$4,576.14	$12,454.68
20		($226.62)	($751.14)	($323.19)	($4,039.82)	$10,580.62	$5,239.86	$17,694.53
						Net Present Value =	($0.00)	

Since the utility retail price is above 22.6 cent, the construction of a stand alone hybrid or wind system is a good investment in Fajardo Puerto Rico.

7.2.4 Final Result, Fajardo Stand Alone Example

Again the hybrid renewable stand alone system in Fajardo, Puerto Rico has a positive net present value of $1,891.61 for a period of 20 years. Figure 7-3 present graphically the results of the cash flow and cumulative cash flow for the stand alone hybrid system in Fajardo, Puerto Rico.

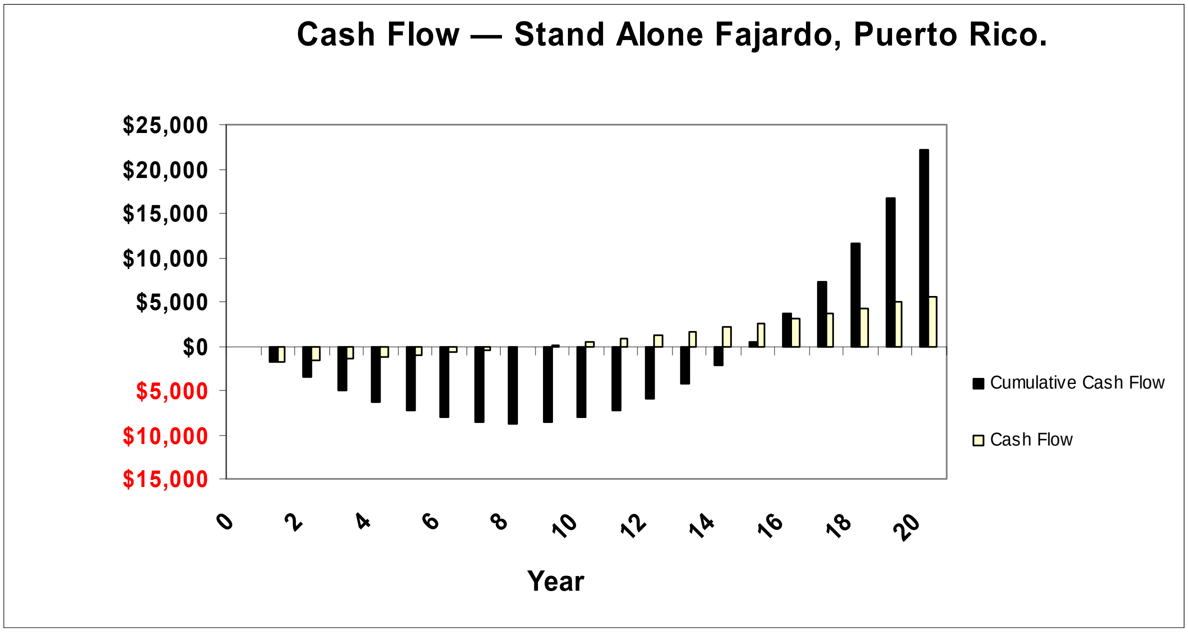

Figure 7-3 Cash Flow for Example of Fajardo, Stand Alone System

7.3 Net Metering and Stand Alone System Analysis with a Utility Rate Escalation of 7%

7.3.1 Stand Alone Results

We applied the procedure described in this thesis to an 800 kWh/month residential load in Fajardo, San Juan and Gurabo. The economic analysis show that a stand alone hybrid power systems in Puerto Rico is economic in Fajardo and not in San Juan and Gurabo. The net present value in Fajardo is positive and is negative in San Juan and Gurabo (See Appendix A). This mean the system will be profitable in Fajardo and will never pay for itself a time period of 20 years for San Juan and Gurabo. Table 7-9 show the net present values calculated for Fajardo, San Juan and Gurabo, Puerto Rico.

TABLE 7-9 Net Present Value Results for Stand Alone Systems

Site	Stand Alone
Fajardo	$1,891.61
San Juan	($4,373.84)
Gurabo	($22,385.53)

Gurabo's net present value is more negative than San Juan's because Gurabo relies completely in PV modules to generate its electricity. The installation of wind turbines in Gurabo is not feasible because the very low wind speed in Gurabo. Since PV modules are more expensive than wind turbines this high cost is expected. On the other hand, Fajardo has the best wind resource and since wind turbines are cheaper than PV modules the net present value for Fajardo is the best of all.

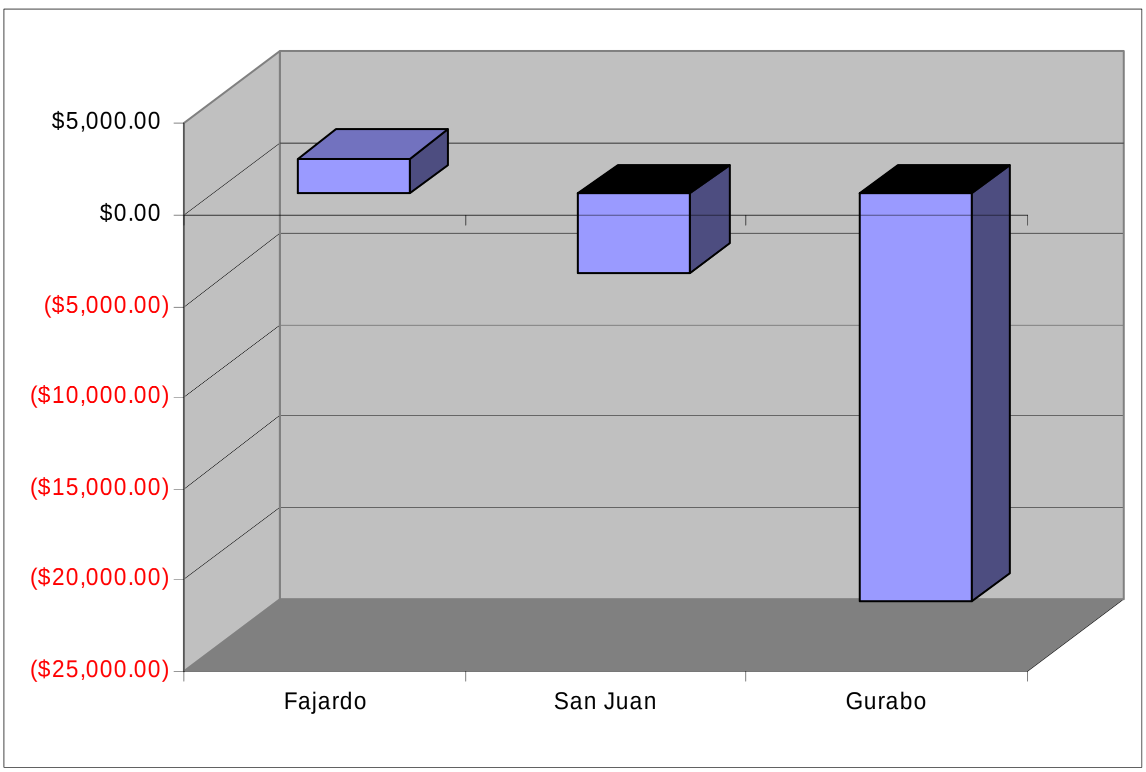

Figure 7-4 Stand Alone Net Present Values

The break even points for these stand alone examples were also calculated. We changed the retail kWh price to determine the break even condition, where the net present value is zero. Table 7-10 shows the retail kWh price to reach a net present value of zero for each hybrid system.

TABLE 7-10 kWh Retail Price for Reach NPV Break Even Points for Stand Alone Hybrid Systems

Site	Stand Alone	
Fajardo	0.226	$/kWh
San Juan	0.255	$/kWh
Gurabo	0.337	$/kWh

When the price per kWh equal or exceed the prices shown then a stand alone hybrid system becomes a good investment.

7.3.2 *Grid Connected Hybrid System Results*

Grid connection and Net Metering programs change the economic analysis dramatically. The net present values of grid connected hybrid systems in Puerto Rico are presented in the Table 7-11.

TABLE 7-11 Net Present Value Results for the Examples of Grid Connected Systems

Site	Selling 800kWh at:	$0.10	Selling 800kWh at:	$0.235	Even at end of year
Fajardo	$33,605.59		$64,624.01		$30,602.25
San Juan	($8,713.88)		$20,662.35		$22,316.21
Gurabo	($27,585.61)		$2,091.26		$3,829.34

The fist column of Table 7-1 shows the site, The second column shows the case where the residential load, 800kWh/month, is served and an additional (800 kWh/month) is sold to the utility at a price per kWh of 10 cents. The third column shows the same situation as column two but the sell price is 23.5 cents per kWh. The last column shows a condition where the hybrid system produces 800kWh/month and no, or almost no, electricity is sold to the utility. The price for sell the electricity in this case is equal to 10 cents per kWh.

Fajardo shows a positive Net Present Value in all situations, (See Appendix A). This is the case because Fajardo has the best wind resource and because wind turbines generate cheaper energy than solar modules.

Net Present Values is positive in San Juan for a system designed not sell kWh or to sell kWh at 23.5 cents per kWh. It show a negative Net Present Value if the kWh selling price is 10 cents. Thus a hybrid renewable power system is feasible for San Juan if it is, Net Metering is present, and grid connected system is design to not sell kWh at the end of the year.

The same happens in Gurabo. The Net Present Value is positive for a system design to not sell kWh or to sell kWh at 23.5 cents/kWh. Gurabo in comparison to San Juan has lower net present values. This is the case because Gurabo must depend on PV modules to generated its electricity. The installation of wind turbines in Gurabo is not possible due to low wind speed. Figure 7-5 shows the results graphically.

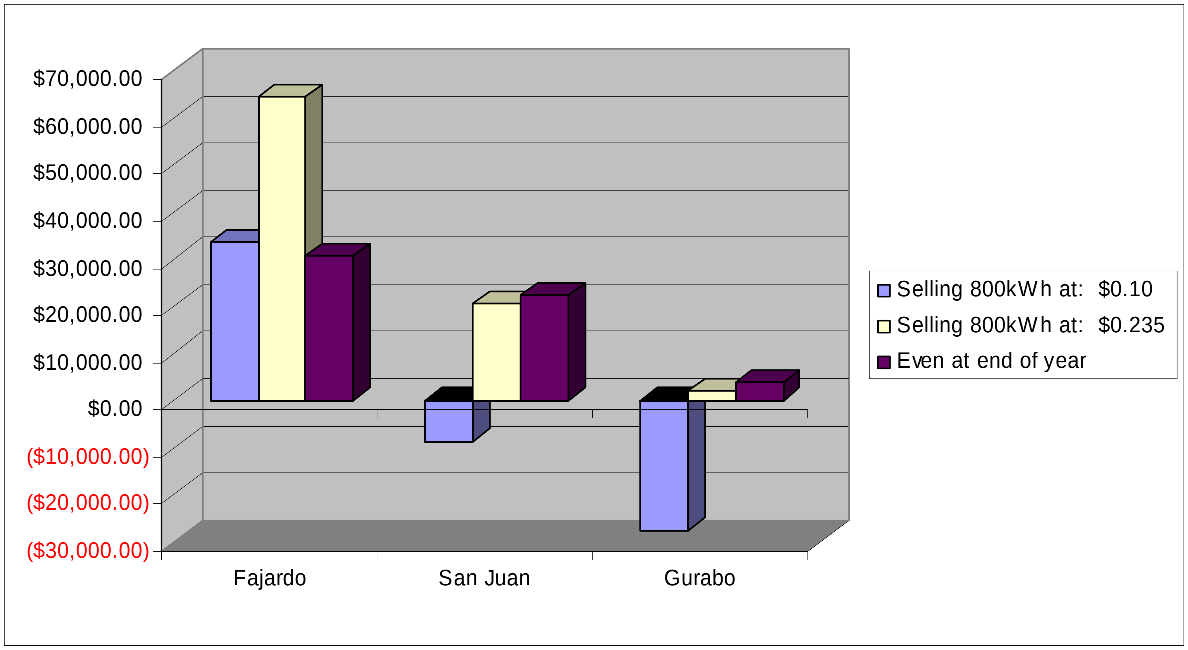

Figure 7-5 Graph Results of Grid Connected Net Present Values

We calculated the selling price of electricity to reach break even. We change the price of retail kWh to find a Net Present Value equal to zero. Table 7-12 shows at what retail price per kWh the Net Present Value is zero.

TABLE 7-12 kWh Retail Price for Reach NPV Break Even Points for Grid Connected Systems

[redacted]

7.4 Economic Analysis of grid Connected and Stand Alone Conditions with Different Utility Rate Escalation

Now we study what happen if the utility rate escalation varies from 5% to 9%. The utility rate escalation is the change in retail price of electricity each year. In Puerto Rico this rate has been increasing substantially during the last four years (See Table 6-4). In the previous examples we used a utility rate escalation of 7%, the lowest in the last 4 year in Puerto Rico. We know change the utility rate escalation to determine how the net present value changes. We will only change the utility rate escalation, all other parameters remained as before.

7.4.1 Fajardo Results for Different Utility Rates Escalation

TABLE 7-13 NPV Results for Fajardo, P.R. at Different Utility Rates Escalation

Utility Rate Escalation of:	Selling 800KWh at: $.10	Selling 800KWh at: $.235	Even at end of year	Stand Alone
Utility Rate Escalation of: 5%	$26,572.71	$51,244.74	$23,569.38	($6,061.29)
Utility Rate Escalation of: 7%	$33,605.59	$64,624.01	$30,602.25	$1,891.61
Utility Rate Escalation of: 9%	$42,374.48	$81,305.88	$39,371.14	$11,807.64

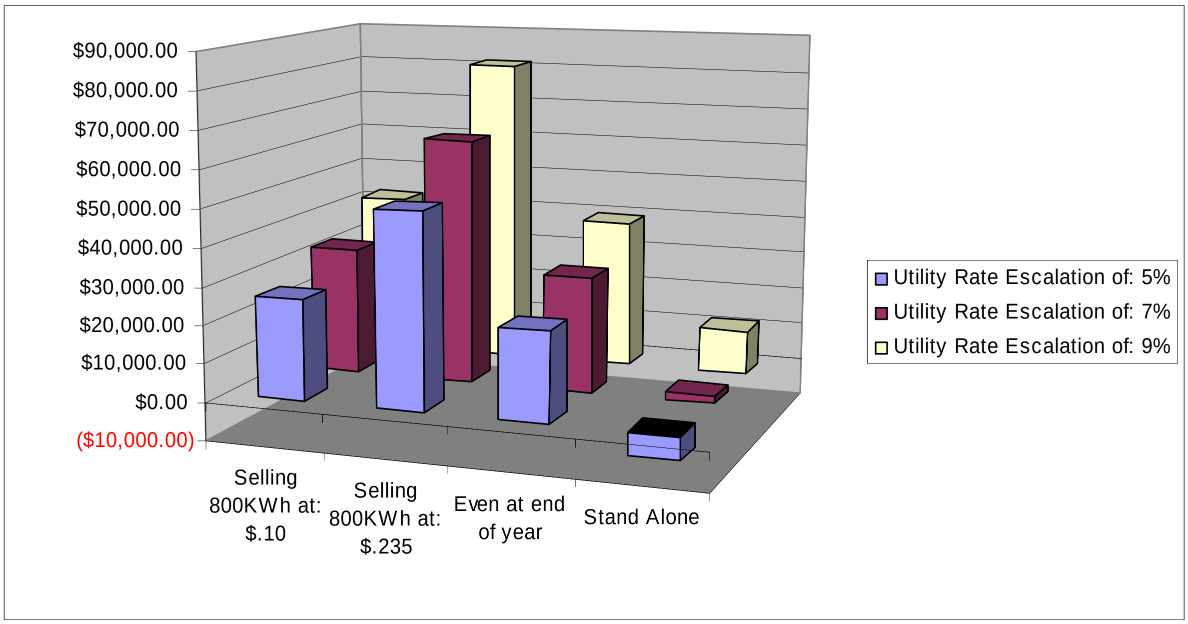

Figure 7-6 Graph of NPV for Fajardo, P.R. at Different Utility Rates Escalation

Table 7-13 and Figure 7-6 show the NPV for Fajardo to be positive in all cases but one. NPV is negative in Fajardo for a stand alone system with a utility rate escalation of 5%.

7.4.2 San Juan Results for Different Utility Rates Escalation

TABLE 7-14 NPV Results for San Juan, PR at Different Utility Rates Escalation

Utility Rate Escalation of:	Selling 800KWh at: $.10	Selling 800KWh at: $.235	Even at end of year	Stand Alone
Utility Rate Escalation of: 5%	($15,746.75)	$7,619.07	$15,283.34	($12,267.15)
Utility Rate Escalation of: 7%	($8,713.88)	$20,662.35	$22,316.21	($4,373.84)
Utility Rate Escalation of: 9%	$55.02	$36,925.28	$31,085.11	$5,467.88

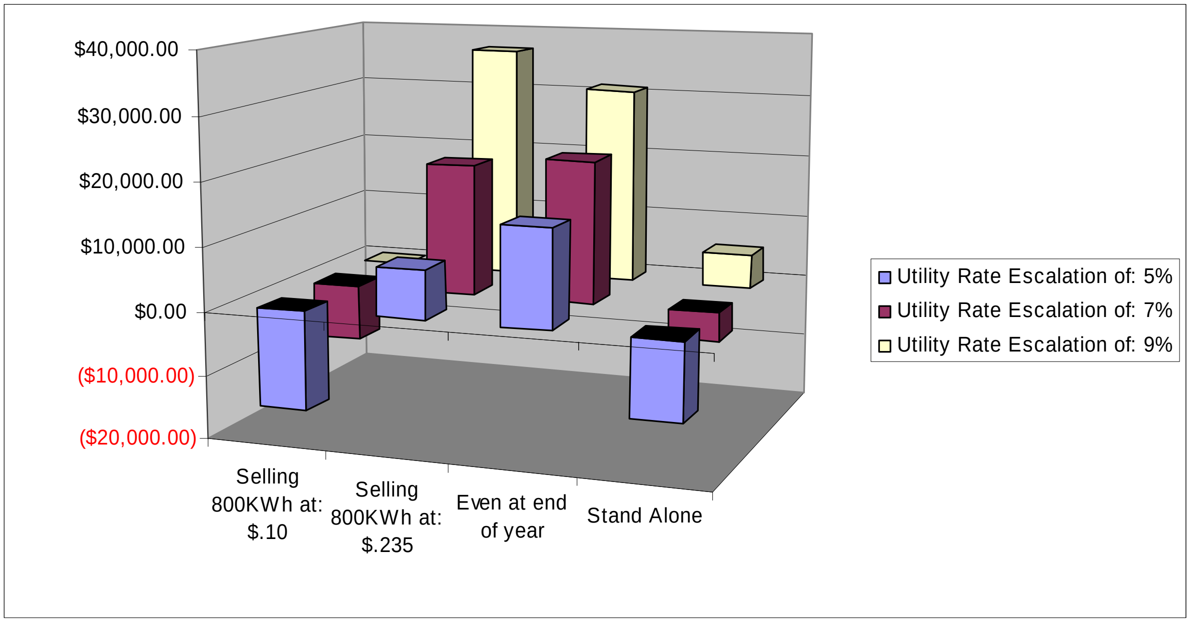

Figure 7-7 Graph of NPV for San Juan, P.R. at Different Utility Rates Escalation

Table 7-14 and Figure 7-7 show that all systems configuration, utility connected or stand alone, are economically feasible for San Juan at a utility rate escalation of 9%.

