Design and Control of a Grid-Tied P-V System for Medium-Sized Household in South Florida

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ABSTRACT

In this paper, the design and installation of a grid-connected P-V system is analyzed in terms of maximum power, size, and cost. This interactive system will be controlled based on the available sun irradiance and demand. The sizing is determined based on the expected loads in a household, the characteristics of the selected P-V module, and meteorological data for the region. Under this grid-tied configuration, the system is capable of supplying most peak loads in a small household with the capability under certain conditions to take advantage of utility net-metering providing energy back to the grid. The system consists of 16 P-V panels connected to 4 parallel inverters optimized to balance single-phase 240/120 Vac power to the main electrical distribution panel. The control of the proposed system is explained and the system is economically evaluated and demonstrates the payoff of the investment.

Keywords: Grid-tied systems, inverter sizing, PV systems, renewable energy sources, and residential applications.

1. INTRODUCTION

Challenges associated with traditional energy sources such as fuel prices, availability, pollution and environmental concerns, combined with the existing distribution system problems impose an imperative necessity to leap forward towards the utilization of renewable energy sources with smart operation and management. Researchers have worked on various ways to develop and design a futuristic power system to easily integrate renewable energy sources and to have more efficiency. One of the most promising renewable energy sources is in photovoltaics (P-Vs). P-V can be integrated either on large scale (utility level) or on small scale (household level). This paper concentrates on small scale integration of P-V. Power companies such as FPL (Florida Power and Light Company) are providing more incentives to the consumers to install P-V in their houses, as meeting the energy deficit on the consumer level can be more efficient and cheaper.

In this study, a P-V system feeding a typical medium-sized house is designed. The load curve is analyzed carefully and the P-V system will be designed to present a balance between the generated power and system cost. The system under study is grid connected, however the connection to the grid and power flow direction can be altered based on supervisory control according to available power from the P-V panels and the required demand. The system operation and management will be addressed. Since a connection to the grid is available and in an effort to reduce the upfront cost to the system, no energy storage will be used. Moreover, with P-V presently still expensive renewable alternative, economical aspects will be considered to select the ultimate size and grid-tied inverters.

This paper is organized as the following: a detailed description of the proposed system and its operation and will be provided in Section 2. Section 3 presents study of the expected loads in the house. The selection of P-V and inverter equipment will be provided in Section 4. Section 5 will complete a comprehensive meteorological study for the location of install. Sections 6 and 7 will define the simulation and results of the entire system. An economic evaluation for the system is given in Section 8 and finally the derived conclusions are given in section 9.

2. PROPOSED SYSTEM

The system under study is grid-tied system sized to operate autonomously with the potential to provide support to the grid. In this system, 16 P-V modules are divided into 4 symmetrical sub-arrays, each sub-array comprises of 4 P-V panels connected together in parallel. Each array is connected to an inverter, the 4 inverters are connected to a single sectionalized AC bus. Selection of the number of P-V panels and ratings of equipment are explained in detail in the following sections. Figure 1 shows a schematic diagram of the proposed system. The loads are divided into two groups. The first group is formed from the loads that are categorized as heavy loads such as HVAC, electric stove, washing machine and dryer. This group includes the loads operated at night as well such as LED lamps. The second group of loads is formed from the other loads such as water heater, LED TV, laptops, computer, iron and microwave. The loads were grouped based on power and hours of operation for each load. The AC bus is divided into 5 sections through 4 switches. The first group of loads is connected to the same section with the grid while the second group is connected to the last section.

The system is operated by a smart controller which measures the aggregated power from each P-V array and the connected load demand then sends control signals to all the switches accordingly. The controller is designed to work autonomously, comparing the demanded power with the available power from the connected solar array. If the available power is not enough, it will check if there are any available sub-arrays to be connected to feed the required demand. If there are still available sub-arrays, the controller starts to connect the available one until the available power meets the required demand. If all sub-arrays are connected and fail to supply the load, the controller will close the switch between sections 1 and 2 to connect this section of the AC bus to the grid.

