Chapter 7

Results and Discussion

7.1 Introduction

This chapter presents and discusses results obtained using the PVONE program to design a stand-alone photovoltaic system. The results presented will range from predicting insolation at a location, to designing the PV system and evaluating its overall economic benefits. The location chosen to test the program, is Blacksburg, Virginia. This is because actual insolation data for Blacksburg is available at the Center for Energy and the Global Environment (CEAGE). The load profile used to design the system is a scaled down version of the load profile for the electrical engineering building, Whittemore Hall at Virginia Tech. This data is also available at CEAGE. The load profile was scaled down to reflect typical load profiles anticipated for small commercial buildings. The results presented below were obtained by running the program as shown in figure 6.1 on page 35. The results obtained from running the block, PV1, are shown in Appendix B. For a complete listing of the input variables used to obtain the results presented in this chapter, see Appendix B.

7.2 Case Study

The PVONE program was used in several case studies to obtain the results presented in this chapter. The case study was done in two categories, Insolation and PV System Design.

1. Insolation: Under this category, five cases are studied for both Flat and Tilt collectors, located in Blacksburg, Virginia. The cases are;

- **Case 1 - Instantaneous Insolation:** This is the amount of insolation available at a specific time and day of the year.
- **Case 2 - Total Insolation:** This is the amount of insolation available for a specified time interval on a given day.
- **Case 3 - Daily Insolation:** This is the total amount of insolation available under clear sky conditions for all the days in a month of the year.
- **Case 4 - Range of Insolation Levels:** It determines how the days of a month will be classified based on their insolation levels.

Case 5 - Predicted Insolation: This is the total amount of insolation available for the days in a month based on how the days have been classified.

2. PV System Design: Under this category, three cases on how a photovoltaic system is designed were studied based on average daily insolation. The module chosen for this study is, Arco Solar M55, photovoltaic module. The cases studied are:

- **Case 1 - Maximum Daily Load:** The PV system will be designed based on the maximum load for a typical day.

- **Case 2 - Average Daily Load:** The PV system will be designed based on the average load for a typical day.

- **Case 3 - Minimum Daily Load:** The PV system will be designed based on the minimum load for a typical day.

7.3 Predicted Insolation - Flat Collector

The results presented in this section were obtained using the PVONE program with Blacksburg, Virginia as the test site. The values obtained represent insolation predicted under clear sky conditions. Table 7.1 shows the instantaneous insolation predicted at 4.00 pm on April 10. Table 7.2 shows the total insolation predicted between 11.00 am and 12:50 pm on April 10. Table 7.3 shows the daily insolation predicted and the overall total insolation available for the month of April. The approximate sunrise and sunset times are also shown. The total insolation available for each month of the year as well as the total annual insolation is shown in Table 7.4. By implementing the standard classification criteria, Table 7.5 shows the range of insolation levels that will be used to classify the days in the month of April. Table 7.6 shows how the days in the month of April have been classified and a new set of insolation values has been predicted for the days based on their classification. The percentage error computed in the last column is between the predicted insolation and the actual insolation values.

7.3.1 Case 1 Instantaneous Insolation

Table 7.1. Instantaneous Insolation (KWh/m^2) For A Flat Collector

INSTANTANEOUS INSOLATION ESTIMATE FOR A SPECIFIC DAY AND TIME FOR A FLAT COLLECTOR		
MONTH		APRIL
JULIAN DAY	TIME	INSTANTANEOUS INSOLATION
100	16.00	0.581

7.3.2 Case 2 Total Insolation

Table 7.2. Total Insolation (KWh/m^2) For A Flat Collector

TOTAL INSOLATION ESTIMATE FOR A SPECIFIC TIME INTERVAL FOR A FLAT COLLECTOR			
MONTH			APRIL
JULIAN DAY	TIME		TOTAL INSOLATION
	T2	T3	
100	11.00	12.50	1.451

7.3.3 Case 3-1 Daily Insolation

Table 7.3. Daily Insolation Estimate

:DAILY INSOLATION ESTIMATE IN KILOWATT HOUR
:PER SQUARE METER FOR A FLAT PLATE COLLECTOR

MONTH	LATITUDE	LONGITUDE
APRIL	37.14 DEG	80.24 DEG

DAY #	JULIAN DAY	SUNRISE HOUR	SUNSET HOUR	DAILY INSOL
1	91	6:13	18:37	6.225
2	92	6:11	18:38	6.275
3	93	6:10	18:39	6.325
4	94	6:08	18:40	6.373
5	95	6:07	18:41	6.422
6	96	6:05	18:42	6.470
7	97	6:04	18:43	6.518
8	98	6:02	18:44	6.565
9	99	6:01	18:45	6.611
10	100	5:59	18:45	6.657
11	101	5:58	18:46	6.703
12	102	5:56	18:47	6.748
13	103	5:55	18:48	6.792
14	104	5:54	18:49	6.836
15	105	5:52	18:50	6.880
16	106	5:51	18:51	6.923
17	107	5:49	18:52	6.965
18	108	5:48	18:53	7.006
19	109	5:47	18:54	7.048
20	110	5:45	18:54	7.088
21	111	5:44	18:55	7.128
22	112	5:43	18:56	7.167
23	113	5:41	18:57	7.206
24	114	5:40	18:58	7.244
25	115	5:39	18:59	7.281
26	116	5:37	19:00	7.318
27	117	5:36	19:01	7.354
28	118	5:35	19:02	7.389
29	119	5:34	19:03	7.424
30	120	5:33	19:04	7.458