7.4.3 Gurabo Results for Different Utility Rates Escalation

TABLE 7-15 NPV Results for Gurabo, PR at Different Utility Rates Escalation

Utility Rate Escalation of:	Selling 800KWh at: $.10	Selling 800KWh at: $.235	Even at end of year	Stand Alone
Utility Rate Escalation of: 5%	($34,618.48)	($11,013.53)	($3,203.53)	($30,371.89)
Utility Rate Escalation of: 7%	($27,585.61)	$2,091.26	$3,829.34	($22,385.53)
Utility Rate Escalation of: 9%	($18,816.71)	$18,430.90	$12,598.24	($12,427.79)

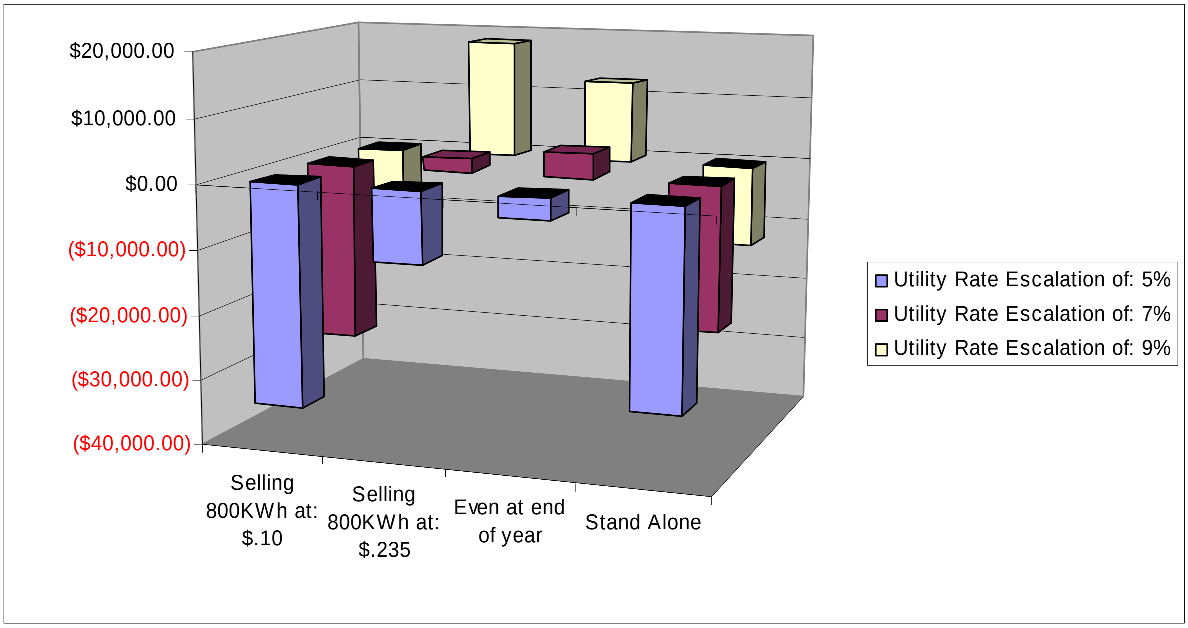

Figure 7-8 Graph of NPV for Gurabo, P.R. at Different Utility Rates Escalation

Table 7-15 and Figure 7-8 show that a PV system in Gurabo is economically feasible at 7% and 9% utility rate escalation only for even at end of year and selling excess energy at 23.5 cent/kWh conditions.

8 Conclusions and Recommendations

8.1 Conclusions

We use integer linear programming to find an optimum, least cost, configuration for a hybrid (wind and photovoltaic) renewable system to satisfy residential demand in selected sites in Puerto Rico. We modeled the wind resource using weibull probability distribution and used Ortiz model to adjust PV output based on available solar radiation data. We evaluate the economic feasibility of the hybrid system using a Net Present Value (NPV) economic analysis. We included in our economic analysis insurance, inflation, utility rate escalation, and O&M costs.

Our conclusions are:

- The Bornay Incline 3000 and 6000 wind turbines are most economical turbines to generate the required energy of 800kWh/month in Fajardo and San Juan, P.R.
- After adjusting the power output for a PV module, based in local temperature and solar radiation, and using [Ortiz, 2006] model we found that the most economical PV module not necessary generates the most economical energy in a year. Our analysis shows the BP solar (SX 170B) is the solar module that generates the cheapest PV energy in Puerto Rico.
- A stand alone hybrid power system that generates 800kWh/month, with a utility escalation rate of 7%, is a good investment in Fajardo P.R.. The NPV of this project reflect, an income of $1,891.61 in a period of 20 years. In San Juan and Gurabo,

where the wind resource is lower, the stand alone system is not economical in a period of 20 years.

- A grid connected hybrid power systems with a utility escalation rate of 7%, Net Metering and designed to supply 800kWh/month are a good investment in Fajardo, San Juan and Gurabo. The NPV is positive in a period of 20 year.
- A grid connected hybrid power system with Net Metering and designed to supply a residential load of 800kWh/month and to sell an excess 800kWh/month to the local utility at the same rate the utility sell the power, and with a utility rate escalation of 7% is a good investment in Fajardo, San Juan and Gurabo The NPV is positive in a period of 20 year.
- A grid connected hybrid power systems with Net Metering, designed to supply a residential load of 800kWh/month and to sell an excess 800kWh/month to the local utility at a rate of 10cents, is a good investment in Fajardo but not in San Juan or Gurabo.
- Fajardo where the wind resource is higher than San Juan and Gurabo, consistently shows a higher NPV, since wind turbines are cheaper than PV modules.

8.2 Recommendations for Future Work

The following are recommendations for future work:

- Collect enough wind speed and solar radiation data to evaluate grid connected and stand alone hybrid power systems for all towns in Puerto Rico.

- Since wind speed and solar radiation may change for year to year, incorporate a risk analysis method capable of do multiple simulation changing wind speed and solar radiation data. This sensitivity analysis may be very useful.
- The economic analysis does not consider externalities or social benefits of renewable energy use. The analysis could be modified to include externalities such as the value of no contaminates of the environment and the social benefit of new jobs creation (installer & maintenance) and the possibility of manufacturing PV modules and wind turbines in Puerto Rico.

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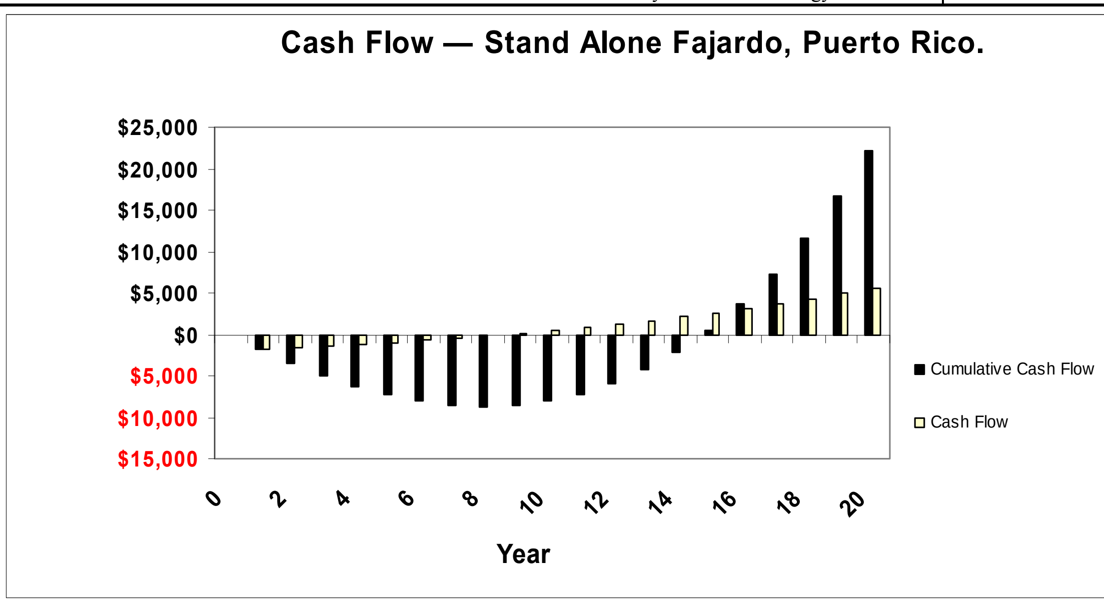
APPENDIX A *DETAILED RESULTS FOR STAND ALONE AND GRID CONNECTED EXAMPLES*

APPENDIX A1 FAJARDO STAND ALONE EXAMPLE

System Specification			**Battery Bank Specifications**		
Location	Fajardo		Selected Battery	US Battery US250	
Analysis	Stand Alone		Battery Capacity C/20	250	Ah
AC Voltage	120	Volts	Battery Voltage	6	Volts
DC Voltage	48	Volts	Battery Bank Voltage	48	Volts
System Efficiency	75%		Days of Autonomy	2	
			Maximum Depth of Discharge	50%	
Energy Consumption			Derate Factor	1	
Load Monthly Average	800	kWh	Required Battery Bank Capacity	2435	
Load Annual Average	9600	kWh	Batteries In Parallel	10	
System Monthly Average	1067	kWh	Batteries In Series	8	
System Annual Average	12800	kWh	Total Batteries =	80	
Results from the Optimization Using Liner Programming					
Type	Manufacture Equipment		Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 3000)		($7,996.00)	1	($7,996.00)
Solar Panel	BP Solar (SX 170B)		($728.97)	5	($3,644.85)
Battery	US Battery US250		($126.35)	80	($10,108.00)
Inverter	Xantrex (SW4048)		($2,178.96)	2	($4,357.92)
Controller	Blue Sky Solar (Solar Boost 3048)		($486.25)	1	($486.25)
				Total Equipment Cost =	($26,593.02)
Total Generated Power					
Type	Manufacture	Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 3000)	3000	11310	1	11310
Solar Panel	BP Solar (SX 170B)	170	323	5	1613
				Total System Annual Energy Generated =	12924



Economic Analysis - Stand Alone Fajardo, P.R.					
Economic Analysis Term	20	yrs	Retail Rate KWh	$0.235	$/kWh
Utility Rate Escalation	7%		Equipments Cost	($26,593.02)	
Inflation Rate	3%		Installation Cost	($2,659.30)	(10% of Equipment Cost)
Down Payment	0%		Battery Replacement at Year 10	($13,584.31)	F=P(F/P,i,n)
Loan Term	20	yrs	Capital Cost	**($42,836.63)**	(Equipment Cost + Installation Cost+Batt Replacement)
Interest Rate	8%		Annual O&M Cost	($129.24)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($428.37)	(1% of Capital Cost)
			Annual Saved Money Per Year	$3,037.05	(kWh Rate Cost multiply by kWh/Year Generated)

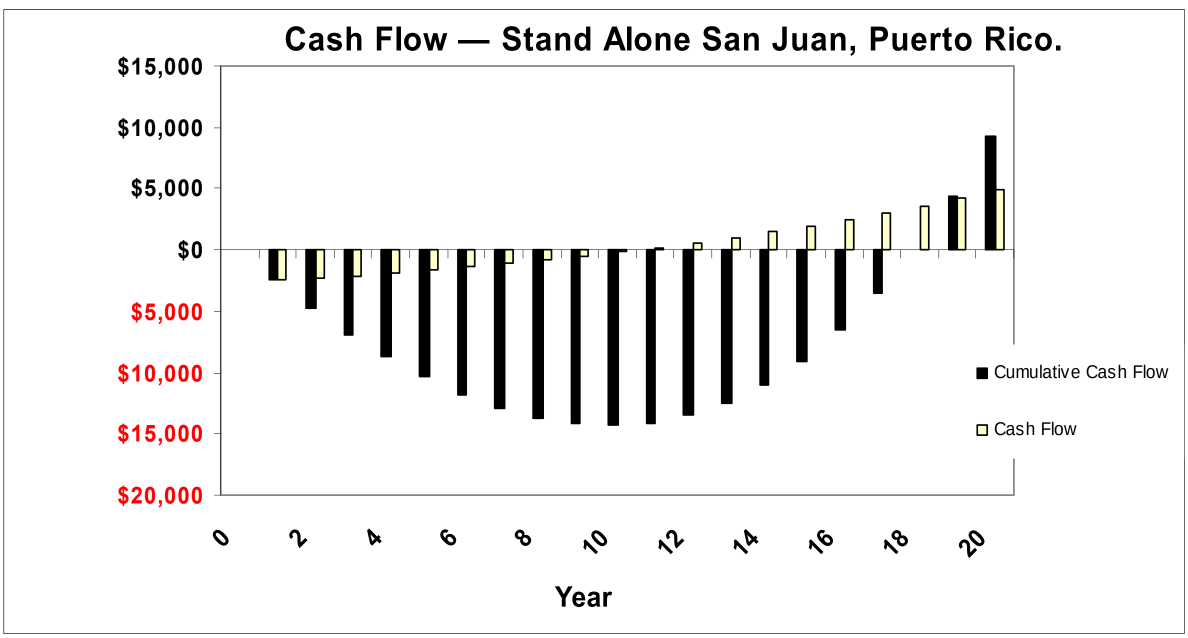
Cash Flow	Expenses					Income		
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Cash Flow	Cumulative Cash Flow
0	$0.00						$0.00	$0.00
1		($129.24)	($428.37)	($3,426.93)	($936.07)	$3,037.05	($1,883.55)	($1,883.55)
2		($133.11)	($441.22)	($3,352.04)	($1,010.96)	$3,249.65	($1,687.69)	($3,571.24)
3		($137.11)	($454.45)	($3,271.17)	($1,091.84)	$3,477.12	($1,477.44)	($5,048.68)
4		($141.22)	($468.09)	($3,183.82)	($1,179.18)	$3,720.52	($1,251.79)	($6,300.48)
5		($145.46)	($482.13)	($3,089.49)	($1,273.52)	$3,980.96	($1,009.63)	($7,310.11)
6		($149.82)	($496.59)	($2,987.60)	($1,375.40)	$4,259.63	($749.79)	($8,059.90)
7		($154.31)	($511.49)	($2,877.57)	($1,485.43)	$4,557.80	($471.01)	($8,530.92)
8		($158.94)	($526.84)	($2,758.74)	($1,604.27)	$4,876.85	($171.94)	($8,702.86)
9		($163.71)	($542.64)	($2,630.40)	($1,732.61)	$5,218.22	$148.86	($8,553.99)
10		($168.62)	($558.92)	($2,491.79)	($1,871.22)	$5,583.50	$492.95	($8,061.04)
11		($173.68)	($575.69)	($2,342.09)	($2,020.92)	$5,974.35	$861.97	($7,199.07)
12		($178.89)	($592.96)	($2,180.42)	($2,182.59)	$6,392.55	$1,257.69	($5,941.38)
13		($184.26)	($610.75)	($2,005.81)	($2,357.20)	$6,840.03	$1,682.01	($4,259.37)
14		($189.79)	($629.07)	($1,817.23)	($2,545.77)	$7,318.83	$2,136.97	($2,122.40)
15		($195.48)	($647.94)	($1,613.57)	($2,749.43)	$7,831.15	$2,624.72	$502.32
16		($201.35)	($667.38)	($1,393.62)	($2,969.39)	$8,379.33	$3,147.60	$3,649.91
17		($207.39)	($687.40)	($1,156.07)	($3,206.94)	$8,965.88	$3,708.09	$7,358.00
18		($213.61)	($708.02)	($899.51)	($3,463.49)	$9,593.49	$4,308.86	$11,666.86
19		($220.02)	($729.26)	($622.43)	($3,740.57)	$10,265.04	$4,952.75	$16,619.61
20		($226.62)	($751.14)	($323.19)	($4,039.82)	$10,983.59	$5,642.83	$22,262.43
						Net Present Value =	$1,891.61	

APPENDIX A2 SAN JUAN STAND ALONE EXAMPLE

System Specification			Battery Bank Specifications		
Location	San Juan		Selected Battery	US Battery US250	
Analysis	Stand Alone		Battery Capacity C/20	250	Ah
AC Voltage	120	Volts	Battery Voltage	6	Volts
DC Voltage	48	Volts	Battery Bank Voltage	48	Volts
System Efficiency	75%		Days of Autonomy	2	
			Maximum Depth of Discharge	50%	
Energy Consumption			Derate Factor	1	
Load Monthly Average	800	kWh	Required Battery Bank Capacity	2435	
Load Annual Average	9600	kWh	Batteries In Parallel	10	
System Monthly Average	1067	kWh	Batteries In Series	8	
System Annual Average	12800	kWh	Total Batteries =	80	

Results from the Optimization Using Liner Programming				
Type	Manufacture Equipment	Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 6000)	($12,038.00)	1	($12,038.00)
Solar Panel	BP Solar (SX 170B)	($728.97)	6	($4,373.82)
Battery	US Battery US250	($126.35)	80	($10,108.00)
Inverter	Xantrex (SW4048)	($2,178.96)	2	($4,357.92)
Controller	Blue Sky Solar (Solar Boost 3048)	($486.25)	1	($486.25)
			Total Equipment Cost =	($31,363.99)

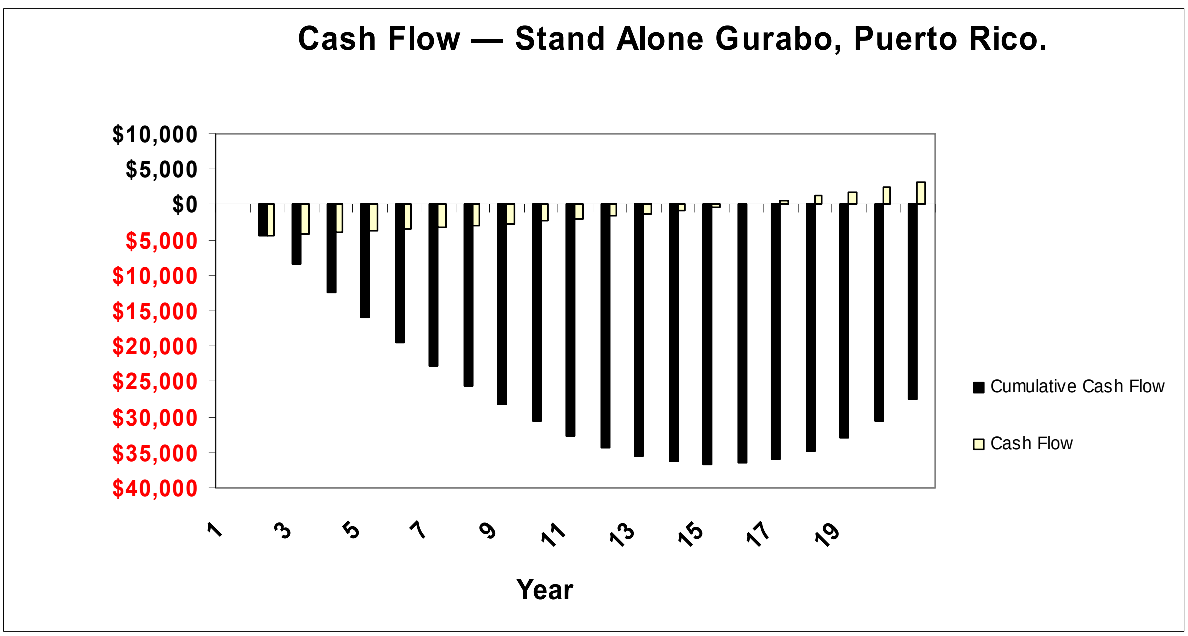
Total Generated Power					
Type	Manufacture	Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 6000)	6000	10966	1	10966
Solar Panel	BP Solar (SX 170B)	170	310	6	1861
				Total System Annual Energy Generated =	12827