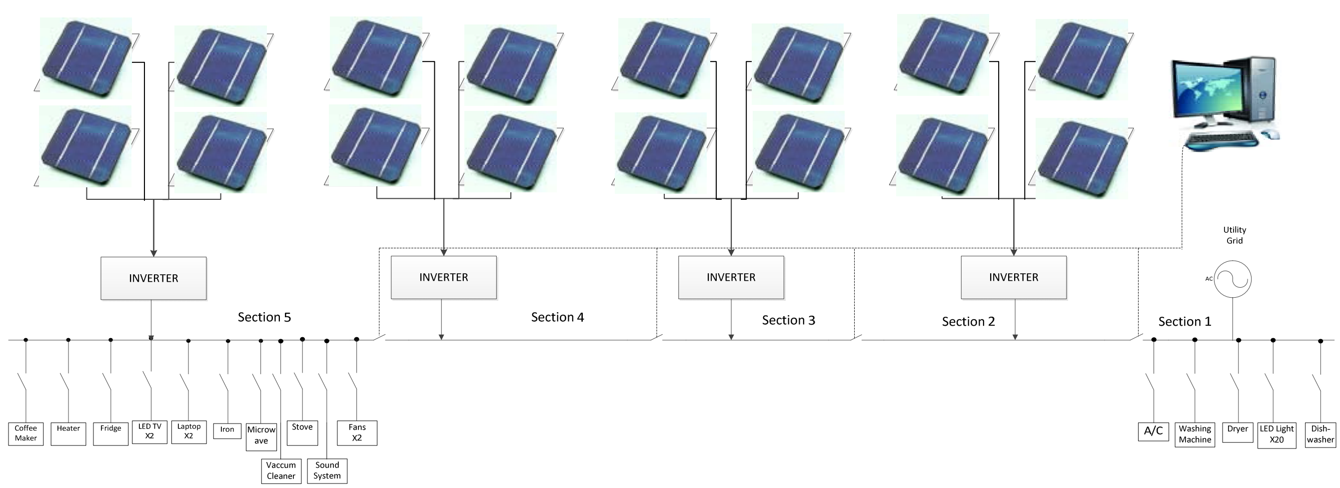


Figure 1: System schematic diagram.

It is assumed that the bulk of loading will occur during the daytime hours thus while the system is harvesting energy, it will also serve a majority of its loads. In a case where there is excess power generated by the P-V, there is an option available to the consumer to sell power back to the grid. This is based on the preferences of the consumer and incentives, if any, provided by FPL. The consumer will have the capability to enable or disable this option. A flow chart of the control algorithm is shown in Figure 2.

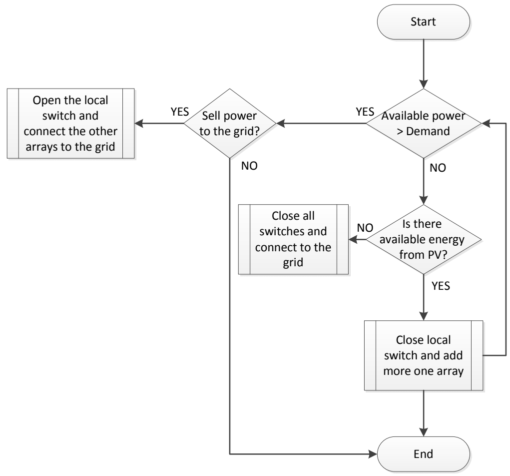


Figure 2: Flow chart of the control algorithm.

3. LOAD ESTIMATION

The first step in design process is to accurately estimate the loads. Typical home appliances with their respective power ratings and estimated operating time per day are listed in Table 1. Most of the equipment used in a household have the rated power in their nameplate. The total energy depends of how many hours the appliance is used and that depends on the user. It is shown that the total energy consumption of the home is 27,616 kWh per year. By dividing over the number of hours in a year (8,760) it yields ≈ 3.2 kW as an average load. Designing the system to supply the average load (3.2 kW) assumes that the load curve is uniform,which is not a valid assumption especially for residential applications.

Table 1: Typical home appliances power ratings and estimated operating time per day.