TOTAL MONTHLY INSOLATION (KWH/SQ.METER) 206.396

7.3.4 Case 3 - 2 Annual Insolation

Table 7.4. Annual Insolation Under Clear Sky Conditions

MONTH	TOTAL INSOLATION
JANUARY	87.647
FEBRUARY	108.614
MARCH	166.955
APRIL	206.396
MAY	244.360
JUNE	248.045
JULY	249.490
AUGUST	223.892
SEPTEMBER	176.512
OCTOBER	134.106
NOVEMBER	91.964
DECEMBER	78.040
TOTAL ANNUAL INSOLATION (IN KWH/SQ. METERS)	2016.022

7.3.5 Case 4 Range of Insolation Levels

Table 7.5. Range of Insolation Levels For A Flat Collector

CLASSIFICATION OF DAYS OF THE MONTH BY DAY TYPE FLAT PLATE COLLECTOR ANALYSIS		
MONTH	APRIL (KWh/SQ.METER)	
DAY TYPE		
SUNNY	>= 6.657	
MOSTLY SUNNY	>= 5.992	< 6.657
PARTLY SUNNY	>= 4.993	< 5.992
PARTLY CLOUDY	>= 3.994	< 4.993
CLOUDY	>= 2.996	< 3.994
OVERCAST	>= 1.997	< 2.996
RAIN/SNOW	< 1.997	

7.3.6 Case 5 Predicted Insolation

Table 7.6. Predicted and Actual Insolation

DAILY INSOLATION PREDICTED IN KILOWATT HOUR PER SQUARE METER FOR A FLAT COLLECTOR

MONTH	LATITUDE	LONGITUDE	YEAR
APRIL	37.14 DEG	80.24 DEG	1990

DAY TYPE	JULIAN DAY	INSOLATION (CLEAR SKY)	INSOLATION (PREDICTED)	INSOLATION (ACTUAL)	PERCENTAGE ERROR
SUNNY					
	95	6.422	7.064	6.948	1.67
	97	6.518	7.169	6.892	4.02
	98	6.565	7.221	7.293	0.99
	103	6.792	7.472	6.661	12.17
	108	7.006	7.707	7.495	2.83
	109	7.048	7.752	6.723	15.31
	112	7.167	7.167	7.114	0.75
	113	7.206	7.206	7.339	1.82
	114	7.244	7.244	6.908	4.86
	117	7.354	7.354	7.026	4.66
MOSTLY SUNNY					
	99	6.611	6.281	6.505	3.45
	115	7.281	6.553	6.143	6.67
	116	7.318	6.586	6.404	2.84
PARTLY SUNNY					
	102	6.748	5.567	5.269	5.66
	104	6.836	5.640	5.513	2.30
	105	6.880	5.676	5.003	13.45
	106	6.923	5.711	5.892	3.07
PARTLY CLOUDY					
	91	6.225	4.202	3.998	5.11
	92	6.275	4.236	4.683	9.55
	94	6.373	4.302	4.169	3.19
	101	6.703	4.524	4.169	8.53
	120	7.458	4.475	4.797	6.72

Table 7.6. Predicted and Actual Insolation (Continued)

CLOUDY					
	110	7.088	3.721	3.399	9.48
	119	7.424	3.341	3.958	15.60
OVERCAST					
	100	6.657	2.496	2.659	6.11
	118	7.389	2.217	2.785	20.41
RAIN/SNOW					
	93	6.325	1.265	1.403	9.84
	96	6.470	1.294	0.773	67.40
	107	6.965	1.393	1.585	12.12
	111	7.128	1.426	1.441	1.07
TOTAL MONTHLY INSOLATION IN KWH/SQ.METERS & PERCENTAGE ERROR					
		206.396	154.260	150.947	2.19

7.4 Predicted Insolation - Tilt Collector

The results presented in this section were obtained using the PVONE program with Blacksburg, Virginia as the test site. The values obtained represent insolation predicted under clear sky conditions. The azimuth angle used to obtain these results was 10.14 degrees resulting in a tilt angle of 27.00 degrees. Table 7.7 shows the instantaneous insolation predicted at 4.00 pm on April 10. Table 7.8 shows the total insolation predicted between 11.00 am and 12.50 pm on April 10. Table 7.9 shows the daily insolation predicted and the overall total insolation available for the month of April. The approximate sunrise and sunset times are shown as well. By implementing the standard classification criteria, Table 7.10 shows the range of insolation levels that will be used to classify the days in the month of April. Table 7.11 shows how the days in the month of April have been classified and a new set of insolation has been predicted. The percentage error computed in the last column is between the predicted insolation and the actual insolation values.

7.4.1 Case 1 Instantaneous Insolation

Table 7.7. Instantaneous Insolation (KWh/m^2) For A Tilt Collector

INSTANTANEOUS INSOLATION ESTIMATE FOR A SPECIFIC DAY AND TIME FOR A TILT COLLECTOR			
MONTH		APRIL	
JULIAN DAY	TIME	TILT ANGLE	INSTANTANEOUS INSOLATION
100	16.00	27.00	0.644

7.4.2 Case 2 Total Insolation

Table 7.8. Total Insolation (KWh/m^2) For A Tilt Collector

TOTAL INSOLATION ESTIMATE FOR A SPECIFIC TIME INTERVAL FOR A TILT PLATE COLLECTOR				
MONTH			APRIL	
JULIAN DAY	TIME T4	TIME T5	TILT ANGLE	TOTAL INSOLATION
100	11.00	12:50	27.00	1.626