Economic Analysis - Stand Alone San Juan, P.R.								
Economic Analysis Term	20	yrs	Retail Rate KWh		0.235	$/kWh		
Utility Rate Escalation	7%		Equipments Cost		($31,363.99)			
Inflation Rate	3%		Installation Cost		($3,136.40)	(10% of Equipment Cost)		
Down Payment	0%		Battery Replacement at Year 10		($13,584.31)	F=P(F/P,i,n)		
Loan Term	20	yrs	Capital Cost		**($48,084.70)**	(Equipment Cost + Installation Cost+Batt Replacement)		
Interest Rate	8%		Annual O&M Cost		($128.27)	($0.01 per KWh Generated [Gipe,2004])		
Insurance	1%		Annual Insurance Cost		($480.85)	(1% of Capital Cost)		
			Annual Saved Money Per Year		$3,014.30	(kWh Cost multiply by kWh/Year Generated)		
Cash Flow	Expenses					Income		Cumulative Cash
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Cash Flow	Flow
0	$0.00						$0.00	$0.00
1		($128.27)	($480.85)	($3,846.78)	($1,050.76)	$3,014.30	($2,492.35)	($2,492.35)
2		($132.12)	($495.27)	($3,762.72)	($1,134.82)	$3,225.30	($2,299.62)	($4,791.98)
3		($136.08)	($510.13)	($3,671.93)	($1,225.60)	$3,451.07	($2,092.68)	($6,884.65)
4		($140.16)	($525.43)	($3,573.88)	($1,323.65)	$3,692.64	($1,870.49)	($8,755.14)
5		($144.37)	($541.20)	($3,467.99)	($1,429.54)	$3,951.13	($1,631.97)	($10,387.11)
6		($148.70)	($557.43)	($3,353.63)	($1,543.91)	$4,227.71	($1,375.96)	($11,763.06)
7		($153.16)	($574.16)	($3,230.11)	($1,667.42)	$4,523.65	($1,101.20)	($12,864.27)
8		($157.75)	($591.38)	($3,096.72)	($1,800.81)	$4,840.30	($806.37)	($13,670.63)
9		($162.49)	($609.12)	($2,952.65)	($1,944.88)	$5,179.12	($490.02)	($14,160.65)
10		($167.36)	($627.40)	($2,797.06)	($2,100.47)	$5,541.66	($150.63)	($14,311.28)
11		($172.38)	($646.22)	($2,629.03)	($2,268.51)	$5,929.58	$213.44	($14,097.84)
12		($177.55)	($665.60)	($2,447.55)	($2,449.99)	$6,344.65	$603.96	($13,493.88)
13		($182.88)	($685.57)	($2,251.55)	($2,645.98)	$6,788.77	$1,022.79	($12,471.09)
14		($188.37)	($706.14)	($2,039.87)	($2,857.66)	$7,263.99	$1,471.95	($10,999.15)
15		($194.02)	($727.32)	($1,811.26)	($3,086.28)	$7,772.46	$1,953.59	($9,045.56)
16		($199.84)	($749.14)	($1,564.35)	($3,333.18)	$8,316.54	$2,470.02	($6,575.53)
17		($205.83)	($771.62)	($1,297.70)	($3,599.83)	$8,898.69	$3,023.71	($3,551.82)
18		($212.01)	($794.77)	($1,009.71)	($3,887.82)	$9,521.60	$3,617.30	$65.48
19		($218.37)	($818.61)	($698.69)	($4,198.84)	$10,188.12	$4,253.61	$4,319.08
20		($224.92)	($843.17)	($362.78)	($4,534.75)	$10,901.28	$4,935.66	$9,254.75
						Net Present Value =	($4,373.84)	

APPENDIX A3 GURABO STAND ALONE EXAMPLE

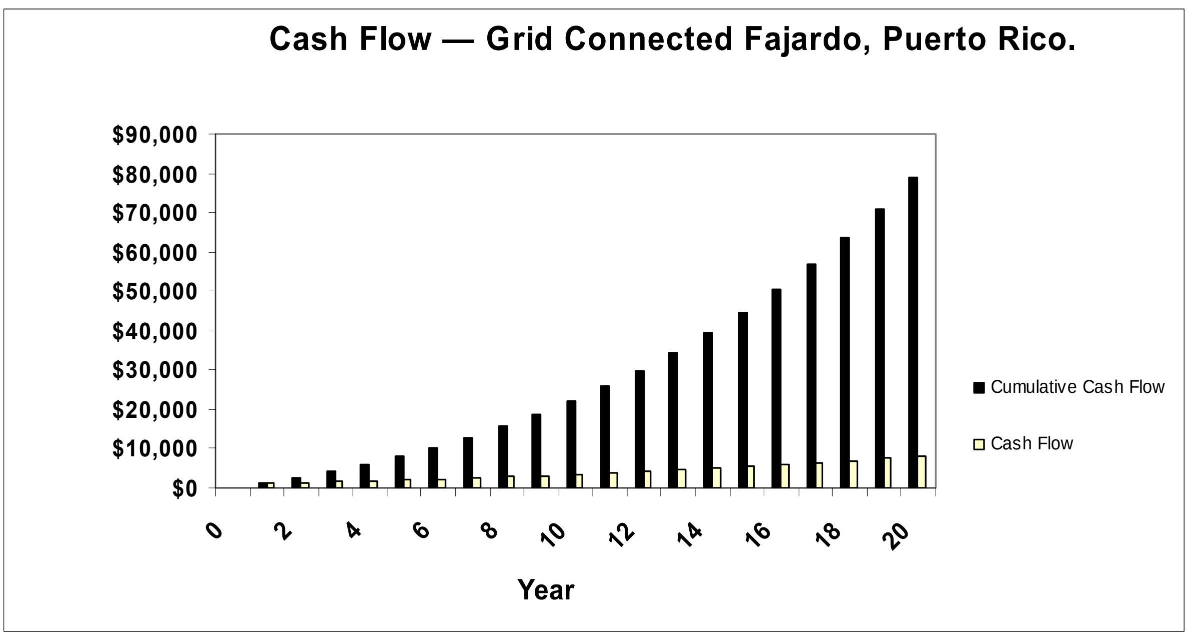
System Specification			Battery Bank Specifications		
Location	Gurabo		Selected Battery	US Battery US250	
Analysis	Stand Alone		Battery Capacity C/20	250	Ah
AC Voltage	120	Volts	Battery Voltage	6	Volts
DC Voltage	48	Volts	Battery Bank Voltage	48	Volts
System Efficiency	75%		Days of Autonomy	2	
			Maximum Depth of Discharge	50%	
Energy Consumption			Derate Factor	1	
Load Monthly Average	800	kWh	Required Battery Bank Capacity	2435	
Load Annual Average	9600	kWh	Batteries In Parallel	10	
System Monthly Average	1067	kWh	Batteries In Series	8	
System Annual Average	12800	kWh	Total Batteries =	80	
Results from the Optimization Using Liner Programming					
Type	Manufacture Equipment		Cost	Quantity	Total Cost
Wind Turbine	none		$0.00	0	$0.00
Solar Panel	BP Solar (SX 170B)		($728.97)	42	($30,616.74)
Battery	US Battery US250		($126.35)	80	($10,108.00)
Inverter	Xantrex (SW4048)		($2,178.96)	2	($4,357.92)
Controller	Outback (Flexmax 80)		($671.10)	2	($1,342.20)
				Total Equipment Cost =	($46,424.86)
Total Generated Power					
Type	Manufacture	Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	none	0	0	0	0
Solar Panel	BP Solar (SX 170B)	170	309	42	12978
				Total System Annual Energy Generated =	12978



Economic Analysis - Stand Alone Gurabo, P.R.								
Economic Analysis Term	20	yrs	Retail Rate KWh		0.235	$/kWh		
Utility Rate Escalation	7%		Equipments Cost		($46,424.86)			
Inflation Rate	3%		Installation Cost		($4,642.49)	(10% of Equipment Cost)		
Down Payment	0%		Battery Replacement at Year 10		($13,584.31)	F=P(F/P,i,n)		
Loan Term	20	yrs	Capital Cost		**($64,651.65)**	(Equipment Cost + Installation Cost+Batt Replacement)		
Interest Rate	8%		Annual O&M Cost		($129.78)	($0.01 per KWh Generated [Gipe,2004])		
Insurance	1%		Annual Insurance Cost		($646.52)	(1% of Capital Cost)		
			Annual Saved Money Per Year		$3,049.83	(kWh Cost multiply by kWh/Year Generated)		
Cash Flow	Expenses					Income		Cumulative Cash
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Cash Flow	Flow
0	$0.00						$0.00	$0.00
1		($129.78)	($646.52)	($5,172.13)	($1,412.78)	$3,049.83	($4,311.38)	($4,311.38)
2		($133.67)	($665.91)	($5,059.11)	($1,525.80)	$3,263.32	($4,121.18)	($8,432.56)
3		($137.68)	($685.89)	($4,937.05)	($1,647.87)	$3,491.75	($3,916.74)	($12,349.30)
4		($141.81)	($706.47)	($4,805.22)	($1,779.70)	$3,736.17	($3,697.02)	($16,046.32)
5		($146.07)	($727.66)	($4,662.84)	($1,922.07)	$3,997.70	($3,460.94)	($19,507.26)
6		($150.45)	($749.49)	($4,509.07)	($2,075.84)	$4,277.54	($3,207.31)	($22,714.57)
7		($154.96)	($771.97)	($4,343.01)	($2,241.91)	$4,576.97	($2,934.88)	($25,649.45)
8		($159.61)	($795.13)	($4,163.65)	($2,421.26)	$4,897.36	($2,642.30)	($28,291.75)
9		($164.40)	($818.99)	($3,969.95)	($2,614.96)	$5,240.18	($2,328.13)	($30,619.87)
10		($169.33)	($843.56)	($3,760.76)	($2,824.16)	$5,606.99	($1,990.82)	($32,610.69)
11		($174.41)	($868.86)	($3,534.82)	($3,050.09)	$5,999.48	($1,628.71)	($34,239.40)
12		($179.65)	($894.93)	($3,290.82)	($3,294.10)	$6,419.44	($1,240.05)	($35,479.45)
13		($185.04)	($921.78)	($3,027.29)	($3,557.62)	$6,868.80	($822.93)	($36,302.38)
14		($190.59)	($949.43)	($2,742.68)	($3,842.23)	$7,349.62	($375.31)	($36,677.69)
15		($196.30)	($977.91)	($2,435.30)	($4,149.61)	$7,864.09	$104.96	($36,572.73)
16		($202.19)	($1,007.25)	($2,103.33)	($4,481.58)	$8,414.58	$620.22	($35,952.51)
17		($208.26)	($1,037.47)	($1,744.81)	($4,840.11)	$9,003.60	$1,172.96	($34,779.56)
18		($214.51)	($1,068.59)	($1,357.60)	($5,227.32)	$9,633.85	$1,765.84	($33,013.72)
19		($220.94)	($1,100.65)	($939.41)	($5,645.50)	$10,308.22	$2,401.71	($30,612.01)
20		($227.57)	($1,133.67)	($487.77)	($6,097.14)	$11,029.79	$3,083.64	($27,528.37)
						Net Present Value =	($22,385.53)	

APPENDIX A4 FAJARDO GRID CONNECTED EXAMPLE

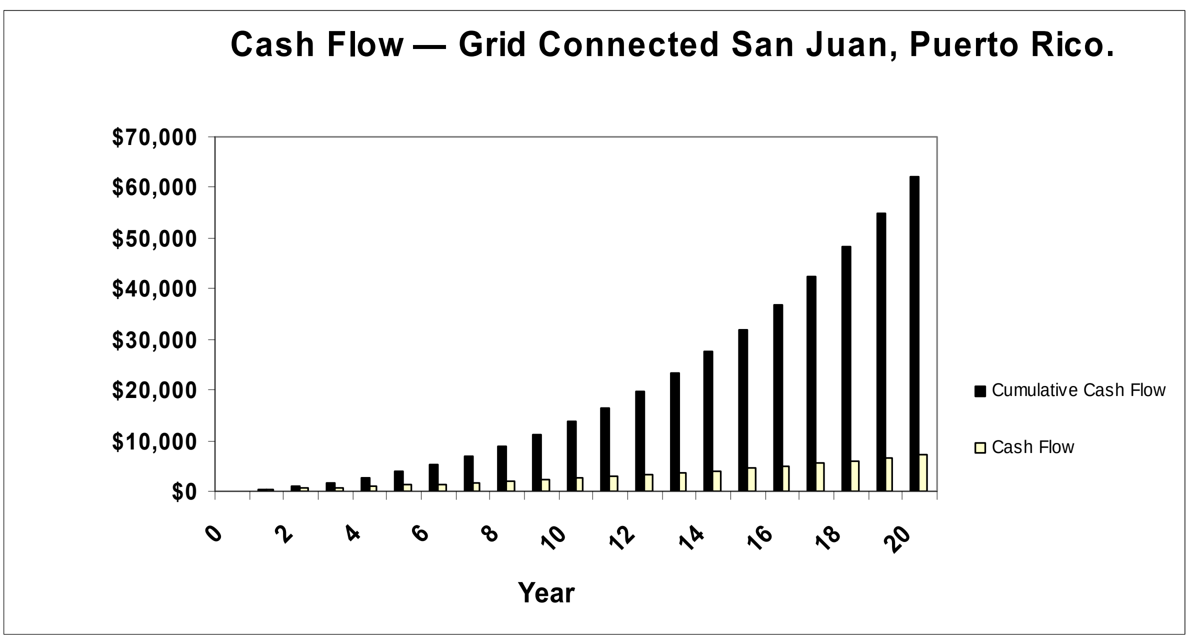
System Specification						
Location	Fajardo			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	0	kWh	Monthly Average		952	kWh
Annual Average	0	kWh	Annual Average		11429	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 3000)			($7,996.00)	1	($7,996.00)
Solar Panel	BP Solar (SX 170B)			($728.97)	1	($728.97)
Inverter	Outback (GVFX3648)			($1,913.00)	1	($1,913.00)
Controller	Blue Sky Solar (Solar Boost 3048)			($486.25)	1	($486.25)
Total Equipment Cost =						($11,124.22)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 3000)		3000	11310	1	11310
Solar Panel	BP Solar (SX 170B)		170	323	1	323
Total System Annual Energy Generated =						11633
Total System Annual Energy Available for Sale to Utility =						172



Economic Analysis - Grid Connected Fajardo, P.R.									
Economic Analysis Term	20	yrs	Retail Rate KWh		0.235	$/kWh			
Utility Rate Escalation	7%		Sale Cost KWh		0.1	$/kWh			
Inflation Rate	3%		Equipments Cost		($11,124.22)				
Down Payment	0%		Installation Cost		($1,112.42)	(10% of Equipment Cost)			
Loan Term	20	yrs	Capital Cost		**($12,236.64)**	(Equipment Cost + Installation Cost)			
Interest Rate	8%		Annual O&M Cost		($116.33)	($0.01 per KWh Generated [Gipe,2004])			
Insurance	1%		Annual Insurance Cost		($122.37)	(1% of Capital Cost)			
			Annual Saved Money Per Year		$2,685.71	(kWh Cost multiply by kWh/Year Generated)			
			Annual Income from Utility KWh Sell		$17.17	(kWh Available for sale multiply by Sale Cost of kWh)			
Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($116.33)	($122.37)	($978.93)	($267.40)	$2,685.71	$17.17	$1,217.86	$1,217.86
2		($119.82)	($126.04)	($957.54)	($288.79)	$2,873.71	$17.17	$1,398.70	$2,616.56
3		($123.41)	($129.82)	($934.44)	($311.89)	$3,074.87	$17.17	$1,592.48	$4,209.05
4		($127.12)	($133.71)	($909.48)	($336.84)	$3,290.12	$17.17	$1,800.13	$6,009.17
5		($130.93)	($137.72)	($882.54)	($363.79)	$3,520.42	$17.17	$2,022.61	$8,031.79
6		($134.86)	($141.86)	($853.43)	($392.89)	$3,766.85	$17.17	$2,260.98	$10,292.77
7		($138.90)	($146.11)	($822.00)	($424.33)	$4,030.53	$17.17	$2,516.36	$12,809.13
8		($143.07)	($150.50)	($788.06)	($458.27)	$4,312.67	$17.17	$2,789.95	$15,599.07
9		($147.36)	($155.01)	($751.39)	($494.93)	$4,614.56	$17.17	$3,083.03	$18,682.10
10		($151.78)	($159.66)	($711.80)	($534.53)	$4,937.58	$17.17	$3,396.97	$22,079.07
11		($156.34)	($164.45)	($669.04)	($577.29)	$5,283.21	$17.17	$3,733.26	$25,812.34
12		($161.03)	($169.38)	($622.85)	($623.47)	$5,653.03	$17.17	$4,093.46	$29,905.80
13		($165.86)	($174.47)	($572.98)	($673.35)	$6,048.74	$17.17	$4,479.26	$34,385.06
14		($170.83)	($179.70)	($519.11)	($727.22)	$6,472.16	$17.17	$4,892.46	$39,277.52
15		($175.96)	($185.09)	($460.93)	($785.40)	$6,925.21	$17.17	$5,335.00	$44,612.52
16		($181.24)	($190.64)	($398.10)	($848.23)	$7,409.97	$17.17	$5,808.93	$50,421.46
17		($186.68)	($196.36)	($330.24)	($916.09)	$7,928.67	$17.17	$6,316.47	$56,737.93
18		($192.28)	($202.25)	($256.95)	($989.38)	$8,483.68	$17.17	$6,859.99	$63,597.92
19		($198.04)	($208.32)	($177.80)	($1,068.53)	$9,077.53	$17.17	$7,442.01	$71,039.93
20		($203.99)	($214.57)	($92.32)	($1,154.01)	$9,712.96	$17.17	$8,065.25	$79,105.18
							Net Present Value =	$30,602.25	