Equipment	Quantity	Power (W)	hr/day	hr/month	kWh/year
HVAC	1	5,000	10.00	300	18,000
Load Washer	1	2,500		8	240
Clothes dryer	1	3,500		8	336
Electric stove	1	4,000	1.00	30	1,440
Dishwasher	1	1,200	1.00	30	432
Electric Water Heater*	1	-	-	-	4,800
Fridge*	1	-	-	-	600
LED Television	2	60	8.00	480	346
Lights	20	20	2.00	1,200	288
Laptop	2	50	2.00	120	72
Fans	2	60	2.00	120	86
Sound System	1	400	2.00	60	288
Iron	1	1,000	0.50	15	180
Vacuum Cleaner	1	1,200	0.25	8	108
Microwave	1	800	0.30	9	86
Coffee maker	1	600	0.20	6	43
Misc.Kitchen Appliances	-	1,000	0.75	23	270
				Total kWh/yr	27,616

4. Equipment Selection

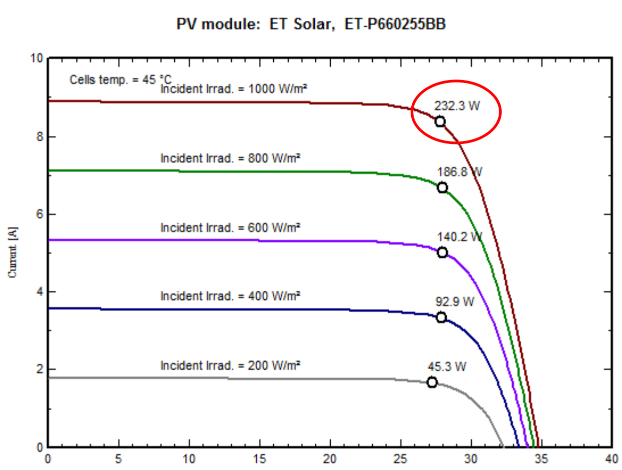
Proper equipment selection is not only required to meet the specifications made in the proposed design, selected with respect to actual meteorological and operational conditions in the household. For this reason, the PVsyst industrial planning software solution was selected to model the entire system. With the capability of importing the specifications of the P-V panels and the inverter, an extensive meteorological database can forecast the available energy hourly for an entire year considering thermal, ohmic, and other parasitic losses.

Since the system being installed is a 4 kW grid-tied system separated into 4 sub-arrays, the method of this design could inadvertently increase losses if the system is over or under-sized. For this reason, the P-V panels have been selected with respect to their cost and actual expected power output as opposed to published nominal values. Making close approximations to the magnitude of power being provided to the inverter will ensure it operates within its peak efficiency region.

4.1 P-V Panel Selection

Selection of the optimal P-V panel needed to be economical but also provide accurate power forecasting with respect to the meteorological study. To meet the 1 kW maximum power input to the inverter, 4 strings of 250 Wp panels will be connected. A simple configuration would simply require the purchase of 15 250-W panels, however, a published rating is a common misconception. Depending on the manufacturer, a 250-W panel realistically produces about 90% of the rated power, or 225 W under normal atmospheric conditions. For this reason, the panels were oversized in order to maximize the power to the inverter. Following this assumption, a panel rated up to 270-W rated panel would be more suitable.

ET Solar currently produces a wide range of polycrystalline silicon panels with efficiencies exceeding 15%. ET Solar has also been known for their affordability when purchasing through their distributer, Wholesalesolar. Three panels (250-W, 255-W, and 305-W) were available from Wholesalesolar at cost of around $1 per watt. Due to the fact that the 305-W would be oversized, the 255-W was analyzed inside the PVsyst planning tool which calculated its maximum output power at 1,000 W/m² to be 232.3 W or 92.9% of the target power shown in Figure 3a. The ET Solar 270-W panel would have provided the ideal solution but it was not available through Wholesalesolar. Fig 3b shows the IV-curve which under the same irradiance conditions produces 249.3 W or 99.7% of the target power.



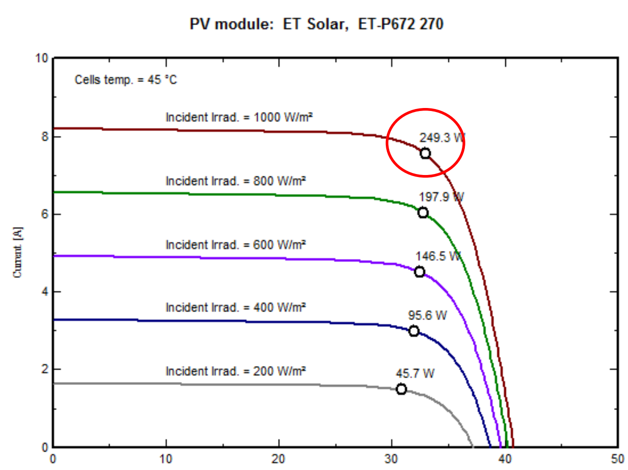


Figure 3: Maximum Power IV Curves for the ET Solar a) 255-W Panel (left) b) 270-W Panel (right)