7.4.3 Case 3 Daily Insolation

Table 7.9. Daily Insolation Estimate For A Tilt Collector

DAILY INSOLATION ESTIMATE IN KILOWATT HOUR PER SQUARE METER FOR A TILT PLATE COLLECTOR

MONTH	LATITUDE	LONGITUDE	TILT ANGLE
APRIL	37.14 DEG	80.24 DEG	27.00 DEG

DAY #	JULIAN Day	SUNRISE HOUR	SUNSET HOUR	DAILY INSOLATION
1	91	6:13	18:37	7.226
2	92	6:11	18:38	7.240
3	93	6:10	18:39	7.254
4	94	6:08	18:40	7.268
5	95	6:07	18:41	7.281
6	96	6:05	18:42	7.293
7	97	6:04	18:43	7.305
8	98	6:02	18:44	7.316
9	99	6:01	18:45	7.327
10	100	5:59	18:45	7.337
11	101	5:58	18:46	7.347
12	102	5:56	18:47	7.356
13	103	5:55	18:48	7.365
14	104	5:54	18:49	7.373
15	105	5:52	18:50	7.381
16	106	5:51	18:49	7.388
17	107	5:49	18:52	7.395
18	108	5:48	18:53	7.401
19	109	5:47	18:54	7.407
20	110	5:45	18:54	7.412
21	111	5:44	18:55	7.417
22	112	5:43	18:56	7.421
23	113	5:41	18:57	7.425
24	114	5:40	18:58	7.429
25	115	5:39	18:59	7.432
26	116	5:37	19:00	7.435
27	117	5:36	19:01	7.438
28	118	5:35	19:02	7.440
29	119	5:34	19:03	7.441
30	120	5:33	19:04	7.443

TOTAL MONTHLY INSOLATION (KWH/SQ.METER) 220.994

7.4.4 Case 4 Range of Insolation Levels

Table 7.10. Range of Insolation Levels For A Tilt Collector

CLASSIFICATION OF DAYS OF THE MONTH BY DAY TYPE
TILT PLATE COLLECTOR ANALYSIS

MONTH	APRIL (KWh/SQ.METER)	
DAY TYPE		
SUNNY	>= 7.337	
MOSTLY SUNNY	>= 6.604	< 7.337
PARTLY SUNNY	>= 5.503	< 6.604
PARTLY CLOUDY	>= 4.402	< 5.503
CLOUDY	>= 3.302	< 4.402
OVERCAST	>= 2.201	< 3.302
RAIN/SNOW	< 2.201	

7.4.5 Case 5 Predicted Insolation

Table 7.11. Predicted and Actual Insolation

DAILY INSOLATION PREDICTED IN KILOWATT HOUR PER SQUARE METER FOR A TILT COLLECTOR

MONTH	LATITUDE	LONGITUDE	YEAR	TILT ANGLE
APRIL	37.14 DEG	80.24 DEG	1990	27.00

DAY TYPE	JULIAN DAY	INSOLATION (CLEAR SKY)	INSOLATION (PREDICTED)	INSOLATION (ACTUAL)	PERCENTAGE ERROR
SUNNY					
	108	7.401	8.141	7.495	8.62
	113	7.425	7.425	7.339	1.18
MOSTLY SUNNY					
	95	7.281	6.917	6.948	0.45
	97	7.305	6.940	6.892	0.69
	98	7.316	6.950	7.293	4.70
	103	7.365	6.997	6.661	5.04
	109	7.407	7.036	6.723	4.66
	112	7.421	6.679	7.114	6.11
	114	7.429	6.686	6.908	3.21
	117	7.438	6.694	7.026	4.73
PARTLY SUNNY					
	99	7.327	6.045	6.505	7.07
	104	7.373	6.083	5.513	10.33
	106	7.388	6.095	5.892	3.45
	115	7.432	5.574	6.143	9.26
	116	7.435	5.576	6.404	12.92
PARTLY CLOUDY					
	92	7.240	4.887	4.683	4.36
	102	7.356	4.965	5.269	5.76
	105	7.381	4.982	5.003	0.42
	120	7.443	5.024	4.797	4.73

Table 7.11. Predicted and Actual Insolation (Continued)

CLOUDY					
	91	7.226	3.794	3.998	5.11
	94	7.268	3.816	4.169	8.48
	101	7.347	3.857	4.169	7.48
	110	7.412	3.891	3.399	14.48
	119	7.441	3.907	3.958	1.29
OVERCAST					
	100	7.337	2.751	2.659	3.48
	118	7.440	2.232	2.785	19.86
RAIN/ SNOW					
	93	7.254	1.451	1.403	3.41
	96	7.293	1.459	0.773	88.70
	107	7.395	1.479	1.585	6.69
	111	7.417	1.483	1.441	2.94
TOTAL MONTHLY INSOLATION IN KWH/SQ.METERS & PERCENTAGE ERROR					
		220.994	149.817	150.947	0.75

7.5 Discussion on Insolation

1 Instantaneous Insolation: From the PVONE program, the instantaneous insolation predicted for Blacksburg under clear sky condition on April 10 at 4.00 pm was 0.581 KWh/m^2 for a flat collector and 0.644 KWh/m^2 for a tilt collector. By tilting the collector, an increase of 10.84% in the amount of instantaneous collected in Blacksburg was obtained. On April 10, 1990, the actual instantaneous insolation measured for Blacksburg at 4.00 pm on a flat collector was 0.648 KWh/$m^2$and on a tilt collector, it was 0.693 KWh/m^2. The instantaneous insolation for a flat collector was within 10.34% of the actual value while the instantaneous insolation obtained using a tilt collector was within 7.1% of the actual value.