APPENDIX A5 SAN JUAN GRID CONNECTED EXAMPLE

System Specification						
Location	San Juan			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	0	kWh	Monthly Average		952	kWh
Annual Average	0	kWh	Annual Average		11429	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 6000)			($12,038.00)	1	($12,038.00)
Solar Panel	BP Solar (SX 170B)			($728.97)	2	($1,457.94)
Inverter	Outback (GVFX3648)			($1,913.00)	2	($3,826.00)
Controller	Blue Sky Solar (Solar Boost 3048)			($486.25)	1	($486.25)
					Total Equipment Cost =	($17,808.19)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 6000)		6000	10966	1	10966
Solar Panel	BP Solar (SX 170B)		170	310	2	620
					Total System Annual Energy Generated =	11586
					Total System Annual Energy Available for Sale to Utility =	132

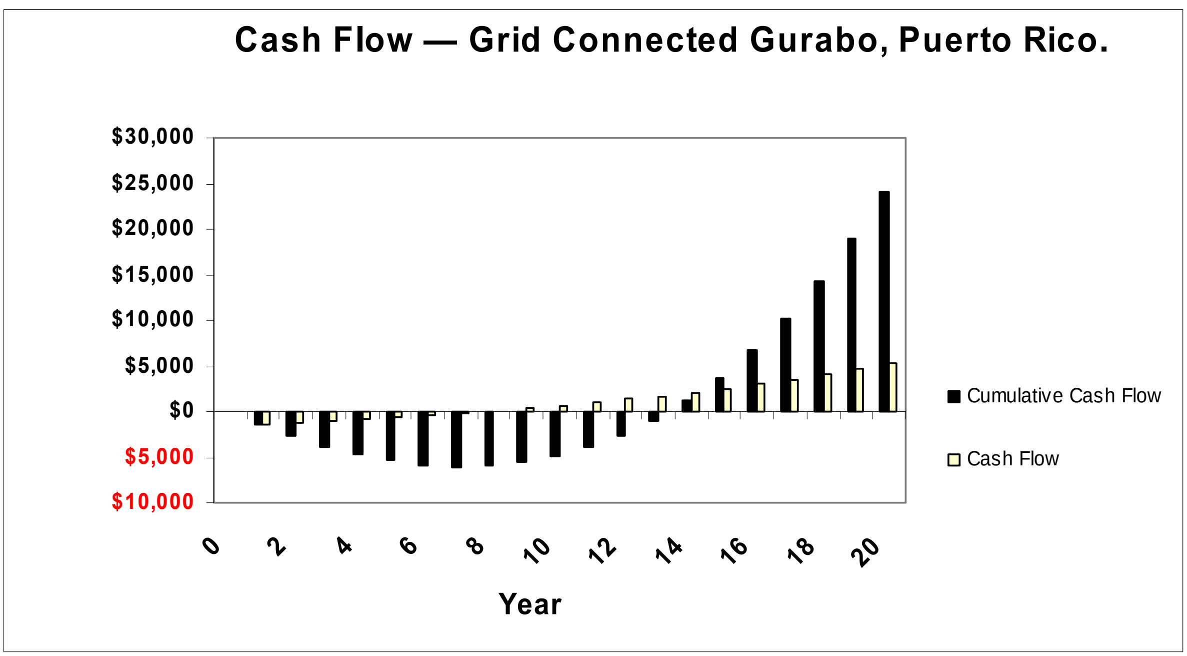


Economic Analysis - Grid Connected San Juan, P.R.					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.1	$/kWh
Inflation Rate	3%		Equipments Cost	($17,808.19)	
Down Payment	0%		Installation Cost	($1,780.82)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($19,589.01)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($115.86)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($195.89)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$13.22	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($115.86)	($195.89)	($1,567.12)	($428.06)	$2,685.71	$13.22	$392.00	$392.00
2		($119.34)	($201.77)	($1,532.88)	($462.31)	$2,873.71	$13.22	$570.65	$962.66
3		($122.92)	($207.82)	($1,495.89)	($499.29)	$3,074.87	$13.22	$762.18	$1,724.83
4		($126.60)	($214.05)	($1,455.95)	($539.24)	$3,290.12	$13.22	$967.50	$2,692.33
5		($130.40)	($220.48)	($1,412.81)	($582.38)	$3,520.42	$13.22	$1,187.59	$3,879.92
6		($134.31)	($227.09)	($1,366.22)	($628.97)	$3,766.85	$13.22	$1,423.49	$5,303.41
7		($138.34)	($233.90)	($1,315.90)	($679.28)	$4,030.53	$13.22	$1,676.33	$6,979.74
8		($142.49)	($240.92)	($1,261.56)	($733.62)	$4,312.67	$13.22	$1,947.30	$8,927.03
9		($146.77)	($248.15)	($1,202.87)	($792.31)	$4,614.56	$13.22	$2,237.68	$11,164.71
10		($151.17)	($255.59)	($1,139.48)	($855.70)	$4,937.58	$13.22	$2,548.85	$13,713.57
11		($155.71)	($263.26)	($1,071.03)	($924.16)	$5,283.21	$13.22	$2,882.28	$16,595.85
12		($160.38)	($271.16)	($997.10)	($998.09)	$5,653.03	$13.22	$3,239.54	$19,835.38
13		($165.19)	($279.29)	($917.25)	($1,077.94)	$6,048.74	$13.22	$3,622.30	$23,457.69
14		($170.14)	($287.67)	($831.01)	($1,164.17)	$6,472.16	$13.22	$4,032.38	$27,490.07
15		($175.25)	($296.30)	($737.88)	($1,257.30)	$6,925.21	$13.22	$4,471.70	$31,961.76
16		($180.51)	($305.19)	($637.30)	($1,357.89)	$7,409.97	$13.22	$4,942.31	$36,904.08
17		($185.92)	($314.35)	($528.66)	($1,466.52)	$7,928.67	$13.22	$5,446.44	$42,350.52
18		($191.50)	($323.78)	($411.34)	($1,583.84)	$8,483.68	$13.22	$5,986.44	$48,336.96
19		($197.24)	($333.49)	($284.64)	($1,710.55)	$9,077.53	$13.22	$6,564.84	$54,901.80
20		($203.16)	($343.49)	($147.79)	($1,847.39)	$9,712.96	$13.22	$7,184.34	$62,086.14
							Net Present Value =	$22,316.21	

APPENDIX A6 GURABO GRID CONNECTED EXAMPLE

System Specification						
Location	Gurabo			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	0	kWh	Monthly Average		952	kWh
Annual Average	0	kWh	Annual Average		11429	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	none			$0.00	0	$0.00
Solar Panel	BP Solar (SX 170B)			($728.97)	38	($27,700.86)
Inverter	Outback (GVFX3648)			($1,913.00)	2	($3,826.00)
Controller	Outback (Flexmax 80)			($671.10)	2	($1,342.20)
					Total Equipment Cost =	($32,869.06)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	none		0	0	0	0
Solar Panel	BP Solar (SX 170B)		170	309	38	11742
					Total System Annual Energy Generated =	11742
					Total System Annual Energy Available for Sale to Utility =	263

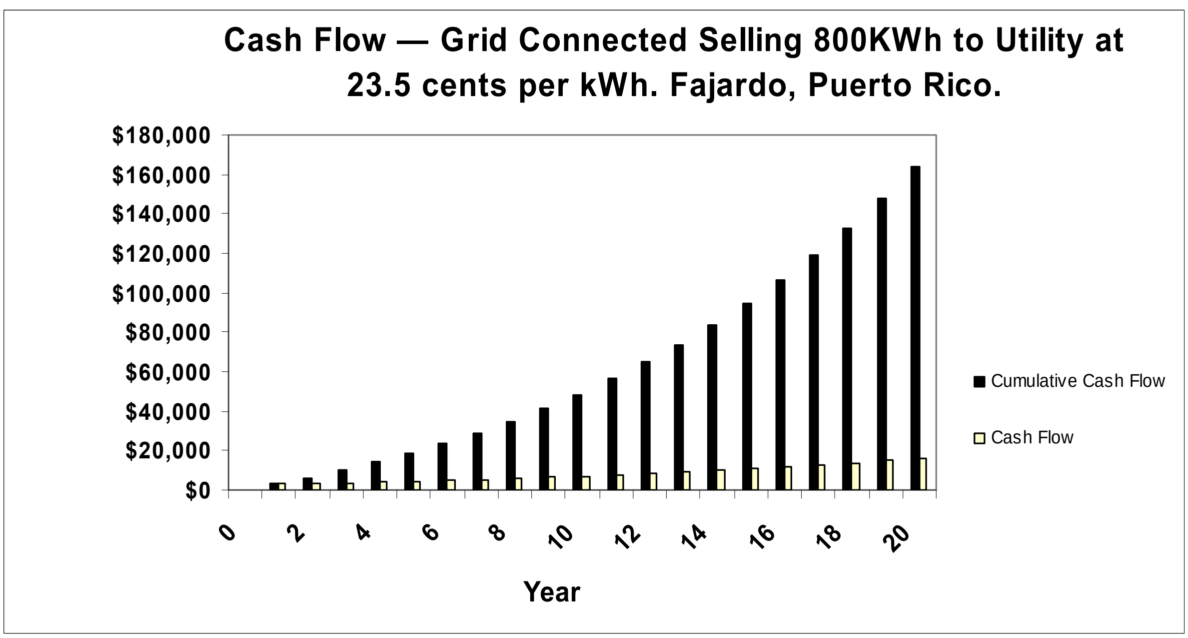


Economic Analysis - Grid Connected Gurabo, P.R.					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.1	$/kWh
Inflation Rate	3%		Equipments Cost	($32,869.06)	
Down Payment	0%		Installation Cost	($3,286.91)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($36,155.97)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($117.42)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($361.56)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$26.33	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($117.42)	($361.56)	($2,892.48)	($790.09)	$2,685.71	$26.33	($1,449.50)	($1,449.50)
2		($120.94)	($372.41)	($2,829.27)	($853.29)	$2,873.71	$26.33	($1,275.87)	($2,725.37)
3		($124.57)	($383.58)	($2,761.01)	($921.56)	$3,074.87	$26.33	($1,089.51)	($3,814.89)
4		($128.31)	($395.09)	($2,687.28)	($995.28)	$3,290.12	$26.33	($889.52)	($4,704.40)
5		($132.16)	($406.94)	($2,607.66)	($1,074.91)	$3,520.42	$26.33	($674.91)	($5,379.31)
6		($136.12)	($419.15)	($2,521.67)	($1,160.90)	$3,766.85	$26.33	($444.65)	($5,823.96)
7		($140.21)	($431.72)	($2,428.80)	($1,253.77)	$4,030.53	$26.33	($197.63)	($6,021.59)
8		($144.41)	($444.67)	($2,328.49)	($1,354.07)	$4,312.67	$26.33	$67.35	($5,954.25)
9		($148.74)	($458.01)	($2,220.17)	($1,462.40)	$4,614.56	$26.33	$351.56	($5,602.68)
10		($153.21)	($471.75)	($2,103.18)	($1,579.39)	$4,937.58	$26.33	$656.38	($4,946.30)
11		($157.80)	($485.91)	($1,976.82)	($1,705.74)	$5,283.21	$26.33	$983.26	($3,963.04)
12		($162.54)	($500.48)	($1,840.37)	($1,842.20)	$5,653.03	$26.33	$1,333.77	($2,629.27)
13		($167.41)	($515.50)	($1,692.99)	($1,989.58)	$6,048.74	$26.33	$1,709.60	($919.67)
14		($172.44)	($530.96)	($1,533.82)	($2,148.74)	$6,472.16	$26.33	$2,112.52	$1,192.85
15		($177.61)	($546.89)	($1,361.92)	($2,320.64)	$6,925.21	$26.33	$2,544.47	$3,737.32
16		($182.94)	($563.30)	($1,176.27)	($2,506.29)	$7,409.97	$26.33	$3,007.50	$6,744.82
17		($188.42)	($580.20)	($975.77)	($2,706.80)	$7,928.67	$26.33	$3,503.81	$10,248.63
18		($194.08)	($597.60)	($759.23)	($2,923.34)	$8,483.68	$26.33	$4,035.76	$14,284.38
19		($199.90)	($615.53)	($525.36)	($3,157.21)	$9,077.53	$26.33	$4,605.86	$18,890.25
20		($205.90)	($634.00)	($272.78)	($3,409.78)	$9,712.96	$26.33	$5,216.83	$24,107.08
							Net Present Value =	$3,829.34	

APPENDIX A7 FAJARDO GRID CONNECTED EXAMPLE (DESIGN TO SELL 800KWH TO UTILITY AT A RATE OF 23.5CENT PER KWH)

System Specification						
Location	Fajardo			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	800	kWh	Monthly Average		1905	kWh
Annual Average	9600	kWh	Annual Average		22857	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 6000)			($12,038.00)	1	($12,038.00)
Solar Panel	N/A			$0.00	0	$0.00
Inverter	Outback (GTFX3048)			($1,760.00)	2	($3,520.00)
Controller	N/A			$0.00	0	$0.00
					Total Equipment Cost =	($15,558.00)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 6000)		6000	23706	1	23706
Solar Panel	N/A		0	0	0	0
					Total System Annual Energy Generated =	23706
					Total System Annual Energy Available for Sale to Utility =	10313

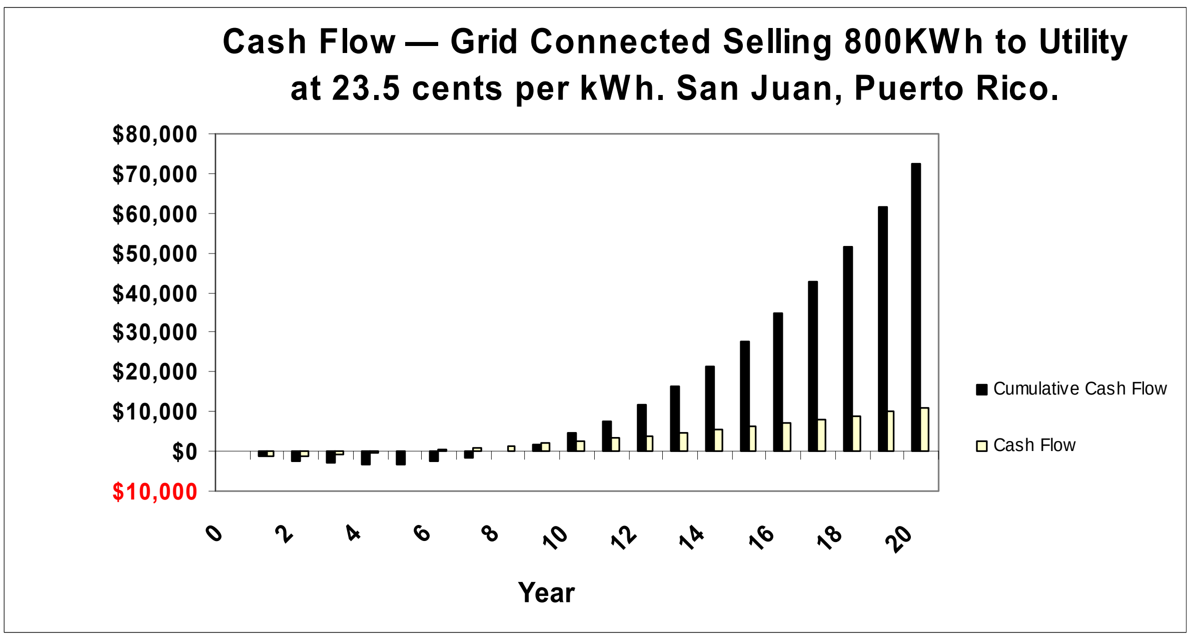


Economic Analysis - Grid Connected Fajardo, P.R. (Desing to sell 800kWh)					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.235	$/kWh
Inflation Rate	3%		Equipments Cost	($15,558.00)	
Down Payment	0%		Installation Cost	($1,555.80)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($17,113.80)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($237.06)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($171.14)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$2,423.56	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($237.06)	($171.14)	($1,369.10)	($373.97)	$2,685.71	$2,423.56	$2,958.00	$2,958.00
2		($244.17)	($176.27)	($1,339.19)	($403.89)	$2,873.71	$2,593.21	$3,303.41	$6,261.41
3		($251.50)	($181.56)	($1,306.87)	($436.20)	$3,074.87	$2,774.74	$3,673.48	$9,934.89
4		($259.04)	($187.01)	($1,271.98)	($471.10)	$3,290.12	$2,968.97	$4,069.96	$14,004.84
5		($266.81)	($192.62)	($1,234.29)	($508.79)	$3,520.42	$3,176.80	$4,494.71	$18,499.56
6		($274.82)	($198.40)	($1,193.59)	($549.49)	$3,766.85	$3,399.17	$4,949.74	$23,449.29
7		($283.06)	($204.35)	($1,149.63)	($593.45)	$4,030.53	$3,637.12	$5,437.16	$28,886.46
8		($291.55)	($210.48)	($1,102.15)	($640.93)	$4,312.67	$3,891.71	$5,959.27	$34,845.73
9		($300.30)	($216.79)	($1,050.88)	($692.20)	$4,614.56	$4,164.13	$6,518.52	$41,364.25
10		($309.31)	($223.30)	($995.50)	($747.58)	$4,937.58	$4,455.62	$7,117.52	$48,481.77
11		($318.59)	($230.00)	($935.70)	($807.38)	$5,283.21	$4,767.52	$7,759.06	$56,240.83
12		($328.15)	($236.90)	($871.11)	($871.97)	$5,653.03	$5,101.24	$8,446.16	$64,686.98
13		($337.99)	($244.00)	($801.35)	($941.73)	$6,048.74	$5,458.33	$9,182.00	$73,868.99
14		($348.13)	($251.32)	($726.01)	($1,017.07)	$6,472.16	$5,840.41	$9,970.04	$83,839.03
15		($358.57)	($258.86)	($644.64)	($1,098.44)	$6,925.21	$6,249.24	$10,813.94	$94,652.96
16		($369.33)	($266.63)	($556.77)	($1,186.31)	$7,409.97	$6,686.69	$11,717.62	$106,370.59
17		($380.41)	($274.63)	($461.86)	($1,281.21)	$7,928.67	$7,154.76	$12,685.31	$119,055.90
18		($391.82)	($282.87)	($359.37)	($1,383.71)	$8,483.68	$7,655.59	$13,721.50	$132,777.40
19		($403.58)	($291.35)	($248.67)	($1,494.41)	$9,077.53	$8,191.48	$14,831.01	$147,608.40
20		($415.69)	($300.09)	($129.12)	($1,613.96)	$9,712.96	$8,764.89	$16,018.99	$163,627.40
							Net Present Value =	$64,624.01	

APPENDIX A8 SAN JUAN GRID CONNECTED EXAMPLE (DESIGN TO SELL 800KWH TO UTILITY AT A RATE OF 23.5CENT PER KWH)

System Specification						
Location	San Juan			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			Total System Energy Consumption			
Monthly Average	800	kWh	Monthly Average		1905	kWh
Annual Average	9600	kWh	Annual Average		22857	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 6000)			($12,038.00)	1	($12,038.00)
Solar Panel	BP Solar (SX 170B)			($728.97)	39	($28,429.83)
Inverter	Outback (GVFX3648)			($1,913.00)	4	($7,652.00)
Controller	Outback (Flexmax 80)			($671.10)	2	($1,342.20)
					Total Equipment Cost =	($49,462.03)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 6000)		6000	10966	1	10966
Solar Panel	BP Solar (SX 170B)		170	310	39	12090
					Total System Annual Energy Generated =	23056
					Total System Annual Energy Available for Sale to Utility =	9767