Unfortunately, the 270-W panel was not practical for two reasons: cost and risk of inverter overloading. The 255-W panel was offered at a cost of $260 or $1.02 per watt. The 270-W, however, was at a cost of $405 or $1.50 per watt, or 47% more. The second reason is related to the generation performance under actual meteorological conditions in Miami, FL which would later reveal that the 270-W panel would overload the inverter. For this reason, the ET P660255B 255-W panel was chosen for this system. This panel is sold with a 25-year warranty and its specifications are shown below in Table 2. The maximum power point occurs at 37.54 V which indicates this is a 40 V panel. This is an important specification for correctly selecting the inverter.

Table 2: Parameters for the ET Solar P660255B 255-W.

Nominal Power	255 W
Area	1.627 m²
V(Maximum Power Point)	30.91 V
V(Open Circuit)	37.54 V
I (Maximum Power Point)	8.250 A
I (Short Circuit)	8.820 A
α	-0.1350 V/℃
β	+0.0035 A/℃
K	-0.4400 W/℃
Efficiency	15.67%

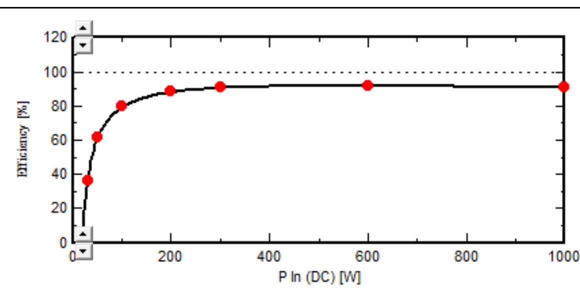
4.2 INVERTER SELECTION

The inverter selection focused on 4 major parameters: meeting the 1 KWac power requirements, verifying the DC Input voltage is compatible with the selected panels, grid-tie functionality, and cost. The current inverter market of today tends to separate between larger loading of 3 KWac and above and smaller, off-grid applications that are much under 1 kWac. In selecting the inverter, it was important to select one with a 120 Vac output capable of a phase-locked loop (PLL) to synchronize the phase between the utility grid and the power generated at the panel. These units also would be expected to obtain individual PLLs to handle each 120 Vac line that enters the household. These two signals, L1 and L2 would be expected to be 180° out of phase.

The 1KW60VG Solar Torrent 1-kW inverter was chosen for this system. The inverter is inexpensive at only $389 and simple to connect. The specifications for this system and its efficiency curve are shown in Table 3. The inverter outputs 1 kWac peak using a wide DC input from 22-60 V with a maximum power point tracking (MPPT) algorithm. The efficiency curve reveals the system is relatively stable around 90% efficiency except when the loading power drops below 100 W. The peak efficiency is witnessed near a 60% loading condition (600 W).

Table 3: Parameters for the Solar Torrent 1KW60VG 1-kWac Inverter and Efficiency Curve

Normal AC Output Power	900 W
Maximum AC Output Power	1,000 W
AC Output Voltage	90 – 130 Vac
AC Output Frequency	45 – 65 Hz
Total Harmonic Distortion (THD)	< 5%
Power Factor	0.99
DC Input Voltage Range	22 – 60 VDC
Peak Inverter Efficiency	92%



5. Meteorological Study

In order to make a reasonable estimation over the solar energy that would be expected over the course of a year, a meteorological study is conducted over the Miami, FL region. The most important element is a 365-day profile of the irradiance spectrum (in W/m²) for this location, but other meteorological parameters will affect the performance of the panels. The second most important detail is the ambient temperature which would affect the output voltage of the panel thus shifting the maximum power point tracking (MPPT) location.

The figures below identify the days of the year where the lowest irradiance and lowest temperature measurements were observed. Figure 4a identifies the minimum temperature of 3.9° C observed on 4 February. The lowest irradiance value of 162 W/m² was observed on 4 January shown in Figure 4b.