2 Total Insolation: On April 10, the total insolation predicted by the PVONE program in Blacksburg, from 11:00 am to 12:50 pm for a flat collector was 1.451 KWh/m^2 and 1.626 KWh/m^2 for a tilt collector. By tilting the collector, a net increase of 12.1% in total insolation that was obtained. The actual total insolation measured on April 10, 1990, during the above mentioned time interval was 1.719 KWh/m^2 for a flat collector and 1.882 KWh/m^2 for a tilt collector. The total insolation obtained using a flat collector was within 15.6% of the actual value while the total insolation obtained using a tilt collector was within 13.6% of the actual value.

3 Daily Insolation: A net increase of 7.1% in the amount of insolation predicted in April was obtained when the collector was tilted. The predicted sunrise and the sunset times are in hours and minutes. Note that by April 7, the daylight saving time will already be in effect for locations in the northern hemisphere. As a result, the sunrise time on April 10, becomes 6:59 am and the sunset time becomes 7:44 pm. Observe that the amount of insolation is increasing from the first day of the month through the last day. This situation is valid only if all the days in the month can be guaranteed as sunny days. However, this is rarely the case as we have experienced in our daily lives. There will be days that will be cloudy, overcast, rainy, partly sunny, mostly sunny and partly cloudy. The insolation that will be available on such days, will be less than the insolation predicted in the given tables. It is at this point that the generic rules discussed in chapter 2 become very important. If a designer of photovoltaic systems can only predict insolation under clear sky conditions, then the system that will be designed under such conditions may be too small because the amount of insolation available was overestimated. For example, Table 7.4 shows the monthly and annual total insolation that is predicted for Blacksburg by using a flat collector. The annual total insolation predicted is 2016.022 KWh/m^2, which is significantly higher than the actual value obtained for 1990, which was 1467.492 KWh/m^2. Actual insolation is the insolation recorded under, sunny, mostly sunny, partly sunny, cloudy, partly cloudy, overcast and rain or snow sky conditions. The predicted value gives an average daily insolation of 5.523 KWh/day and the actual value in 1990 was 4.021 KWh/day. If both values are used to size a PV system for the same load demand, the predicted value will result in a smaller system compared to a system sized using the actual value. On the other hand, if the system is designed based on the

minimum insolation that is predicted, the system may be oversized, thereby increasing the overall cost of the system and the project may be deemed infeasible. To get a better handle on the amount of insolation available at a location, the seven group classification [15], discussed in chapter 2, has been programmed. The seven group classification was used to determine the range of insolation levels for a given month based on the type of collector used.

4 Range of Insolation Levels: The range of insolation levels depends on the type of collector used at the location. If the collector is tilted, the amount of insolation collected is increased as discussed earlier. This means, the insolation levels for the various day type will be higher than insolation levels for the same day type if a flat collector is used. For example, a cloudy in April in Blacksburg will be a day having insolation greater than or equal 2.996 KWh/m^2 but less than 3.994 KWh/m^2 if a flat collector is used. For a tilt collector, a cloudy day will be a day having insolation greater than or equal to 3.302 KWh/m^2 but less than 4.402 KWh/m^2.

5 Predicted Insolation: Based on the insolation levels determined for the various day types, the PVONE program will search the insolation data provided for the month and pick out the Julian days that conform to the different ranges of insolation levels. The program will then assign these numbers to the predicted insolation under clear sky conditions. After successfully assigning these numbers, the program will execute a series of subroutines based on the multipliers for adjusting clear sky insolation, given in Table 2.2 on page 12 and then calculates the percentage error between the new predicted insolation and the actual insolation. Results obtained are shown on Tables 7.6 and 7.11 for flat and tilt collectors respectively. In both cases, the insolation predicted under clear sky conditions is significantly reduced. In the case of a flat collector, there was a 25.26% decrease between the clear sky insolation and the predicted insolation and for the tilt collector, there was a decrease of 32.21%. Shown in the fifth columns of both tables, is the percentage error between the predicted insolation obtained using the seven group classification and the generic rules, and the actual insolation for each day of the month. A comparison is also made between the total predicted insolation and the total actual insolation. For the flat collector, the percentage error was 2.19% and for the tilt collector, the percentage error was 0.75%.

The tilt collector had a lower percentage error because the tilt angle used was the recommended angle for the month of April. If the tilt angle is further decreased, there is no significant gain in the amount of insolation collected. If the tilt angle is greater than the latitude, there is a reduction in the amount of insolation obtained. This observation is consistent with the recommendation for tilting a collector in April [1].

7.6 Photovoltaic System Design

This section of the research presents results obtained when the PVONE program was used to design three PV systems. The systems designed were based on using the maximum daily load, the average daily load, and the minimum daily load as the system load respectively. All the systems were designed based on the average daily insolation in Blacksburg. The module chosen to design these systems was Arco Solar M 55 photovoltaic module. The characteristics of the chosen module are shown in Table 7.12 below.

Table 7.12. Characteristics of Arco Solar M55 Module

PHOTOVOLTAIC MODULE CHARACTERISTICS		
RATED POWER	53.00	WATTS
AREA OF MODULE	0.427	SQ.METERS
CURRENT AT LOAD	3.05	AMPS
VOLTAGE AT LOAD	17.40	VOLTS
SHORT-CIRCUIT CURRENT	3.27	AMPS
OPEN-CIRCUIT VOLTAGE	21.80	VOLTS
EFFICIENCY AT PEAK POWER	12.42	PERCENT

7.6.1 Case 1 Maximum Daily Load

The results presented in this section were obtained when the maximum daily load was used as the design load. Table 7.13 shows the PV array characteristics obtained. Figure 7.1 shows the annual PV energy output of the array and how it compares to the annual load demand. Figure 7.2 shows the daily PV energy output and how it compares to the daily load demand. From both figures it is observed that there will be time periods when the PV system is unable to meet the load demand. This implies the PV systems will need a storage system that will be able to provide enough energy during such periods. Table 7.14 shows the storage requirement for the PV array. To find out whether it is possible to implement the system that has been designed in Blacksburg, an economic analysis is performed. Table 7.15 shows the itemized cost of the major components and Table 7.16 shows the annual loan payments, the present value the net present value obtained if the system is implemented in Blacksburg.