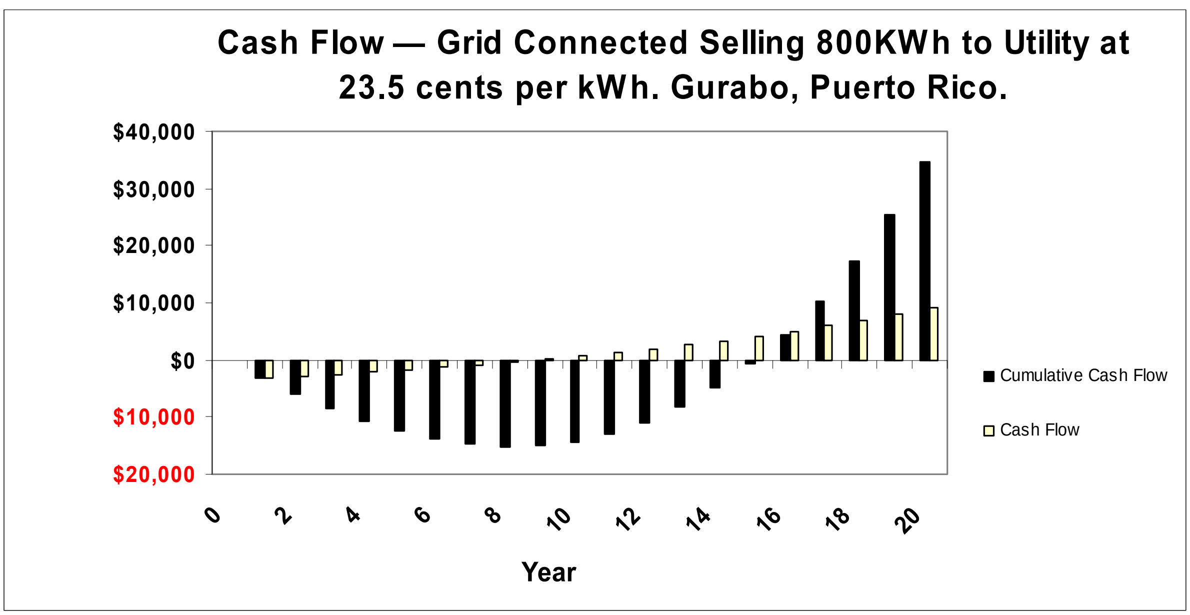


Economic Analysis - Grid Connected San Juan, P.R. (Desing to sell 800kWh)					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.235	$/kWh
Inflation Rate	3%		Equipments Cost	($49,462.03)	
Down Payment	0%		Installation Cost	($4,946.20)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($54,408.23)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($230.56)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($544.08)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$2,295.25	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($230.56)	($544.08)	($4,352.66)	($1,188.94)	$2,685.71	$2,295.25	($1,335.27)	($1,335.27)
2		($237.48)	($560.40)	($4,257.54)	($1,284.06)	$2,873.71	$2,455.92	($1,009.84)	($2,345.12)
3		($244.60)	($577.22)	($4,154.82)	($1,386.78)	$3,074.87	$2,627.84	($660.71)	($3,005.82)
4		($251.94)	($594.53)	($4,043.88)	($1,497.72)	$3,290.12	$2,811.79	($286.17)	($3,291.99)
5		($259.50)	($612.37)	($3,924.06)	($1,617.54)	$3,520.42	$3,008.61	$115.57	($3,176.42)
6		($267.28)	($630.74)	($3,794.66)	($1,746.94)	$3,766.85	$3,219.21	$546.44	($2,629.98)
7		($275.30)	($649.66)	($3,654.90)	($1,886.70)	$4,030.53	$3,444.56	$1,008.53	($1,621.45)
8		($283.56)	($669.15)	($3,503.96)	($2,037.63)	$4,312.67	$3,685.68	$1,504.04	($117.41)
9		($292.07)	($689.23)	($3,340.95)	($2,200.65)	$4,614.56	$3,943.67	$2,035.34	$1,917.92
10		($300.83)	($709.90)	($3,164.90)	($2,376.70)	$4,937.58	$4,219.73	$2,604.98	$4,522.90
11		($309.85)	($731.20)	($2,974.77)	($2,566.83)	$5,283.21	$4,515.11	$3,215.67	$7,738.57
12		($319.15)	($753.14)	($2,769.42)	($2,772.18)	$5,653.03	$4,831.17	$3,870.32	$11,608.88
13		($328.72)	($775.73)	($2,547.65)	($2,993.95)	$6,048.74	$5,169.35	$4,572.04	$16,180.93
14		($338.59)	($799.00)	($2,308.13)	($3,233.47)	$6,472.16	$5,531.21	$5,324.18	$21,505.10
15		($348.74)	($822.97)	($2,049.45)	($3,492.15)	$6,925.21	$5,918.39	$6,130.28	$27,635.39
16		($359.20)	($847.66)	($1,770.08)	($3,771.52)	$7,409.97	$6,332.68	$6,994.18	$34,629.57
17		($369.98)	($873.09)	($1,468.36)	($4,073.24)	$7,928.67	$6,775.97	$7,919.96	$42,549.53
18		($381.08)	($899.29)	($1,142.50)	($4,399.10)	$8,483.68	$7,250.28	$8,912.00	$51,461.53
19		($392.51)	($926.26)	($790.57)	($4,751.03)	$9,077.53	$7,757.80	$9,974.96	$61,436.49
20		($404.29)	($954.05)	($410.49)	($5,131.11)	$9,712.96	$8,300.85	$11,113.87	$72,550.36
							Net Present Value =	$20,662.35	

APPENDIX A9 GURABO GRID CONNECTED EXAMPLE (DESIGN TO SELL 800KWH TO UTILITY AT A RATE OF 23.5CENT PER KWH)

System Specification						
Location	Gurabo			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	800	kWh	Monthly Average		1905	kWh
Annual Average	9600	kWh	Annual Average		22857	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	N/A			$0.00	0	$0.00
Solar Panel	BP Solar (SX 170B)			($728.97)	75	($54,672.75)
Inverter	Outback (GVFX3648)			($1,913.00)	4	($7,652.00)
Controller	Outback (Mx60)			($497.76)	5	($2,488.80)
Total Equipment Cost =						($64,813.55)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	N/A		0	0	0	0
Solar Panel	BP Solar (SX 170B)		170	309	75	23175
Total System Annual Energy Generated =						23175
Total System Annual Energy Available for Sale to Utility =						9867

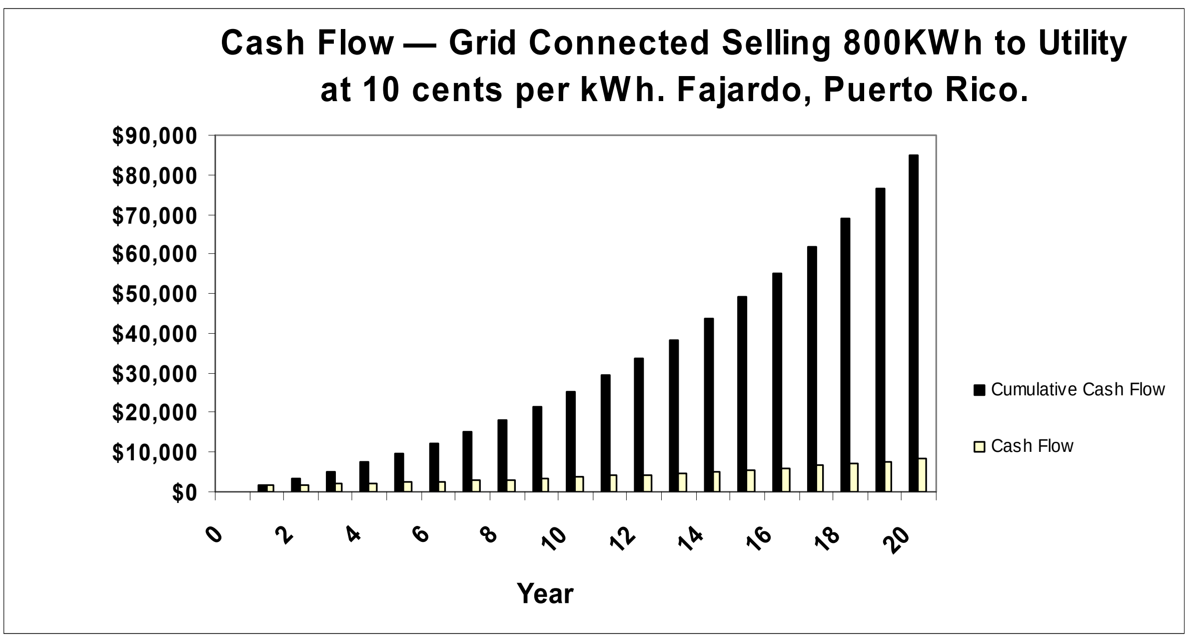


Economic Analysis - Grid Connected Gurabo, P.R. (Desing to sell 800kWh)					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.235	$/kWh
Inflation Rate	3%		Equipments Cost	($64,813.55)	
Down Payment	0%		Installation Cost	($6,481.36)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($71,294.91)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($231.75)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($712.95)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$2,318.75	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($231.75)	($712.95)	($5,703.59)	($1,557.95)	$2,685.71	$2,318.75	($3,201.78)	($3,201.78)
2		($238.70)	($734.34)	($5,578.96)	($1,682.59)	$2,873.71	$2,481.06	($2,879.81)	($6,081.60)
3		($245.86)	($756.37)	($5,444.35)	($1,817.19)	$3,074.87	$2,654.73	($2,534.17)	($8,615.76)
4		($253.24)	($779.06)	($5,298.97)	($1,962.57)	$3,290.12	$2,840.56	($2,163.16)	($10,778.93)
5		($260.84)	($802.43)	($5,141.97)	($2,119.58)	$3,520.42	$3,039.40	($1,764.99)	($12,543.91)
6		($268.66)	($826.50)	($4,972.40)	($2,289.14)	$3,766.85	$3,252.16	($1,337.70)	($13,881.61)
7		($276.72)	($851.30)	($4,789.27)	($2,472.27)	$4,030.53	$3,479.81	($879.22)	($14,760.83)
8		($285.02)	($876.84)	($4,591.49)	($2,670.05)	$4,312.67	$3,723.40	($387.34)	($15,148.17)
9		($293.57)	($903.14)	($4,377.88)	($2,883.66)	$4,614.56	$3,984.04	$140.33	($15,007.83)
10		($302.38)	($930.24)	($4,147.19)	($3,114.35)	$4,937.58	$4,262.92	$706.33	($14,301.50)
11		($311.45)	($958.14)	($3,898.04)	($3,363.50)	$5,283.21	$4,561.32	$1,313.39	($12,988.11)
12		($320.80)	($986.89)	($3,628.96)	($3,632.58)	$5,653.03	$4,880.61	$1,964.42	($11,023.69)
13		($330.42)	($1,016.49)	($3,338.36)	($3,923.19)	$6,048.74	$5,222.26	$2,662.54	($8,361.15)
14		($340.33)	($1,046.99)	($3,024.50)	($4,237.04)	$6,472.16	$5,587.82	$3,411.11	($4,950.05)
15		($350.54)	($1,078.40)	($2,685.54)	($4,576.00)	$6,925.21	$5,978.96	$4,213.68	($736.36)
16		($361.06)	($1,110.75)	($2,319.46)	($4,942.08)	$7,409.97	$6,397.49	$5,074.11	$4,337.75
17		($371.89)	($1,144.07)	($1,924.09)	($5,337.45)	$7,928.67	$6,845.31	$5,996.48	$10,334.22
18		($383.05)	($1,178.40)	($1,497.10)	($5,764.45)	$8,483.68	$7,324.49	$6,985.17	$17,319.40
19		($394.54)	($1,213.75)	($1,035.94)	($6,225.60)	$9,077.53	$7,837.20	$8,044.90	$25,364.30
20		($406.38)	($1,250.16)	($537.89)	($6,723.65)	$9,712.96	$8,385.81	$9,180.69	$34,544.98
							Net Present Value =	$2,091.26	

APPENDIX A10 FAJARDO GRID CONNECTED EXAMPLE (DESIGN TO SELL 800KWH TO UTILITY AT A RATE OF 10CENT PER KWH)

System Specification						
Location	Fajardo			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			Total System Energy Consumption			
Monthly Average	800	kWh	Monthly Average		1905	kWh
Annual Average	9600	kWh	Annual Average		22857	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 6000)			($12,038.00)	1	($12,038.00)
Solar Panel	N/A			$0.00	0	$0.00
Inverter	Outback (GTFX3048)			($1,760.00)	2	($3,520.00)
Controller	N/A			$0.00	0	$0.00
					Total Equipment Cost =	($15,558.00)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 6000)		6000	23706	1	23706
Solar Panel	N/A		0	0	0	0
					Total System Annual Energy Generated =	23706
					Total System Annual Energy Available for Sale to Utility =	10313

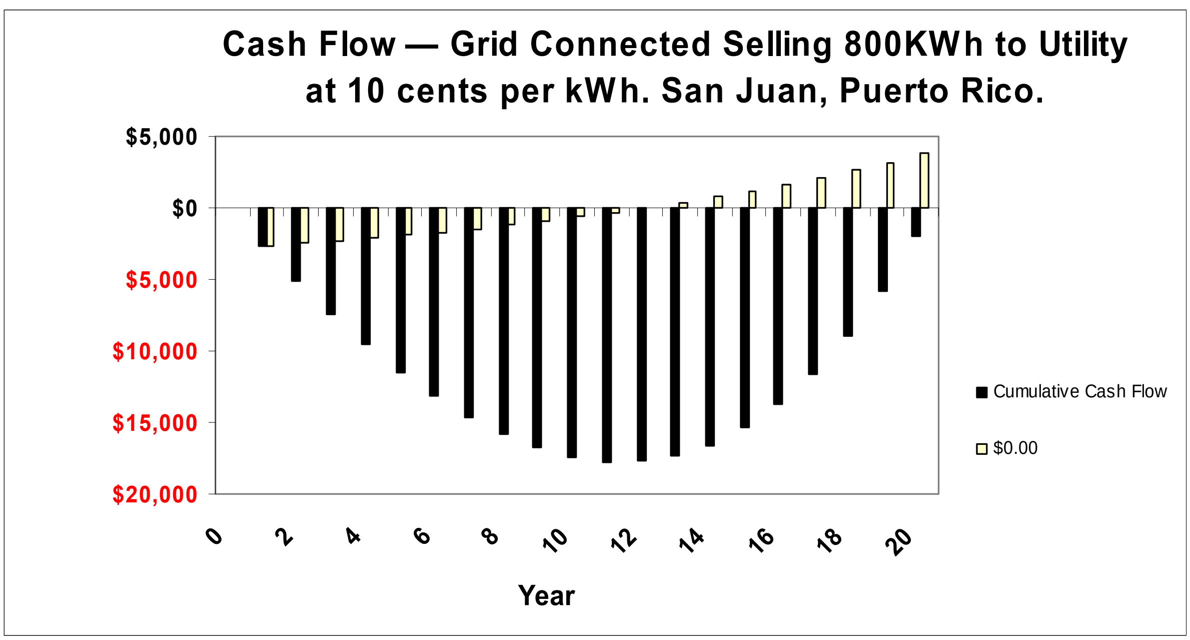


Economic Analysis - Grid Connected Fajardo, P.R. (Desing to sell 800kWh)					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.1	$/kWh
Inflation Rate	3%		Equipments Cost	($15,558.00)	
Down Payment	0%		Installation Cost	($1,555.80)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($17,113.80)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($237.06)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($171.14)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$1,031.30	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($237.06)	($171.14)	($1,369.10)	($373.97)	$2,685.71	$1,031.30	$1,565.74	$1,565.74
2		($244.17)	($176.27)	($1,339.19)	($403.89)	$2,873.71	$1,031.30	$1,741.50	$3,307.24
3		($251.50)	($181.56)	($1,306.87)	($436.20)	$3,074.87	$1,031.30	$1,930.04	$5,237.28
4		($259.04)	($187.01)	($1,271.98)	($471.10)	$3,290.12	$1,031.30	$2,132.29	$7,369.57
5		($266.81)	($192.62)	($1,234.29)	($508.79)	$3,520.42	$1,031.30	$2,349.22	$9,718.79
6		($274.82)	($198.40)	($1,193.59)	($549.49)	$3,766.85	$1,031.30	$2,581.87	$12,300.66
7		($283.06)	($204.35)	($1,149.63)	($593.45)	$4,030.53	$1,031.30	$2,831.35	$15,132.01
8		($291.55)	($210.48)	($1,102.15)	($640.93)	$4,312.67	$1,031.30	$3,098.86	$18,230.87
9		($300.30)	($216.79)	($1,050.88)	($692.20)	$4,614.56	$1,031.30	$3,385.69	$21,616.56
10		($309.31)	($223.30)	($995.50)	($747.58)	$4,937.58	$1,031.30	$3,693.20	$25,309.76
11		($318.59)	($230.00)	($935.70)	($807.38)	$5,283.21	$1,031.30	$4,022.85	$29,332.60
12		($328.15)	($236.90)	($871.11)	($871.97)	$5,653.03	$1,031.30	$4,376.22	$33,708.82
13		($337.99)	($244.00)	($801.35)	($941.73)	$6,048.74	$1,031.30	$4,754.98	$38,463.80
14		($348.13)	($251.32)	($726.01)	($1,017.07)	$6,472.16	$1,031.30	$5,160.93	$43,624.72
15		($358.57)	($258.86)	($644.64)	($1,098.44)	$6,925.21	$1,031.30	$5,596.00	$49,220.72
16		($369.33)	($266.63)	($556.77)	($1,186.31)	$7,409.97	$1,031.30	$6,062.24	$55,282.96
17		($380.41)	($274.63)	($461.86)	($1,281.21)	$7,928.67	$1,031.30	$6,561.86	$61,844.81
18		($391.82)	($282.87)	($359.37)	($1,383.71)	$8,483.68	$1,031.30	$7,097.21	$68,942.02
19		($403.58)	($291.35)	($248.67)	($1,494.41)	$9,077.53	$1,031.30	$7,670.83	$76,612.85
20		($415.69)	($300.09)	($129.12)	($1,613.96)	$9,712.96	$1,031.30	$8,285.41	$84,898.26
							Net Present Value =	$33,605.59	

Appendix A11 San Juan Grid Connected Example (Design to sell 800kWh to Utility at a rate of 10cent per kWh)

System Specification						
Location	San Juan			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	800	kWh		Monthly Average	1905	kWh
Annual Average	9600	kWh		Annual Average	22857	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	Bornay (Inclin 6000)			($12,038.00)	1	($12,038.00)
Solar Panel	BP Solar (SX 170B)			($728.97)	39	($28,429.83)
Inverter	Outback (GVFX3648)			($1,913.00)	4	($7,652.00)
Controller	Outback (Flexmax 80)			($671.10)	2	($1,342.20)
					Total Equipment Cost =	($49,462.03)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	Bornay (Inclin 6000)		6000	10966	1	10966
Solar Panel	BP Solar (SX 170B)		170	310	39	12090
					Total System Annual Energy Generated =	23056
					Total System Annual Energy Available for Sale to Utility =	9767