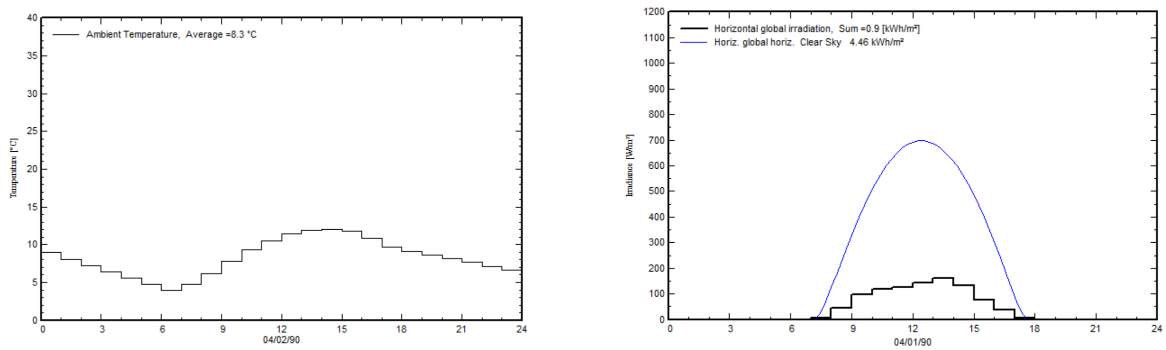


Figure 4: a) Hourly Temperatures on 4 February (left) b) Hourly Irradiance Profile on 4 January (right)

Figure 5a and 5b below depict the maximum temperature and minimum irradiance conditions. The highest recorded average temperature was recorded on 28 June of 36.4° C. The maximum irradiance occurs in on 29 May revealing a maximum irradiance of 1,034 W/m².

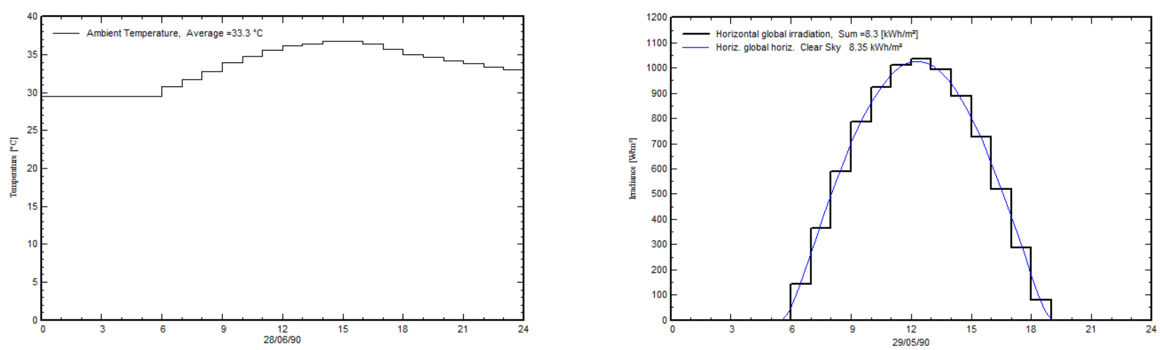


Figure 5: a) Hourly Temperatures on 28 June (left), b) Hourly Irradiance Profile for 29 May (right)

Although the current-versus-voltage (IV) curves in PVSyst provide for temperature input, this temperature does not reflect the ambient temperature but that of the silicon P-V surface. For instance, providing the ambient input of 3.9° C under the maximum irradiance of 1,035 W/m² produces a MPPT at 287.7 W. This value, however, is not possible as the minimum temperature occurred during the night without irradiance. Even if the temperature remained low, once the daytime sun is absorbed on the P-V cell, the P-V temperature would rise before it approached the maximum irradiance. For this reason, in the maximum power case, we will calculate the IV curve under normal cell temperature conditions.

5.1 Maximum Loading Conditions

In order to calculate the maximum loading conditions, the irradiance for every hour on 29 May is analyzed with the peak value occuring at 12:00. PVSyst provides up to 5 IV and PV (power-versus-voltage) curves to be displayed. For convenience, a range of values over the course of the day were chosen representing the irradiance at 06:00 (144 W/m²), 08:00 (589 W/m²), 12:00 (1,034 W/m²), 15:00 (727 W/m²), and 17:00 (286 W/m²). The IV and PV curves for the maximum power level case are shown in Figure 6a and 6b. These plots indicate the maximum power absorbed at each panel is 240 W. For each inverter, this would provide a maximum input power of 960 W or 96% loading to the inverter.