Table 7.13. PV Array Characteristics

PV SYSTEM CHARACTERISTICS	
DESIGN LOAD	160 KWh/day
OUTPUT VOLTAGE	354 Volts
OUTPUT CURRENT	64 Amps
OUTPUT FREQUENCY	60 Hz
PV ARRAY CHARACTERISTICS	
RATED ARRAY POWER	44.78 KW
ARRAY AREA	359.73 Sq.M
NUMBER OF MODULES	845
NUMBER OF SUB-ARRAYS	5
NUMBER OF MODULES IN PARALLEL	13
NUMBER OF MODULES IN SERIES	13
SUB-ARRAY RATINGS	
PEAK POWER	11.195 KW
PEAK VOLTAGE	226.20 VOLTS
PEAK CURRENT	39.65 AMPS
OPEN-CIRCUIT VOLTAGE	283.40 VOLTS
SHORT-CIRCUIT CURRENT	42.51 AMPS

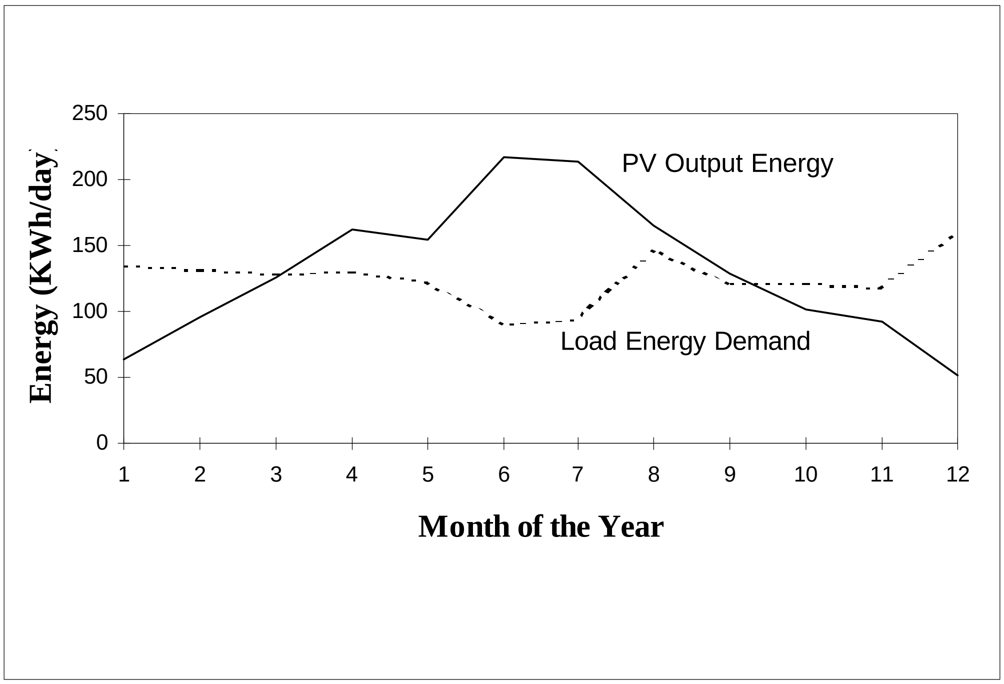

Figure 7.1. Annual PV Output Energy and Annual Load Energy Demand

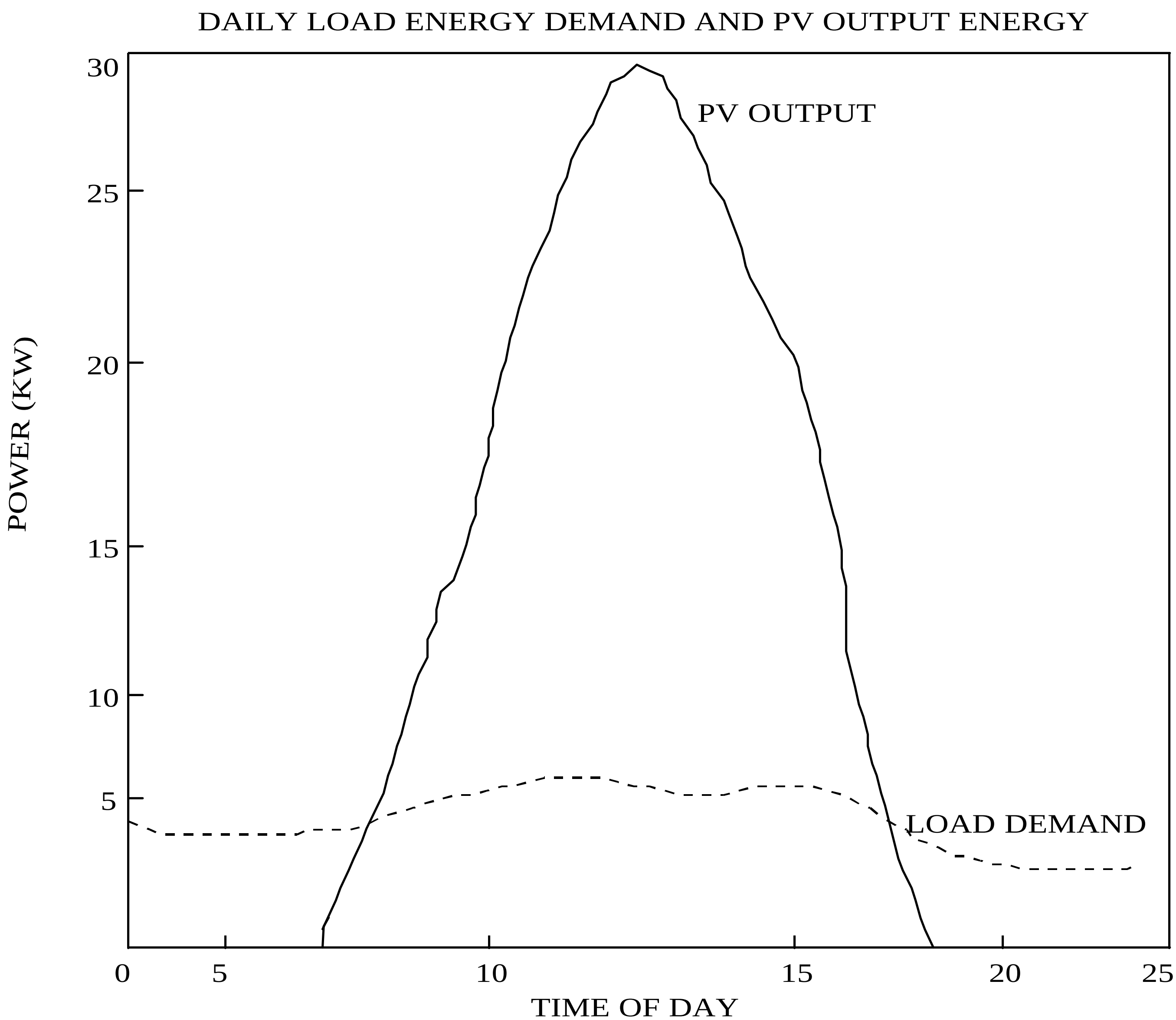

Figure 7.2. Daily PV Output Energy and Daily Load Energy Demand

Table 7.14. Storage Requirements For PV System

STORAGE REQUIREMENTS	
COLDEST 24-HOUR TEMPERATURE	-15 Deg
CAPACITY CORRECTION FACTOR	80 %
DEPTH OF DISCHARGE	60 %
SYSTEM AVAILABILITY	95 %
DAYS OF AUTONOMY DESIRED	18 Days
BATTERY CAPACITY	4688 Ah
INDIVIDUAL BATTERY CAPACITY	180 Ah
NOMINAL BATTERY VOLTAGE	6 V
NUMBER OF BATTERIES IN PARALLEL	26
NUMBER OF BATTERIES IN SERIES	26
TOTAL NUMBER OF BATTERIES	676

Table 7.15. PV System Cost

PHOTOVOLTAIC SYSTEM COST ANALYSIS	
EXPECTED LIFETIME OF SYSTEM	25 Years
MODULE COST	$ 253500.00
SUPPORT STRUCTURE COST	$ 19000.00
POWER CONDITIONER COST	$ 94800.00
BATTERY BANK COST	$ 128440.00
CONTROL ROOM COST	$ 25350.00
WIRING MATERIALS COST	$ 12675.00
DESIGN & INSTALLATION COST	$ 50700.00
LAND AREA COST	$ 38025.00
INSURANCE PREMIUM	$ 6000.00
OPERATION & MAINTENANCE	$ 6000.00
PRICE ESCALATION RATE	20 %
TAX OR DEPRECIATION CREDIT DEDUCTED	33 %