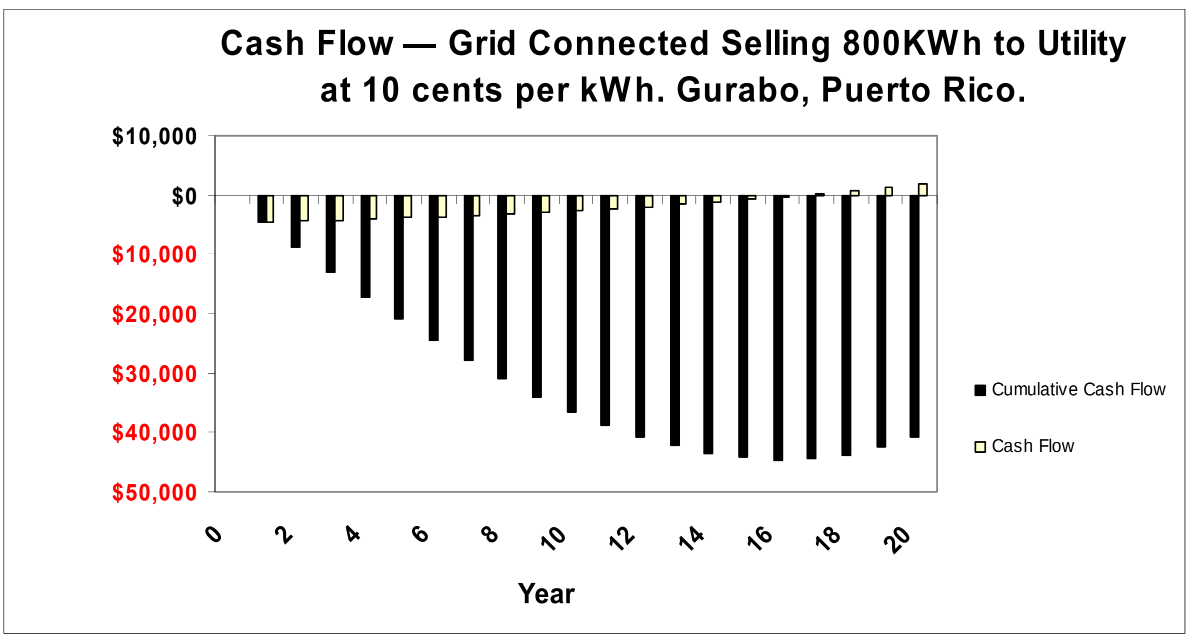


Economic Analysis - Grid Connected San Juan, P.R. (Desing to sell 800kWh)						
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh	
Utility Rate Escalation	7%		Sale Cost KWh	0.1	$/kWh	
Inflation Rate	3%		Equipments Cost	($49,462.03)		
Down Payment	0%		Installation Cost	($4,946.20)	(10% of Equipment Cost)	
Loan Term	20	yrs	Capital Cost	**($54,408.23)**	(Equipment Cost + Installation Cost)	
Interest Rate	8%		Annual O&M Cost	($230.56)	($0.01 per KWh Generated [Gipe,2004])	
Insurance	1%		Annual Insurance Cost	($544.08)	(1% of Capital Cost)	
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)	
			Annual Income from Utility KWh Sell	$976.70	(kWh Available for sale multiply by Sale Cost of kWh)	

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($230.56)	($544.08)	($4,352.66)	($1,188.94)	$2,685.71	$976.70	($2,653.82)	($2,653.82)
2		($237.48)	($560.40)	($4,257.54)	($1,284.06)	$2,873.71	$976.70	($2,489.06)	($5,142.88)
3		($244.60)	($577.22)	($4,154.82)	($1,386.78)	$3,074.87	$976.70	($2,311.84)	($7,454.72)
4		($251.94)	($594.53)	($4,043.88)	($1,497.72)	$3,290.12	$976.70	($2,121.25)	($9,575.98)
5		($259.50)	($612.37)	($3,924.06)	($1,617.54)	$3,520.42	$976.70	($1,916.34)	($11,492.31)
6		($267.28)	($630.74)	($3,794.66)	($1,746.94)	$3,766.85	$976.70	($1,696.06)	($13,188.38)
7		($275.30)	($649.66)	($3,654.90)	($1,886.70)	$4,030.53	$976.70	($1,459.33)	($14,647.70)
8		($283.56)	($669.15)	($3,503.96)	($2,037.63)	$4,312.67	$976.70	($1,204.94)	($15,852.64)
9		($292.07)	($689.23)	($3,340.95)	($2,200.65)	$4,614.56	$976.70	($931.63)	($16,784.27)
10		($300.83)	($709.90)	($3,164.90)	($2,376.70)	$4,937.58	$976.70	($638.05)	($17,422.32)
11		($309.85)	($731.20)	($2,974.77)	($2,566.83)	$5,283.21	$976.70	($322.74)	($17,745.06)
12		($319.15)	($753.14)	($2,769.42)	($2,772.18)	$5,653.03	$976.70	$15.85	($17,729.21)
13		($328.72)	($775.73)	($2,547.65)	($2,993.95)	$6,048.74	$976.70	$379.39	($17,349.82)
14		($338.59)	($799.00)	($2,308.13)	($3,233.47)	$6,472.16	$976.70	$769.67	($16,580.15)
15		($348.74)	($822.97)	($2,049.45)	($3,492.15)	$6,925.21	$976.70	$1,188.60	($15,391.55)
16		($359.20)	($847.66)	($1,770.08)	($3,771.52)	$7,409.97	$976.70	$1,638.21	($13,753.35)
17		($369.98)	($873.09)	($1,468.36)	($4,073.24)	$7,928.67	$976.70	$2,120.70	($11,632.64)
18		($381.08)	($899.29)	($1,142.50)	($4,399.10)	$8,483.68	$976.70	$2,638.41	($8,994.23)
19		($392.51)	($926.26)	($790.57)	($4,751.03)	$9,077.53	$976.70	$3,193.86	($5,800.37)
20		($404.29)	($954.05)	($410.49)	($5,131.11)	$9,712.96	$976.70	$3,789.72	($2,010.64)
							Net Present Value =	($8,713.88)	

APPENDIX A12 GURABO GRID CONNECTED EXAMPLE (DESIGN TO SELL 800KWH TO UTILITY AT A RATE OF 10CENT PER KWH)

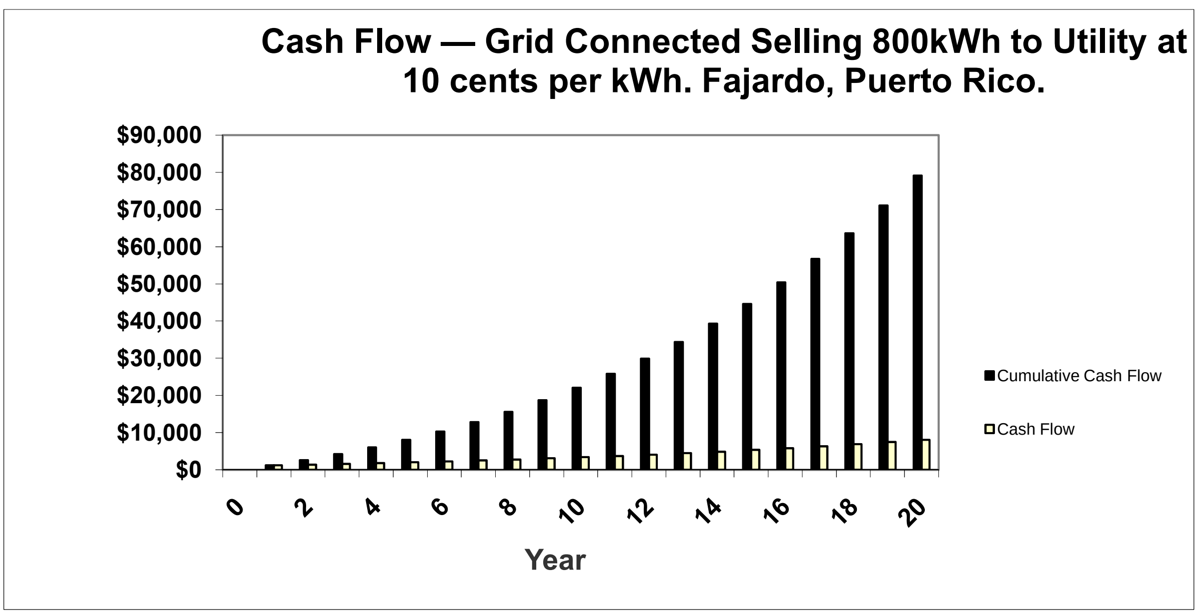
System Specification						
Location	Gurabo			AC Voltage	120	Volts
Analysis	Net Metering			DC Voltage	48	Volts
System Efficiency	84%					
Load Energy Consumption						
Monthly Average	800	kWh				
Annual Average	9600	kWh				
Energy I Design to sell to Utility			**Total System Energy Consumption**			
Monthly Average	800	kWh	Monthly Average		1905	kWh
Annual Average	9600	kWh	Annual Average		22857	kWh
Results from the Optimization Using Liner Programming						
Type	Manufacture Equipment			Cost	Quantity	Total Cost
Wind Turbine	N/A			$0.00	0	$0.00
Solar Panel	BP Solar (SX 170B)			($728.97)	75	($54,672.75)
Inverter	Outback (GVFX3648)			($1,913.00)	4	($7,652.00)
Controller	Outback (Mx60)			($497.76)	5	($2,488.80)
					Total Equipment Cost =	($64,813.55)
Total Generated Power						
Type	Manufacture		Rated Capacity (Watts)	Annual Energy Generated (kWh/year)	Quantity	Total Annual Energy Generated (kWh/year)
Wind Turbine	N/A		0	0	0	0
Solar Panel	BP Solar (SX 170B)		170	309	75	23175
					Total System Annual Energy Generated =	23175
					Total System Annual Energy Available for Sale to Utility =	9867



Economic Analysis - Grid Connected Gurabo, P.R. (Desing to sell 800kWh)					
Economic Analysis Term	20	yrs	Retail Rate KWh	0.235	$/kWh
Utility Rate Escalation	7%		Sale Cost KWh	0.1	$/kWh
Inflation Rate	3%		Equipments Cost	($64,813.55)	
Down Payment	0%		Installation Cost	($6,481.36)	(10% of Equipment Cost)
Loan Term	20	yrs	Capital Cost	**($71,294.91)**	(Equipment Cost + Installation Cost)
Interest Rate	8%		Annual O&M Cost	($231.75)	($0.01 per KWh Generated [Gipe,2004])
Insurance	1%		Annual Insurance Cost	($712.95)	(1% of Capital Cost)
			Annual Saved Money Per Year	$2,685.71	(kWh Cost multiply by kWh/Year Generated)
			Annual Income from Utility KWh Sell	$986.70	(kWh Available for sale multiply by Sale Cost of kWh)

Cash Flow	Expenses					Income			Cumulative
Term In Year	Fixed Cost	O&M	Insurance	Loan Interest	Loan Principal	Saved Money	Utility Sell	Cash Flow	Cash Flow
0	$0.00							$0.00	$0.00
1		($231.75)	($712.95)	($5,703.59)	($1,557.95)	$2,685.71	$986.70	($4,533.83)	($4,533.83)
2		($238.70)	($734.34)	($5,578.96)	($1,682.59)	$2,873.71	$986.70	($4,374.17)	($8,908.00)
3		($245.86)	($756.37)	($5,444.35)	($1,817.19)	$3,074.87	$986.70	($4,202.20)	($13,110.20)
4		($253.24)	($779.06)	($5,298.97)	($1,962.57)	$3,290.12	$986.70	($4,017.03)	($17,127.22)
5		($260.84)	($802.43)	($5,141.97)	($2,119.58)	$3,520.42	$986.70	($3,817.69)	($20,944.91)
6		($268.66)	($826.50)	($4,972.40)	($2,289.14)	$3,766.85	$986.70	($3,603.16)	($24,548.07)
7		($276.72)	($851.30)	($4,789.27)	($2,472.27)	$4,030.53	$986.70	($3,372.33)	($27,920.40)
8		($285.02)	($876.84)	($4,591.49)	($2,670.05)	$4,312.67	$986.70	($3,124.03)	($31,044.43)
9		($293.57)	($903.14)	($4,377.88)	($2,883.66)	$4,614.56	$986.70	($2,857.00)	($33,901.43)
10		($302.38)	($930.24)	($4,147.19)	($3,114.35)	$4,937.58	$986.70	($2,569.89)	($36,471.32)
11		($311.45)	($958.14)	($3,898.04)	($3,363.50)	$5,283.21	$986.70	($2,261.23)	($38,732.55)
12		($320.80)	($986.89)	($3,628.96)	($3,632.58)	$5,653.03	$986.70	($1,929.50)	($40,662.05)
13		($330.42)	($1,016.49)	($3,338.36)	($3,923.19)	$6,048.74	$986.70	($1,573.02)	($42,235.07)
14		($340.33)	($1,046.99)	($3,024.50)	($4,237.04)	$6,472.16	$986.70	($1,190.01)	($43,425.08)
15		($350.54)	($1,078.40)	($2,685.54)	($4,576.00)	$6,925.21	$986.70	($778.58)	($44,203.66)
16		($361.06)	($1,110.75)	($2,319.46)	($4,942.08)	$7,409.97	$986.70	($336.68)	($44,540.34)
17		($371.89)	($1,144.07)	($1,924.09)	($5,337.45)	$7,928.67	$986.70	$137.86	($44,402.48)
18		($383.05)	($1,178.40)	($1,497.10)	($5,764.45)	$8,483.68	$986.70	$647.39	($43,755.09)
19		($394.54)	($1,213.75)	($1,035.94)	($6,225.60)	$9,077.53	$986.70	$1,194.40	($42,560.69)
20		($406.38)	($1,250.16)	($537.89)	($6,723.65)	$9,712.96	$986.70	$1,781.58	($40,779.11)
							Net Present Value =	($27,585.61)	

APPENDIX A13 FAJARDO GRID CONNECTED EXAMPLE (DESIGN TO SELL 800KWH TO UTILITY AT A RATE OF 10CENT PER KWH) MULTIPLE WIND TURBINES ALLOWED IN THE OPTIMIZATION



[redacted]

APPENDIX B *MATLAB FUNCTION (WINDP) USE FOR CALCULATED ENERGY GENERATED BY WIND TURBINES*

```
function[EnergiaTotalWindTurbine,CostWT,winddata,ScaleFactor,ShapeFactor,ms,pdfwind,EnergiaWindTurbine,Vpro
medio01,Vrmc] = WindP(x,desiredheight);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[type, sheets] = xlsfinfo('Library.xls');
CostWT = xlsread('Library.xls', 'windturbine', 'D3:D23');

% CapeSanJuan Yunque
if x==1
winddata = xlsread('Library.xls', 'winddata', 'C6:N6');
windplace='Cape San Juan Yunque';
ShapeFactor=3;
end
% Yunque
if x==2
winddata = xlsread('Library.xls', 'winddata', 'C7:N7');
windplace='Yunque';
ShapeFactor=3;
end
% GuraboTown
if x==3
winddata = xlsread('Library.xls', 'winddata', 'C8:N8');
windplace='Gurabo Town';
ShapeFactor=1.5;
end
% ViejoSanJuan
if x==4
winddata = xlsread('Library.xls', 'winddata', 'C9:N9');
windplace='Old San Juan';
ShapeFactor=2.5;
end
% Buchanan
if x==5
winddata = xlsread('Library.xls', 'winddata', 'C10:N10');
windplace='Buchanan';
ShapeFactor=2;
end
% RioBlanco
if x==6
winddata = xlsread('Library.xls', 'winddata', 'C11:N11');
windplace='Rio Blanco';
ShapeFactor=1.5;
end
% RoosveltRoads
if x==7
winddata = xlsread('Library.xls', 'winddata', 'C12:N12');
windplace='Roosvelt Roads';
ShapeFactor=3;
end
% FajardoCity
if x==8
winddata = xlsread('Library.xls', 'winddata', 'C13:N13');
windplace='Fajardo City';
ShapeFactor=3;
end
% Catalina
if x==9
winddata = xlsread('Library.xls', 'winddata', 'C14:N14');
windplace='Catalina';
ShapeFactor=1.5;
end
% Aguirre
if x==10
winddata = xlsread('Library.xls', 'winddata', 'C15:N15');
windplace='Aguirre';
ShapeFactor=2;
end
% Cuyon
if x==11
```

```
winddata = xlsread('Library.xls', 'winddata', 'C16:N16');
windplace='Cuyon';
ShapeFactor=3;
end
% Croem
if x==12
winddata = xlsread('Library.xls', 'winddata', 'C17:N17');
windplace='Croem';
ShapeFactor=2.5;
end
% CapeSanJuan
if x==13
winddata = xlsread('Library.xls', 'winddata', 'C18:N18');
windplace='Cape San Juan';
ShapeFactor=3;
end
% AguadillaAirport
if x==14
winddata = xlsread('Library.xls', 'winddata', 'C19:N19');
windplace='Aguadilla Airport';
ShapeFactor=3;
end
% Aes
if x==15
winddata = xlsread('Library.xls', 'winddata', 'C20:N20');
windplace='AES';
ShapeFactor=2;
end
% IslaVerde
if x==16
winddata = xlsread('Library.xls', 'winddata', 'C21:N21');
windplace='Isla Verde';
ShapeFactor=3;
end

if x==17
        windplace='Cape San Juan All Values';
        enero = xlsread('Library.xls', 'winddatafajardo', 'B3:Y33');
        febrero = xlsread('Library.xls','winddatafajardo', 'B37:Y67');
        marzo = xlsread('Library.xls', 'winddatafajardo', 'B71:Y101');
        abril = xlsread('Library.xls', 'winddatafajardo', 'B105:Y135');
        mayo = xlsread('Library.xls', 'winddatafajardo', 'B139:Y169');
        junio = xlsread('Library.xls', 'winddatafajardo', 'B173:Y203');
        julio = xlsread('Library.xls', 'winddatafajardo', 'B207:Y237');
        agosto = xlsread('Library.xls', 'winddatafajardo', 'B241:Y271');
        septiembre = xlsread('Library.xls', 'winddatafajardo', 'B275:Y305');
        octubre = xlsread('Library.xls', 'winddatafajardo', 'B309:Y339');
        noviembre = xlsread('Library.xls', 'winddatafajardo', 'B343:Y373');
        diciembre = xlsread('Library.xls', 'winddatafajardo', 'B377:Y407');

winddata =
vertcat(enero,febrero,marzo,abril,mayo,junio,julio,agosto,septiembre,octubre,noviembre,diciembre);
%winddata = vertcat(febrero,marzo,abril,mayo,julio,agosto,noviembre,diciembre);


%Height Correction
desiredheight=desiredheight;
measured=25;
wind=(winddata)*(desiredheight/measured)^(1/7);

%Weibull Paramaters
ms=[0:24/24:24];

wind(1:1)=[];
wind=sort(wind*0.4469444);
wind=abs(wind);
[parameterswind,pci]=wblfit(wind);
ScaleFactor =parameterswind(1);
ShapeFactor =parameterswind(2);
pdfwind=wblpdf(ms,parameterswind(1),parameterswind(2));

Pcurve=xlsread('Library.xls', 'windpowercurve', 'B4:V28');

day=365;
hours=24;
energy=day*hours;
```

```
%power calculation
Pfactor=0;
pc=1;
Pfirst=1;
Plast=25;
EnergiaWindTurbine=[];
while pc <= 21

EnergiaWindTurbine(pc,:)=(Pcurve(Pfirst:Plast).*pdfwind).*energy     ;
EnergiaTotalWindTurbine(pc,:)=trapz(ms,EnergiaWindTurbine(pc,:));
%EnergiaNormalizadawind=EnergiaWindTurbine./max(EnergiaWindTurbine);

pc=pc+1;
Pfirst=Pfirst+25;
Plast=Plast+25;
end

%Power Curve Graphic
subplot(3,2,1:2)
plot(ms,Pcurve)
xlabel('M/S');
ylabel('Power Output [KW]');
title('Wind Turbine Power Curve');

%Graphic PDF
subplot(3,2,3:4)
plot(ms,pdfwind) %Grafica funcion de densidad de probabilidad PDF (a)
xlabel('M/S');
ylabel('f(V)');
title('PDF (Year)');

%Graphic Total Wind Energy Output
subplot(3,2,5:6)
plot(ms,EnergiaWindTurbine)
xlabel('M/S');
ylabel('Energy [KWh/year]');
title('Total Wind Turbine Energy Output');

Vpromedio01=trapz(ms,pdfwind.*ms);

v3pdf=pdfwind.*(ms.^3);                          %V^3 x PDF(V)
disp('RMC Wind Speed [m/s]:')
Vrmc=(trapz(ms,v3pdf))^(1/3);     %Cubic Root of the Integration of V^3 x PDF(V) = RMC Wind Speed

return
end

%Height Correction
desiredheight=desiredheight;
measured=25;
wind=(winddata)*(desiredheight/measured)^(1/7);

%n=1 for arithmetic mean, n=2 for root mean square, n=3 for cubic root cube
n=3;
[u,N]=size(wind);
AverageVelocity=((1/N)*(sum(wind.^n)))^(1/n);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Weibull Paramaters
%wblpdf(m/s, scale factor n or a or c, shape factor k or b or ?)
ShapeFactor
ScaleFactor=AverageVelocity/(gamma(1+(1/(ShapeFactor))));

ms=[0:24/24:24];
pdfwind=wblpdf(ms,ScaleFactor,ShapeFactor);


Pcurve=xlsread('Library.xls', 'windpowercurve', 'B4:V28');

day=365;
hours=24;
energy=day*hours;

%power calculation
Pfactor=0;
```

```
pc=1;
Pfirst=1;
Plast=25;
EnergiaWindTurbine=[];
while pc <= 21

EnergiaWindTurbine(pc,:)=(Pcurve(Pfirst:Plast).*pdfwind).*energy ;
EnergiaTotalWindTurbine(pc,:)=trapz(ms,EnergiaWindTurbine(pc,:));
%EnergiaNormalizadawind=EnergiaWindTurbine./max(EnergiaWindTurbine);

pc=pc+1;
Pfirst=Pfirst+25;
Plast=Plast+25;
end

%Power Curve Graphic
subplot(3,2,1:2)
plot(ms,Pcurve)
xlabel('M/S');
ylabel('Power Output [KW]');
title('Wind Turbine Power Curve');

%Graphic PDF
subplot(3,2,3:4)
plot(ms,pdfwind) %Grafica funcion de densidad de probabilidad PDF (a)
xlabel('M/S');
ylabel('f(V)');
title('PDF (Year)');

%Graphic Total Wind Energy Output
subplot(3,2,5:6)
plot(ms,EnergiaWindTurbine)
xlabel('M/S');
ylabel('Energy [KWh/year]');
title('Total Wind Turbine Energy Output');

Vpromedio01=trapz(ms,pdfwind.*ms);

v3pdf=pdfwind.*(ms.^3);                          %V^3 x PDF(V)
disp('RMC Wind Speed [m/s]:')
Vrmc=(trapz(ms,v3pdf))^(1/3);     %Cubic Root of the Integration of V^3 x PDF(V) = RMC Wind Speed
```