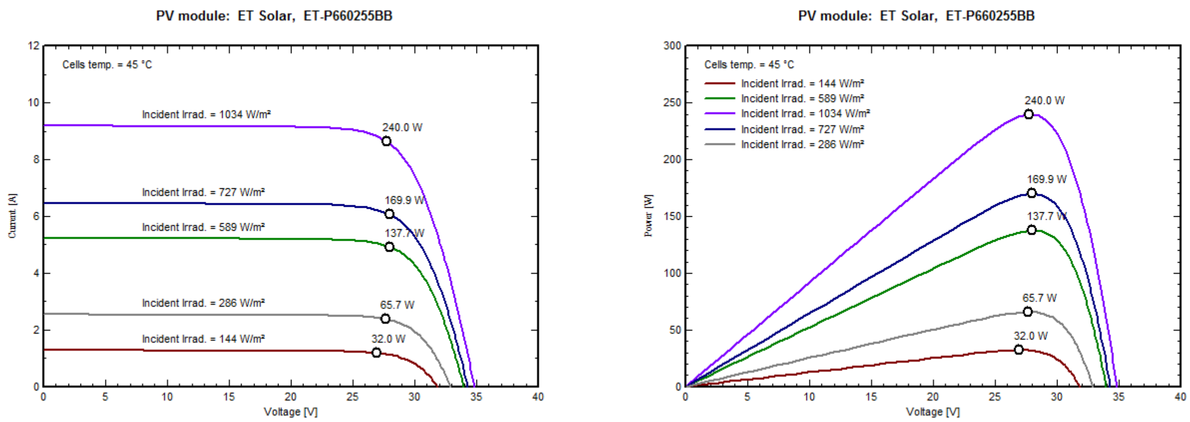


Figure 6: Power Generated under Maximum Loading on 29 May a) IV-Curve (left) b) PV-Curve (right)

5.2 Minimum Loading Conditions

For the minimum input power case, we will take into account the maximum temperature for two major reasons. Although it is not typical to observe the lowest irradiance levels when the ambient temperature is at its peak, it is not impossible. Additionally, in this case the cloud attenuation levels are so great that it is unlikely the panel is receiving direct sunlight thereby significantly increasing the temperature of the silicon. Once again, to construct the IV and PV curves, the hourly irradiance data collected on 4 January is analyzed. For a case of heavy cloud attenuation dropping the peak irradiance to 162 W/m², it can be assumed that the temperature of the surface of the silicon is close to ambient. For this reason, we the IV and PV curves are calculated using the maximum temperature of 36˚C at 08:00 (44 W/m²), 10:00 (117 W/m²), 12:00 (144 W/m²), 13:00 (162 W/m²), and 15:00 (75 W/m²).

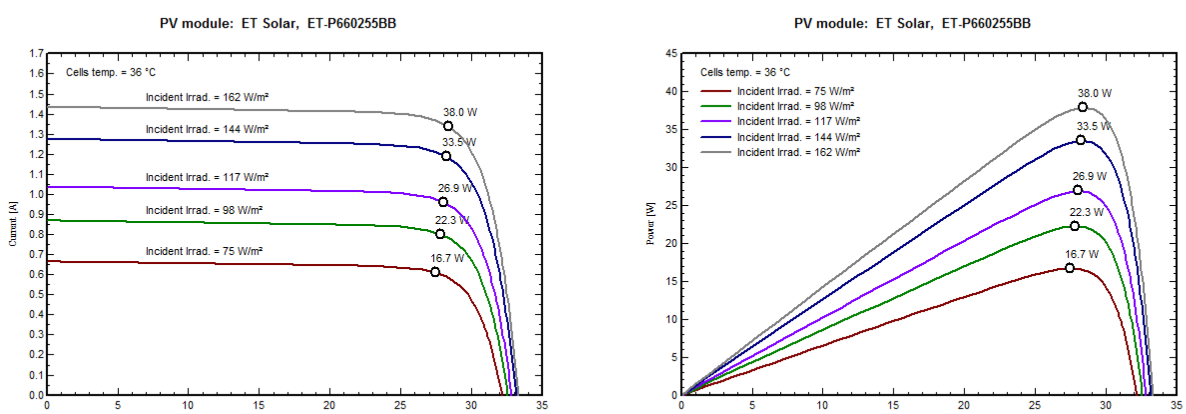


Figure 7: Power Generated at Minimum Loading on 4 January a) IV-Curve (left) b) PV-Curve (right)

The IV and PV curves indicate the maximum energy absorbed on the panel for 4 January was 36 W. For each inverter, this would provide a low input power of only 144 W or 15% loading. This case is where we would expect to see the largest drop in efficiency from the inverters but thankfully the case is isolated and would still provide adequate power to meet the minimum power threshold of 20 W.