SALVAGE VALUE	$ 65000.00
TOTAL PV SYSTEM COST	$ 651844.02

Table 7.16 Present Value and Benefits For PV System

PHOTOVOLTAIC SYSTEM PRESENT VALUE ANALYSIS	
EXPECTED LIFETIME OF SYSTEM	25 Years
TOTAL PV SYSTEM COST	$ 651844.02
LOAN DOWN PAYMENT	$ 325922.01
YEARS TO PAYOFF LOAN	15 Years
LOAN DISCOUNT RATE	12.00 %
LOAN PRICE ESCALATION RATE	20.00 %
LOAN UNIFORM PRESENT WORTH	27.22
PRESENT ELECTRICITY COST	$ 0.10
ELECTRICITY PRICE ESCALATION RATE	20.00 %

ANNUAL LOAN PAYMENTS ($)	PRESENT VALUE ($)	NET PRESENT VALUE ($)
47853.25	505526.35	46973.04

7.6.2 Case 2 Average Daily Load

The results presented in this section were obtained when the average daily load was used as the design load. Table 7.17 shows the PV array characteristics obtained. Figure 7.3 shows the annual PV energy output of the array and how it compares to the annual load demand. Figure 7.4 shows the daily PV energy output and how it compares to the daily load demand. From both figures it is observed that there will be time periods when the PV system is unable to meet the load demand. This implies the PV systems will need a storage system that will be able to provide enough energy during such periods. Table 7.18 shows the storage requirement for the PV array. To find out whether it is possible to implement the system that has been designed in Blacksburg, an economic analysis is performed. Table 7.19 show the itemized cost of the major components and Table 7.20 shows the annual loan payments, the present value and the net present value obtained if the system is implemented in Blacksburg.