APPENDIX C *MATLAB FUNCTION (SOLARP) USE FOR CALCULATED ENERGY GENERATED BY SOLAR MODULES*

```
function [PVpoweryear,CostPV,PVmaxpower] = SolarP(selected,T,Type);
if type=1

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Solar Example Using Eduardo Ivan Formulas
CostPV = xlsread('Library.xls', 'solarpanel', 'D5:D17');

[type, sheets] = xlsfinfo('Library.xls');

%Call Average Solar Radiation Values
PVAverageRadiationValuesExcel = xlsread('Library.xls', 'solardata', 'B16:O16');
PVAverageradiationday=PVAverageRadiationValuesExcel(1,selected);

LightInDay=6 ;   %Asume 6 hours the sun shines
PVHourRad=(PVAverageradiationday/LightInDay)*1000;

Vopi = xlsread('Library.xls', 'solarpanel', 'G5:G17');
Iopi = xlsread('Library.xls', 'solarpanel', 'H5:H17');
Isci = xlsread('Library.xls', 'solarpanel', 'J5:J17');
Voci = xlsread('Library.xls', 'solarpanel', 'I5:I17');
Tcii = xlsread('Library.xls', 'solarpanel', 'K5:K17');
TCVi = xlsread('Library.xls', 'solarpanel', 'L5:L17');
PVmaxpower=[];
Ii=[];
Pi=[];
Vi=[];
i=1;

while i<=13

% Vop = optimal voltage
Vop=Vopi(i,1)
% Iop = optimal current
Iop=Iopi(i,1)
% Isc = short-circuit current at 25ºC and 1000W/m^2
Isc=Isci(i,1) %se cambia
% Voc = open-circuit voltage at 25ºC and 1000W/m^2
Voc=Voci(i,1)  %se cambia
% Vmax = Open-circuit voltage at 25ºC and more than 1200W/m^2 (usually, Vmax is close to 1.03*Voc)
Vmax=Voc*1.03
%Vmax=33.5
% Vmin = Open-circuit voltage at 25ºC and less than 200W/m^2, (usually, Vmin is close to 0.85*Voc)
Vmin=Voc*0.85
%Vmin=31
% T = The solar panel temperature in ºC
T=T
% Ei = the effective solar irradiation in W/m^2
Ei=PVHourRad
% Tn = nominal temperature at Standard Test Conditions (STC) 25ºC
Tn=25
% Ein = nominal effective solar irradiation at (STC) 1000W/m^2
Ein=1000
% Tci = The temperature coefficient of Isc in A/ºC
Tci=Tcii(i,1)
% TCV = the temperature coefficient of Voc in V/ºC. Sometimes the
% manucfacture provides TCV in terms of (mV/ºC) just divide TCV by 1000 to
% convert in terms of (V/ºC)
TCV=TCVi(i,1)
% b = the characteristic constant for the PVM based on the I-V Curve
b=1;
bnew=.1;
while abs(bnew-b)>.00000001
   old=bnew;
    bnew=((Vop-Voc)/(Voc*log(1-((Iop)/(Isc))*(1-exp((-1)/(b))))));
   b=old ;
end
```

```
b=bnew;
% s = number of PVM with the same electrical characteristics connecred in
% series
s=1
% p = number of PVM with the same electrical characteristics connecred in
% parallel
p=1
% Ix = short circuit current at any given Ei and T, V is zero
Ix=p*(Ei/Ein)*[Isc+Tci*(T-Tn)]
% Vx = open circuit voltage at any given Ei and T, I is zero
Vx=s*(Ei/Ein)*TCV*(T-Tn) + s*Vmax - s*(Vmax-Vmin)*exp((Ei/Ein)*log((Vmax-Voc)/(Vmax-Vmin)))
% V = voltage to calculate power
%V=Vop
%r=round(Voc)+10;
r=60;
separacion=1/10;
V=[0:separacion:r];
[h,r]=size(V);
% P(V) = power at a specific voltage V
n=0;
while n < r
P(1+n)=[(V(1+n)*Ix)/(1-exp((-1)/b))]*[1-exp(((V(1+n))/(b*Vx))-(1/b))];
if(P(1+n)<0)
    P(1+n)=0;
end
n=n+1;
end

% I(V) = Current at a specific voltage V
n=0;
while n < r
I(1+n)=(Ix/(1-exp((-1)/b)))*[1-exp(((V(1+n))/(b*Vx))-(1/b))];
if(I(1+n)<0)
    I(1+n)=0;
end
n=n+1;
end
% Optimizacion para encontrar Pmax y Vop de la data de la grafica
options = optimset('TolFun',1e-8);
Vopcal = fminbnd(@(V)-[(V*Ix)/(1-exp((-1)/b))]*[1-exp(((V)/(b*Vx))-(1/b))],0,r,options);
Pmaxcal=[(Vopcal*Ix)/(1-exp((-1)/b))]*[1-exp(((Vopcal)/(b*Vx))-(1/b))];

PVmaxpower(i,:)=Pmaxcal;  % In KW
Ii(i,:)=I;
Pi(i,:)=P;
i=i+1;
end

PVpoweryear=LightInDay*365*PVmaxpower/1000;  %In KWh in a year

%Graph Power vs Voltage
subplot(2,2,1:2)
plot(V,Pi)
xlabel('V');
ylabel('P');
title('Voltage vs Power');
%Graph Power vs Current
subplot(2,2,3:4)
plot(V,Ii)
xlabel('V');
ylabel('I');
title('Voltage vs Current');

break
end

[type, sheets] = xlsfinfo('Library.xls');
CostPV2 = xlsread('Library.xls', 'solarpanel', 'D5:D17');

PVradiation = xlsread('Library.xls', 'solardata', 'B4:O15');
% First Analisis Sum All Month Average Radiations
PVradiationallday=sum(PVradiation);
PVrad=PVradiationallday(1,selected);
PVeffi = xlsread('Library.xls', 'solarpanel', 'B5:B17');
Cf=Cf; %Correction Factor
```

```
i=1;
while i<=13
PVpoweryear(i,:)=Cf*PVrad*PVeffi(i,1)*30.4 ; % 30.4 = days in a month
i=i+1;
end
PVmaxpower=1000*PVpoweryear/365/6;
```

APPENDIX D *MATLAB FUNCTION (BATTERY) USE FOR CALCULATED NUMBER OF BATTERIES REQUIRED BY THE BATTERY BANKS*

```
function [BatteryBankRequiredPowerWh,
EnergyBatteryWh,CostB,AmpHourBattery,VoltageBattery,RequiredBatteryCapacity,BatteryParalell,BatterySerie,Ba
tteryRequired] = battery(LoadEnergyDailyAC, SystemEffiST, DCSystemVoltage,
StorageDay,MaximunDepthofDischarge,DerateFactor)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input the Battery's Cost, Voltage and AmpHour at C/20 raiting from a
% excel document where all the data is available
CostB = xlsread('Library.xls', 'battery', 'B3:B29');
AmpHourBattery = xlsread('Library.xls', 'battery', 'F3:F29');
VoltageBattery = xlsread('Library.xls', 'battery', 'C3:C29');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate the battery bank required enrgy using equation from the chapter
% of batteries
numelB=numel(CostB)

InverterEffi=.9
AmpHourLoadDay=(1000*LoadEnergyDailyAC/InverterEffi)/DCSystemVoltage;
RequiredBatteryCapacity=(AmpHourLoadDay*StorageDay)/(MaximunDepthofDischarge*DerateFactor);
BatteryBankRequiredPowerWh=RequiredBatteryCapacity*DCSystemVoltage;
EnergyBatteryWh=AmpHourBattery.*VoltageBattery;
BatteryParalell=RequiredBatteryCapacity./AmpHourBattery;
for i=1:numelB
BatteryParalell(i,:)=ceil(BatteryParalell(i,:));
end
BatterySerie=DCSystemVoltage./VoltageBattery;
BatteryRequired=BatteryParalell.*BatterySerie;
```

APPENDIX E *MATLAB PROGRAM (STHYBRID) USE FOR SIZING THE OPTIMUM STAND ALONE CONFIGURATION USING LINEAR PROGRAMMING*

```
clc
clear all
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Load Power and Energy Data

LoadMaxPowerAC=7.746 %KW
LoadEnergyDailyAC=23.904  %KWh/Day

LoadEnergyMonthlyAC=800  %KWh/Day
LoadEnergyDailyAC=LoadEnergyMonthlyAC/31.5  %KWh/Day
LoadEnergyYearAC=LoadEnergyMonthlyAC*12  %KWh/Yearly

ACSystemVoltage=120  %AC Voltage
DCSystemVoltage=48   %DC Voltage

SystemEffi=.75  %Efficiency Of Stand Alone System =.75
TimeYears=1
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Battery Data
StorageDay=2
MaximunDepthofDischarge=.50
DerateFactor=1
Breplacement=2

[BatteryBankRequiredPowerWh,
EnergyBatteryWh,CostB,AmpHourBattery,VoltageBattery,RequiredBatteryCapacity,BatteryParalell,BatterySerie,Ba
tteryRequired] = battery(LoadEnergyDailyAC, SystemEffi, DCSystemVoltage,
StorageDay,MaximunDepthofDischarge,DerateFactor);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Power Calculation

% %Wind Turbine Data Site
% Cape San Juan USDA=1
% Yunque=2
% Gurabo Town=3
% Viejo San Juan=4
% Buchanan=5
% Rio Blanco=6
% Roosvelt Roads=7
% Fajardo City=8
% Catalina=9
% Aguirre=10
% Cuyon=11
% Croem=12
% Cape San Juan=13
% Aguadilla Airport=14
% Aes=15
% Isla Verde=16
% Cape San Juan 8600 values=17
windsite=4;
desiredheight=25; %Wind Turbine desired height

[EnergyYearWT,CostWT,WindSpeedVelocity,ScaleFactor,ShapeFactor,ms,pdfwind,EnergiaYearWTdetail,WindSpeedAver
ageV,WindSpeedVrmc] =weibulll(windsite,desiredheight) %Pwindturbines in KWh in year

% disp('Press Any Key To Continue Solar Analisis:');
% pause

% Mayaguez = 1
% San Juan = 2
% Ponce = 3
% Cabo Rojo = 4
% Cataño = 5
% Manatí = 6
```

```
% Fajardo = 7
% Rio Grande = 8
% Gurabo = 9
% Juana Diaz = 10
% Isabela = 11
% Lajas = 12
% Aguadilla = 13
% Ceiba = 14
solarsite=2
T=32.5 %temperature in Solar Panel
Cf=.98 %Correction Factor

[PVpoweryear1,CostPV,PVmaxpower1] = EduardoSolar(solarsite,T); %PVpoweryear in KWh  PVmaxpower in KW

[PVpoweryear2,CostPV2,PVmaxpower2] = PVefficiency(solarsite,T,Cf);
% disp('Press Any Key To Continue Optimization:');
% pause
% PVPowerYear=[PVpoweryear1,PVpoweryear2];
% PVMaxPower=[PVmaxpower1,PVmaxpower2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
EnergyYearWT;
PowerWTMax=xlsread('Library.xls', 'windturbine', 'C3:C23');
CostWT;
[na,WindTurbines]=xlsread('Library.xls', 'windturbine', 'B3:B23');
%Solar
PowerPVSCT=xlsread('Library.xls', 'solarpanel', 'C5:C17');
EnergyYearPV=PVpoweryear1;
CostPV;
[na,SolarPanels]=xlsread('Library.xls', 'solarpanel', 'A5:A17');
%Battery
BatteryBankRequiredPowerWh; %
EnergyBatteryWh; %power available in each battery
CostB;
CostBatteryBank=CostB.*BatteryRequired;
[na,Battery]=xlsread('Library.xls', 'battery', 'A3:A29');
%Inverter
PowerInv=xlsread('Library.xls', 'inverter', 'D3:D34'); % Power in Watts
CostInv=xlsread('Library.xls', 'inverter', 'C3:C34');
[na,Inv]=xlsread('Library.xls', 'inverter', 'A3:A34');
%Controller
PowerContr=xlsread('Library.xls', 'controller', 'D3:D26').*DCSystemVoltage;  % Power in Watts
CostContr=xlsread('Library.xls', 'controller', 'C3:C26');
VmContr=xlsread('Library.xls', 'controller', 'F3:F26');
[na,Contr]=xlsread('Library.xls', 'controller', 'A3:A26');
%KWh Utility Cost
CostKWh=.17

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%counter number of equipments
numelWT=numel(WindTurbines)
numelPV=numel(SolarPanels)
numelB=numel(Battery)
numelInv=numel(Inv)
numelContr=numel(Contr)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A=[TimeYears*(EnergyYearWT'*1),
TimeYears*(EnergyYearPV'*1),EnergyBatteryWh'.*0,PowerInv'.*0,PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,ones(numelB,1)',PowerInv'*0,PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,-BatteryRequired',PowerInv'*0,PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,EnergyBatteryWh'.*0,PowerInv'.*1,PowerContr'.*0;
   EnergyYearWT'.*0, -PowerPVSCT'.*1,EnergyBatteryWh'.*0,PowerInv'.*0,PowerContr'.*1;
   -ones(numel(EnergyYearWT),1)', EnergyYearPV'.*0,EnergyBatteryWh'.*0,PowerInv'.*0,PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,EnergyBatteryWh'.*0,-ones(numel(PowerInv),1)',PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,EnergyBatteryWh'.*0,PowerInv'*0,-ones(numel(PowerContr),1)']


B=[TimeYears*(LoadEnergyYearAC/SystemEffi);  %KWh
   1; %only one battery bank
   -100; %maximun number of battery in the bank
   LoadMaxPowerAC*1000; %inverter constrain
   0; %contoller constrain
   -1;%Only x type of wind turbine
   -1;%Only x type of Inv
   -1]%Only x type of Contrl
```

```
ctype=['G','G','G','G','G','G','G','G']';
%--------------------------------------------------------
%lb=[zeros(1,numelWT),6*ones(1,numelPV), zeros(1,numelB+numelInv+numelContr)]';

lb=[zeros(1,numelWT+numelPV+numelB+numelInv+numelContr)]';
xmin=[ones(1,numelWT+numelPV+numelB+numelInv+numelContr)]';
ubWT=ones(1,numelWT);
ubPV=ones(1,numelPV);
ubB=ones(1,numelB);   %Not For Net Metering
ubInv=ones(1,numelInv);
ubCont=ones(1,numelContr);
ub=[1*ubWT, 70*ubPV,1*ubB,1*ubInv,1*ubCont]';


varsize=size(ub)
i=1;
I=[];
while i<=varsize(1)
    I(1,i)='I';
    i=i+1;
end
varsize=(numelPV)
i=1;
while i<=varsize(1)
    I(1,21+i)='C';
    i=i+1;
end
vartype=char(I)'

f=[CostWT', CostPV', CostBatteryBank', CostInv',CostContr']'

schoptions=schoptionsset('ilpSolver','glpk','solverVerbosity',0);   %ILP solver options (use default
values)

disp('The solution is:');
[xmin,fmin,status,extra] = ilinprog(schoptions,1,f,A,B,ctype,lb,ub,vartype)

%%%%%%%%%Bounds
x=xmin
for i=1:numelWT+numelPV+numelB+numelInv+numelContr
     xmin(i,:)=ceil(xmin(i,:));
end
fmin=[sum(f.*xmin)]
%Battery
for i=1:numelB
 xmin(i+numelWT+numelPV,1)=BatteryRequired(i,1).*xmin(i+numelWT+numelPV,1);
end


 [x1]=linprog(f,-A,-B,[],[],lb,ub);
for i=1:numelB
 x1(i+numelWT+numelPV,1)=BatteryRequired(i,1).*x1(i+numelWT+numelPV,1);
end


 xt=[xmin,x1]

TimeYears*(LoadEnergyYearAC/SystemEffi)
sum([TimeYears*(EnergyYearWT'*1),
TimeYears*(EnergyYearPV'*1),EnergyBatteryWh'*0,PowerInv'*0,PowerContr'.*0]'.*xmin)


BatteryBankRequiredPowerWh
sum([EnergyYearWT'*0, EnergyYearPV'*0,EnergyBatteryWh'*1,PowerInv'*0,PowerContr'.*0]'.*xmin)


LoadMaxPowerAC*1000
sum([EnergyYearWT'*0, EnergyYearPV'*0,EnergyBatteryWh'*0,PowerInv'*1,PowerContr'.*0]'.*xmin) %Watts

sum([EnergyYearWT'*0, PowerPVSCT'*1,EnergyBatteryWh'*0,PowerInv'*0,PowerContr'.*0]'.*xmin)
sum([EnergyYearWT'*0, PowerPVSCT'*0,EnergyBatteryWh'*0,PowerInv'*0,PowerContr'.*1]'.*xmin)

cost=f;
ft=[sum(cost.*xmin),sum(cost.*x1)]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
con={'Wind Turbines','Opt','Solar Panel','Opt','Battery','Opt','Inverter','Opt','Controller','Opt'};

numelWT=numel(WindTurbines);
numelPV=numel(SolarPanels);
numelB=numel(Battery);
numelInv=numel(Inv);
numelContr=numel(Contr);


for i=1:numelWT
    con(i+1,1)=WindTurbines(i,1);
    con(i+1,2)={xmin(i,1)};
end
for i=1:numelPV
    con(i+1,3)=SolarPanels(i,1);
    con(i+1,4)={xmin(i+numelWT,1)};
end
for i=1:numelB
    con(i+1,5)=Battery(i,1);
    con(i+1,6)={xmin(i+numelWT+numelPV,1)};
end

for i=1:numelInv
    con(i+1,7)=Inv(i,1);
    con(i+1,8)={xmin(i+numelWT+numelPV+numelB,1)};
end

for i=1:numelContr
    con(i+1,9)=Contr(i,1);
    con(i+1,10)={xmin(i+numelWT+numelPV+numelB+numelInv,1)};
end

conpower={'Wind Turbines','Cost($)','PowerYearKWh','Opt','Solar
Panel','Cost($)','PowerYearKWh','Opt','Battery','Cost($)','AmpHourBattery','VoltageBattery','Power
Wh','Opt','Inverter','Cost($)','Power Watts','Opt','Controller','Cost($)','Power Watts','Opt','Max PV
Voltage'};

for i=1:numelWT
    conpower(i+1,1)=WindTurbines(i,1);
    conpower(i+1,2)={CostWT(i,1)};
    conpower(i+1,3)={EnergyYearWT(i,1)};
    conpower(i+1,4)={xmin(i,1)};

end
for i=1:numelPV
    conpower(i+1,5)=SolarPanels(i,1);
    conpower(i+1,6)={CostPV(i,1)};
    conpower(i+1,7)={EnergyYearPV(i,1)};
    conpower(i+1,8)={xmin(i+numelWT,1)};
end
for i=1:numelB
    conpower(i+1,9)=Battery(i,1);
    conpower(i+1,10)={CostB(i,1)};
    conpower(i+1,11)={AmpHourBattery(i,1)};
    conpower(i+1,12)={VoltageBattery(i,1)};
    conpower(i+1,13)={EnergyBatteryWh(i,1)};
    conpower(i+1,14)={xmin(i+numelWT+numelPV,1)};
end

for i=1:numelInv
    conpower(i+1,15)=Inv(i,1);
    conpower(i+1,16)={CostInv(i,1)};
    conpower(i+1,17)={PowerInv(i,1)};
    conpower(i+1,18)={xmin(i+numelWT+numelPV+numelB,1)};
end

for i=1:numelContr
    conpower(i+1,19)=Contr(i,1);
    conpower(i+1,20)={CostContr(i,1)};
    conpower(i+1,21)={PowerContr(i,1)};
    conpower(i+1,22)={xmin(i+numelWT+numelPV+numelB+numelInv,1)};
    conpower(i+1,23)={VmContr(i,1)};
end
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %Excel Output
EquipmentCostf=[CostWT', CostPV', CostB', CostInv',CostContr']';
```

```
EquipmentCost=sum(EquipmentCostf.*xmin);
BatterytotalCostf=[CostWT'.*0, CostPV'.*0, CostB', CostInv'.*0,CostContr'.*0]';
BatterytotalCost=sum(BatterytotalCostf.*xmin);
GeneretedPowerYear=sum([(EnergyYearWT'*1),
(EnergyYearPV'*1),EnergyBatteryWh'*0,PowerInv'*0,PowerContr'.*0]'.*xmin)
HomePower=TimeYears*(LoadEnergyYearAC/SystemEffi)
%
xlswrite('output.xls', windsite,'st','A8');
xlswrite('output.xls', solarsite,'st','A10');
xlswrite('output.xls', EquipmentCost,'st','D42');
xlswrite('output.xls', BatterytotalCost,'st','D46');
xlswrite('output.xls', DCSystemVoltage,'st','L3');
xlswrite('output.xls', RequiredBatteryCapacity,'st','L4');

xlswrite('output.xls', LoadEnergyMonthlyAC,'st','A4');
xlswrite('output.xls', GeneretedPowerYear,'st','F4');
xlswrite('output.xls', conpower,'st','C12');
```