Following a full simulation of the system within PVSyst, a normalized system performance (SP) parameter will be calculated which will allow us to determine the actual maximum and minimum power levels generated under these respective conditions.

6. System Design Simulation

The final system design is performed using the PVSyst v 6.19 simulation software. The initial configuration window for the system is shown below in Figure 8. The “FL Solar Project” requires a number of parameters to be met. The first section “Site and Meteo” provides the meteorological input to the system. Under the input parameters, the orientation of the panels must also be defined. For a fixed panel, the tilt angle is typically equal to the latitude of the location. Miami is at approximately 25°N latitude thus the tilt is specified at 25°.

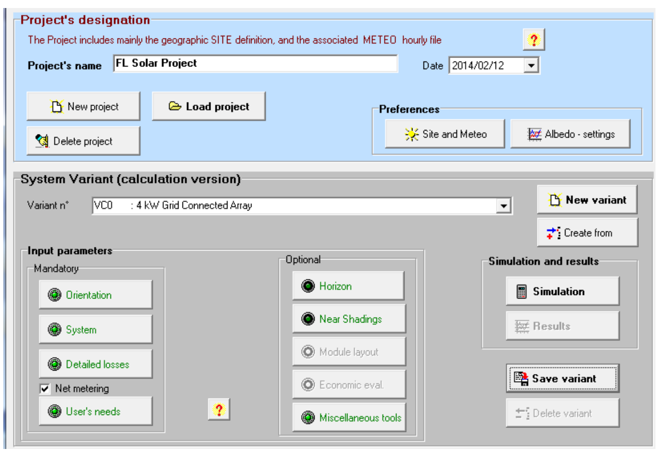


Figure 8: Project Configuration

Figure 9: 4 kW Grid Tie Equipment Configuration

The next input introduces the actual equipment configuration as is planned to be setup on the property (Figure 9). The ET Solar 255-W panel was already included in the software, but the inverter needed to be defined. Using the datasheet provided from Solar Torrent, the inverter parameters were defined separately. Each inverter (1-4) is defined as a sub-array where 4 strings of panels are connected to each. Pre-planning of the system optimization resulted in an overload loss factor of 0%.

Following the configuration of the equipment in the “Design” tab, the “Net Metering” option is enabled providing input for the user load profile. A number of profiles have been provided that can provide an advanced hourly analysis based on the actual power usage. These types will become valuable in the future as smart metering enhances to a point where virtually all electronics and appliances are monitored. However, for this case, we have provided a yearly energy loading profile as was displayed previously in Table 1 indicating a user load profile of 27,616 kWh/year.

7. Results

The results following a comprehensive simulation are shown below in Table 4. A number of elements are displayed depicting the total potential energy in kWh/m² that could be harvested for each month of the year totaling a potential of 1,766.2 kWh/m²/year. The following column "E Avail" depicts the usable energy that was supplied to the household after the inverter. This represents the total accountable generation power of 5887.9 kWh/year. A comparison is made to the energy actually harvested by the array before losses at 6,509 kWh/year. "E Load" then depicts the household energy profile that was calculated in Table 1. The PR, or Performance Rating depicts the total efficiency ratio between the incident energy at the P-V array and output from the inverter. The average energy conversion is 76%.

Table 4: P-V Array Energy Generation Results

	GlobHor kWh/m²	T Amb °C	E Avail kWh	EArray kWh	E Load kWh	E User kWh	PR	EffInvR %
January	109.4	18.41	460.2	508.9	2344	460.2	0.789	90.4
February	118.3	20.31	462.7	510.3	2117	462.7	0.779	90.7
March	159.2	22.61	548.9	605.2	2344	548.5	0.764	90.7
April	180.0	24.51	555.5	613.9	2268	555.4	0.751	90.5
May	184.5	26.91	524.2	581.0	2344	524.2	0.746	90.2
June	167.8	28.31	463.9	515.0	2268	463.9	0.749	90.1
July	180.8	28.91	505.6	560.2	2344	505.6	0.746	90.3
August	173.3	28.61	514.2	569.6	2344	514.2	0.743	90.3
September	146.9	27.41	473.3	524.1	2268	473.3	0.748	90.3
October	134.7	25.51	490.2	541.7	2344	490.2	0.758	90.5
November	109.4	22.81	443.1	488.2	2268	443.1	0.778	90.8
December	101.9	19.81	446.1	491.9	2344	446.1	0.789	90.7
Year	1766.2	24.53	5887.9	6509.9	27594	5887.4	0.760	90.4

Figure 10 depicts the performance ratio (PR) with respect to the array reference energy (harvested energy at the array) and the available energy at the output. Figure 11 shows a normalized distribution per installed single kW array. This is a convenient plot to show in this system as each sub-array has already been broken into single kW units. The plot shows the P-V collection and system losses in purple and green and highlights the average usable power output from each inverter to the household panel in red.