Table 7.17. PV Array Characteristics

PV SYSTEM CHARACTERISTICS	
DESIGN LOAD	125 KWh/day
OUTPUT VOLTAGE	300 Volts
OUTPUT CURRENT	74 Amps
OUTPUT FREQUENCY	60 Hz
PV ARRAY CHARACTERISTICS	
RATED ARRAY POWER	34.98 KW
ARRAY AREA	281.04 Sq.M
NUMBER OF MODULES	660
NUMBER OF SUB-ARRAYS	4
NUMBER OF MODULES IN PARALLEL	15
NUMBER OF MODULES IN SERIES	11
SUB-ARRAY RATINGS	
PEAK POWER	8.745 KW
PEAK VOLTAGE	191.40 VOLTS
PEAK CURRENT	45.75 AMPS
OPEN-CIRCUIT VOLTAGE	239.80 VOLTS
SHORT-CIRCUIT CURRENT	49.05 AMPS

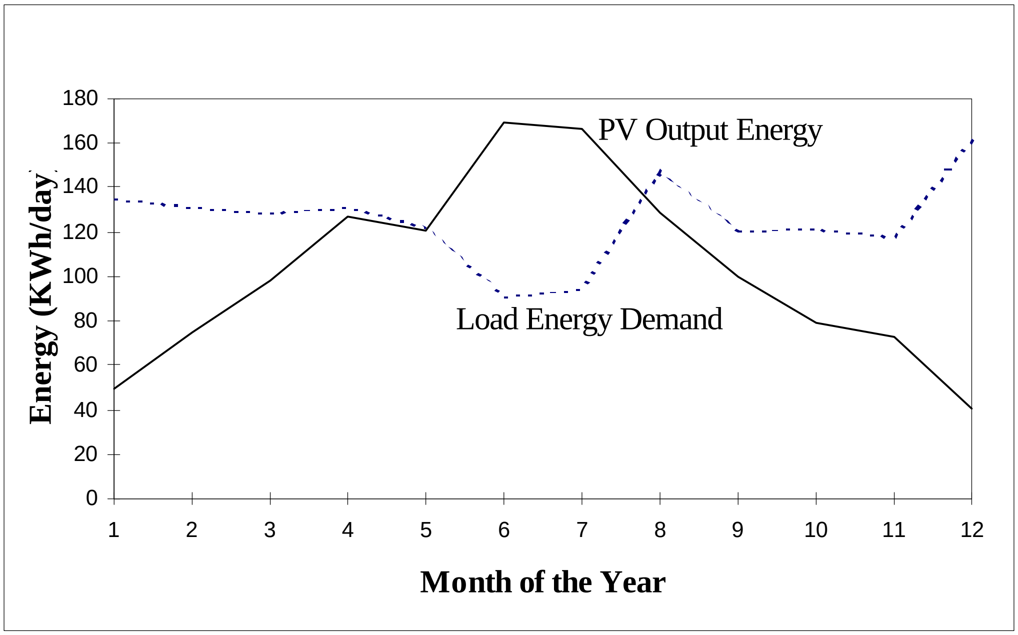

Figure 7.3. Annual PV Output Energy and Annual Load Energy Demand

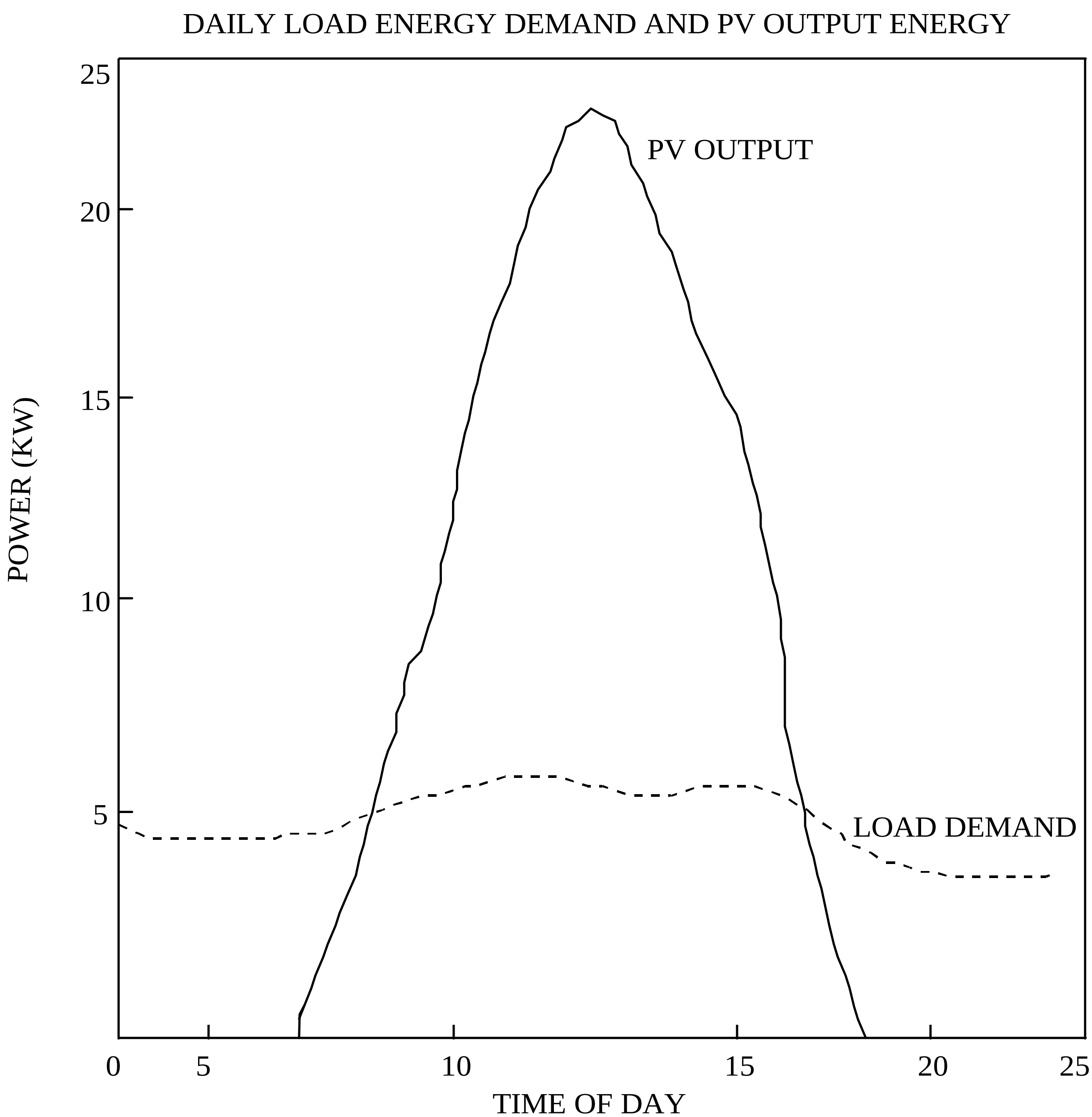

Figure 7.4. Daily PV Output Energy and Daily Load Energy Demand

Table 7.18. Storage Requirements For PV System

STORAGE REQUIREMENTS	
COLDEST 24-HOUR TEMPERATURE	-15 Deg
CAPACITY CORRECTION FACTOR	80 %
DEPTH OF DISCHARGE	60 %
SYSTEM AVAILABILITY	95 %
DAYS OF AUTONOMY DESIRED	18 Days
BATTERY CAPACITY	4688 Ah
INDIVIDUAL BATTERY CAPACITY	180 Ah
NOMINAL BATTERY VOLTAGE	6 V
NUMBER OF BATTERIES IN PARALLEL	26
NUMBER OF BATTERIES IN SERIES	22
TOTAL NUMBER OF BATTERIES	572

Table 7.19. PV System Cost

PHOTOVOLTAIC SYSTEM COST ANALYSIS	
EXPECTED LIFETIME OF SYSTEM	25 Years
MODULE COST	$ 198000.00
SUPPORT STRUCTURE COST	$ 14850.00
POWER CONDITIONER COST	$ 74250.00
BATTERY BANK COST	$ 108680.00
CONTROL ROOM COST	$ 19800.00
WIRING MATERIALS COST	$ 9900.00
DESIGN & INSTALLATION COST	$ 39600.00
LAND AREA COST	$ 29700.00
INSURANCE PREMIUM	$ 5000.00
OPERATION & MAINTENANCE	$ 5000.00
PRICE ESCALATION RATE	20 %
TAX OR DEPRECIATION CREDIT DEDUCTED	33 %
SALVAGE VALUE	$ 50000.00
TOTAL PV SYSTEM COST	$ 529984.42

Table 7.20 Present Value and Benefits For PV System

PHOTOVOLTAIC SYSTEM PRESENT VALUE ANALYSIS	
EXPECTED LIFETIME OF SYSTEM	25 Years
TOTAL PV SYSTEM COST	$ 529984.42