APPENDIX F *MATLAB PROGRAM (NMHYBRID) USE FOR SIZING THE OPTIMUM STAND ALONE CONFIGURATION USING LINEAR PROGRAMMING*

```
clc
clear all
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Load Power and Energy Data

LoadMaxPowerAC=7.746 %KW
%LoadEnergyDailyAC=23.904  %KWh/Day

LoadEnergyMonthlyAC=800  %KWh/Day
LoadEnergyDailyAC=LoadEnergyMonthlyAC/31.5  %KWh/Day


LoadEnergyYearAC=LoadEnergyMonthlyAC*12  %KWh/Yearly

ACSystemVoltage=120  %AC Voltage
DCSystemVoltage=48   %DC Voltage

SystemEffi=.84  %Efficiency Of Stand Alone System =.75
TimeYears=1

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Power Calculation

% %Wind Turbine Data Site
% Cape San Juan USDA=1
% Yunque=2
% Gurabo Town=3
% Viejo San Juan=4
% Buchanan=5
% Rio Blanco=6
% Roosvelt Roads=7
% Fajardo City=8
% Catalina=9
% Aguirre=10
% Cuyon=11
% Croem=12
% Cape San Juan=13
% Aguadilla Airport=14
% Aes=15
% Isla Verde=16
% Cape San Juan 8600 values=17
windsite=13;
desiredheight=25; %Wind Turbine desired height

[EnergyYearWT,CostWT,WindSpeedVelocity,ScaleFactor,ShapeFactor,ms,pdfwind,EnergiaYearWTdetail,WindSpeedAver
ageV,WindSpeedVrmc] =weibulll(windsite,desiredheight) %Pwindturbines in KWh in year

% disp('Press Any Key To Continue Solar Analisis:');
% pause

% Mayaguez = 1
% San Juan = 2
% Ponce = 3
% Cabo Rojo = 4
% Cataño = 5
% Manatí = 6
% Fajardo = 7
% Rio Grande = 8
% Gurabo = 9
% Juana Diaz = 10
% Isabela = 11
% Lajas = 12
% Aguadilla = 13
% Ceiba = 14
solarsite=7
```

```
T=32.5 %temperature in Solar Panel
Cf=.98 %Correction Factor

[PVpoweryear1,CostPV,PVmaxpower1] = EduardoSolar(solarsite,T); %PVpoweryear in KWh  PVmaxpower in KW

[PVpoweryear2,CostPV2,PVmaxpower2] = PVefficiency(solarsite,T,Cf);
% disp('Press Any Key To Continue Optimization:');
% pause
% PVPowerYear=[PVpoweryear1,PVpoweryear2];
% PVMaxPower=[PVmaxpower1,PVmaxpower2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Wind
EnergyYearWT;
PowerWTMax=xlsread('Library.xls', 'windturbine', 'C3:C23');
CostWT;
[na,WindTurbines]=xlsread('Library.xls', 'windturbine', 'B3:B23');
%Solar
PowerPVSCT=xlsread('Library.xls', 'solarpanel', 'C5:C17');
EnergyYearPV=PVpoweryear1;
CostPV;
[na,SolarPanels]=xlsread('Library.xls', 'solarpanel', 'A5:A17');
%Inverter
PowerInv=xlsread('Library.xls', 'inverter', 'D3:D34'); % Power in Watts
CostInv=xlsread('Library.xls', 'inverter', 'C3:C34');
[na,Inv]=xlsread('Library.xls', 'inverter', 'A3:A34');
%Controller
PowerContr=xlsread('Library.xls', 'controller', 'D3:D26').*DCSystemVoltage;  % Power in Watts
CostContr=xlsread('Library.xls', 'controller', 'C3:C26');
VmContr=xlsread('Library.xls', 'controller', 'F3:F26');
[na,Contr]=xlsread('Library.xls', 'controller', 'A3:A26');
%KWh Utility Cost
CostKWh=.235

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%counter number of equipments
numelWT=numel(WindTurbines)
numelPV=numel(SolarPanels)
numelInv=numel(Inv)
numelContr=numel(Contr)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Ley 114 Agosto 2007 maximo de 300KWh al dia pueden ser acreditados
KWh=0; %Buy or sell
KWhyear=KWh*12;

A=[TimeYears*(EnergyYearWT'*1), TimeYears*(EnergyYearPV'*1),PowerInv'.*0,PowerContr'.*0;
   -PowerWTMax'.*1, -PowerPVSCT'.*1,PowerInv'.*1,PowerContr'.*0;
   EnergyYearWT'.*0, -PowerPVSCT'.*1,PowerInv'.*0,PowerContr'.*1;
   -ones(numel(EnergyYearWT),1)', EnergyYearPV'.*0,PowerInv'.*0,PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,-ones(numel(PowerInv),1)',PowerContr'.*0;
   EnergyYearWT'.*0, EnergyYearPV'.*0,PowerInv'*0,-ones(numel(PowerContr),1)']

B=[(TimeYears*(LoadEnergyYearAC/SystemEffi))+(KWhyear/SystemEffi);  %KWh
   0; %inverter constrain
   0; %contoller constrain
   -1;%Only x type of wind turbine
   -1;%Only x type of Inv
   -1]%Only x type of Contrl

ctype=['G','G','G','G','G','G']';
%-------------------------------------------------------
lb=[zeros(1,numelWT+numelPV+numelInv+numelContr)]';

ubWT=ones(1,numelWT);
ubPV=ones(1,numelPV);
ubInv=ones(1,numelInv);
ubCont=ones(1,numelContr);
ub=[1*ubWT, 900*ubPV,1*ubInv,1*ubCont]';

varsize=size(ub)
i=1
I=[]
while i<=varsize(1)
    I(1,i)='I'
    i=i+1
end
```

```
varsize=(numelPV)
i=1;
while i<=varsize(1)
    I(1,21+i)='C';
    i=i+1;
end
vartype=char(I)'


f=[CostWT', CostPV', CostInv',CostContr']'

schoptions=schoptionsset('ilpSolver','glpk','solverVerbosity',0);   %ILP solver options (use default values)

disp('The solution is:');
[xmin,fmin,status,extra] = ilinprog(schoptions,1,f,A,B,ctype,lb,ub,vartype)

%%%%%%%%%Bounds
x=xmin
for i=1:numelWT+numelPV+numelInv+numelContr
     xmin(i,:)=ceil(xmin(i,:));
end
fmin=[sum(f.*xmin)]



  [x1]=linprog(f,-A,-B,[],[],lb,ub);
xt=[xmin,x1]

TimeYears*(LoadEnergyYearAC/SystemEffi);
sum([TimeYears*(EnergyYearWT'*1), TimeYears*(EnergyYearPV'*1),PowerInv'*0,PowerContr'.*0]'.*xmin);

sum([PowerWTMax'.*1, -PowerPVSCT'.*1,PowerInv'*0,PowerContr'.*0]'.*xmin) ;
sum([EnergyYearWT'*0, EnergyYearPV'*0,PowerInv'*1,PowerContr'.*0]'.*xmin) ;%Watts

sum([EnergyYearWT'*0, PowerPVSCT'*1,PowerInv'*0,PowerContr'.*0]'.*xmin);
sum([EnergyYearWT'*0, PowerPVSCT'*0,PowerInv'*0,PowerContr'.*1]'.*xmin);

cost=[CostWT', CostPV', CostInv',CostContr']';
f=(sum(cost.*xmin))
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
con={'Wind Turbines','Opt','Solar Panel','Opt','Inverter','Opt','Controller','Opt'};

numelWT=numel(WindTurbines);
numelPV=numel(SolarPanels);
numelB=numel(Battery);
numelInv=numel(Inv);
numelContr=numel(Contr);


for i=1:numelWT
    con(i+1,1)=WindTurbines(i,1);
    con(i+1,2)={xmin(i,1)};
end
for i=1:numelPV
    con(i+1,3)=SolarPanels(i,1);
    con(i+1,4)={xmin(i+numelWT,1)};
end

for i=1:numelInv
    con(i+1,5)=Inv(i,1);
    con(i+1,6)={xmin(i+numelWT+numelPV,1)};
end

for i=1:numelContr
    con(i+1,7)=Contr(i,1);
    con(i+1,8)={xmin(i+numelWT+numelPV+numelInv,1)};
end
% con(22,7)={'KWh Buy or Sell'};
% con(22,8)={xmin(1+numelWT+numelPV+numelInv+numelContr,1)};
% con
f

conpower={'Wind Turbines','Cost($)','PowerYearKWh','Opt','Solar
Panel','Cost($)','PowerYearKWh','Opt','Inverter','Cost($)','Power
Watts','Opt','Controller','Cost($)','Power Watts','Opt','Max PV Voltage'};
```

```
for i=1:numelWT
    conpower(i+1,1)=WindTurbines(i,1);
    conpower(i+1,2)={CostWT(i,1)};
    conpower(i+1,3)={EnergyYearWT(i,1)};
    conpower(i+1,4)={xmin(i,1)};

end
for i=1:numelPV
    conpower(i+1,5)=SolarPanels(i,1);
    conpower(i+1,6)={CostPV(i,1)};
    conpower(i+1,7)={EnergyYearPV(i,1)};
    conpower(i+1,8)={xmin(i+numelWT,1)};
end

for i=1:numelInv
    conpower(i+1,9)=Inv(i,1);
    conpower(i+1,10)={CostInv(i,1)};
    conpower(i+1,11)={PowerInv(i,1)};
    conpower(i+1,12)={xmin(i+numelWT+numelPV,1)};
end

for i=1:numelContr
    conpower(i+1,13)=Contr(i,1);
    conpower(i+1,14)={CostContr(i,1)};
    conpower(i+1,15)={PowerContr(i,1)};
    conpower(i+1,16)={xmin(i+numelWT+numelPV+numelInv,1)};
    conpower(i+1,17)={VmContr(i,1)};

end

% conpower(22,15)={'KWh Buy or Sell'};
% conpower(22,16)={xmin(1+numelWT+numelPV+numelInv+numelContr,1)};


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Excel Output
EquipmentCostf=[CostWT', CostPV', CostInv',CostContr']';
EquipmentCost=sum(EquipmentCostf.*xmin);
GeneretedPowerYear=sum([(EnergyYearWT'*1), (EnergyYearPV'*1),PowerInv'*0,PowerContr'.*0]'.*xmin)
HomePower=TimeYears*(LoadEnergyYearAC/SystemEffi)

xlswrite('output.xls', windsite,'nm','A8');
xlswrite('output.xls', solarsite,'nm','A10');
xlswrite('output.xls', EquipmentCost,'nm','D42');
xlswrite('output.xls', KWh,'nm','A6');

xlswrite('output.xls', LoadEnergyMonthlyAC,'nm','A4');
xlswrite('output.xls', GeneretedPowerYear,'nm','F4');
xlswrite('output.xls', conpower,'nm','C12');
```

APPENDIX G *SIMPLE INTEGER LINEAR PROGRAMMING VALIDATION EXAMPLE FOR RUN IN MATLAB WITH TORSCHE TOOLBOX*

```
clc;
disp('Integer linear programming Validation.');
disp('----------------------------------------------------------');
disp(' ');

disp('An Example of Hybrid Grid Connected Power System.');
disp(' ');
disp('Home Load of 800kWh/monthly or 9600kWh/yearly');
disp(' ');
disp('Two Wind Turbines available for buy');
disp('Wind Turbine 1 cost $8000 and generate 8000kWh/yearly');
disp('Wind Turbine 2 cost $9000 and generate 9000kWh/yearly');
disp(' ');
disp('Two Solar Panels available for buy');
disp('Solar Module 1 cost $600 and generate 300kWh/yearly');
disp('Solar Module 2 cost $700 and generate 300kWh/yearly');
disp(' ');
disp('min cost 8000*Wt1 + 9000*Wt2 + 600*PV1 + 700*PV2');
disp(' ');
disp('Subject to:');
disp('       9600 kWh <= 8000*Wt1 + 9000*Wt2 + 300*PV1 + 300*PV2');
disp('where:');
disp('     x1>=0, x2>=0, x3>=0,x4>=0');
disp('     x1,x2,x3,x4 are integer variables');
disp(' ');

f=[8000,9000,600,700]';                %objective function
A=[8000,9000,300,300];                  %matrix representing linear constraints
b=[9600];           %right sides for the inequality constraints
ctype=['G']';       %sense of the inequalities
lb=[0,0,0,0]';                %lower bounds of variables
ub=[inf inf inf inf]';          %upper bounds of variables
vartype=['I','I','I','I']';     %types of variables

schoptions=schoptionsset('ilpSolver','glpk','solverVerbosity',0);   %ILP solver options (use
default values)

disp('The solution is:');
[ixmin,ifmin] = ilinprog(schoptions,1,f,A,b,ctype,lb,ub,vartype)
```