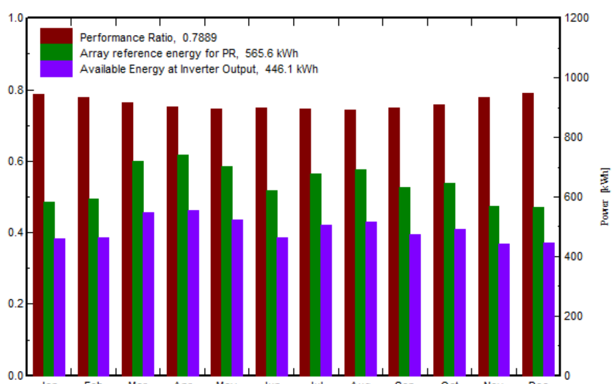


Figure 10: Energy Generated & Usable Energy & PR

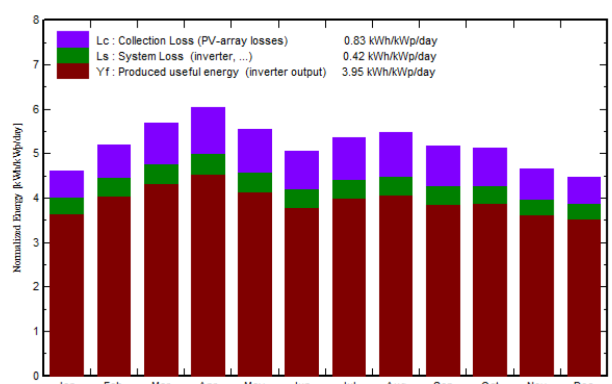


Figure 11: Productions per 1 kW Sub-array

8. ECONOMIC EVALUATION

In order to make the solution financially viable, the costs of the system have to be evaluated. Building and design of the system were based on commercially available equipment in the market thus additional costs of designing or producing customized components have been eleminated. The total system cost has been calculated using the prices which were published from Wholesale Solar and Solar Torrent. The ET P660255B panels cost $260 each. With 4 arrays connected in a string to each of the 4 inverters, we have a total of 16 panels totalling $4,160. Each of the 4 inverters were published at a cost of $389 each totalling $1,556. The wiring and holders would be expected to run an additional $1,000 total. Thus the cost of the system will be $7,320.44 with the taxes included. From Table 4, we know the generated energy is 5,888 kWh/yr. A simple calculation with respect to the price per kWh ($0.11/kWh) in South Florida (FPL) yields:

$$5888\ \frac{kWh}{yr}\ \text{x}\ \frac{\$0.11}{kWh} = \$647.68/yr$$

Using this figure with respect to the energy generation cost of $647.68 per year, we see a payoff period in 11.4 years. This investment appears to be a great deal of money, but following an 11 year period, the load profile of the household would continue to be reduced by 21%. Since the system does not include batteries for energy storage, the upfront cost was signficantly reduced. In addition, in the event of major outages or disasters, the homeowner would have a resilent household which in the future could help to support grid structure in the case of a disaster and potentially earn tax credits. Finally, this amount would continue to save the homeowner a great deal of money per year as with inflation, the cost per kilowatt-hour in 11 years would be significantly higher.

9. CONCLUSION

In this paper, a comprehensive procedure for designing a standalone P-V system for a grid-connected residential application is provided. The design was based on commercially available equipment taking into account empirical P-V panel measurements with respect to a comprehensive meteorlogical analysis to calculate the energy harvested each year. The consumption of a reasonably-sized house was estimated to determine the number of required P-V modules taking into consideration a minimization of the total cost. An economic evaluation for the system was prepared based on the market price of the used equipment as well as the energy savings under Januray 2014 FPL electrical rate. The system demonstrates a return of the investment in just over 11 years.

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