LOAN DOWN PAYMENT	$ 264499.21
YEARS TO PAYOFF LOAN	15 Years
LOAN DISCOUNT RATE	12.00 %
LOAN PRICE ESCALATION RATE	20.00 %
LOAN UNIFORM PRESENT WORTH	27.22
PRESENT ELECTRICITY COST	$ 0.10
ELECTRICITY PRICE ESCALATION RATE	20.00 %

ANNUAL LOAN PAYMENTS ($)	PRESENT VALUE ($)	NET PRESENT VALUE ($)
38979.66	410798.92	20841.23

7.6.3 Case 3 Minimum Daily Load

The results presented in this section were obtained when the minimum daily load was used as the design load. Table 7.21 shows the PV array characteristics obtained. Figure 7.5 shows the annual PV energy output of the array and how it compares to the annual load demand. Figure 7.6 shows the daily PV energy output and how it compares to the daily load demand. From both figures it is observed that there will be time periods when the PV system is unable to meet the load demand. This implies the PV system will need a storage system that will be able to provide enough energy during such periods. Table 7.22 shows the storage requirement for the PV array. To find out whether it is possible to implement the system that has been designed in Blacksburg, an economic analysis is performed. Table 7.23 shows the itemized cost of the major components and Table 7.24 shows the annual loan payments, the present value and the net present value obtained if the system is implemented in Blacksburg.

Table 7.21. PV Array Characteristics

PV SYSTEM CHARACTERISTICS	
DESIGN LOAD	91 KWh/day
OUTPUT VOLTAGE	272 Volts
OUTPUT CURRENT	59 Amps
OUTPUT FREQUENCY	60 Hz

PV ARRAY CHARACTERISTICS	
RATED ARRAY POWER	25.44 KW
ARRAY AREA	204.59 Sq.M
NUMBER OF MODULES	480
NUMBER OF SUB-ARRAYS	4
NUMBER OF MODULES IN PARALLEL	12
NUMBER OF MODULES IN SERIES	10

SUB-ARRAY RATINGS	
PEAK POWER	6.360 KW
PEAK VOLTAGE	174.00 VOLTS
PEAK CURRENT	36.60 AMPS
OPEN-CIRCUIT VOLTAGE	218.00 VOLTS
SHORT-CIRCUIT CURRENT	39.24 AMPS

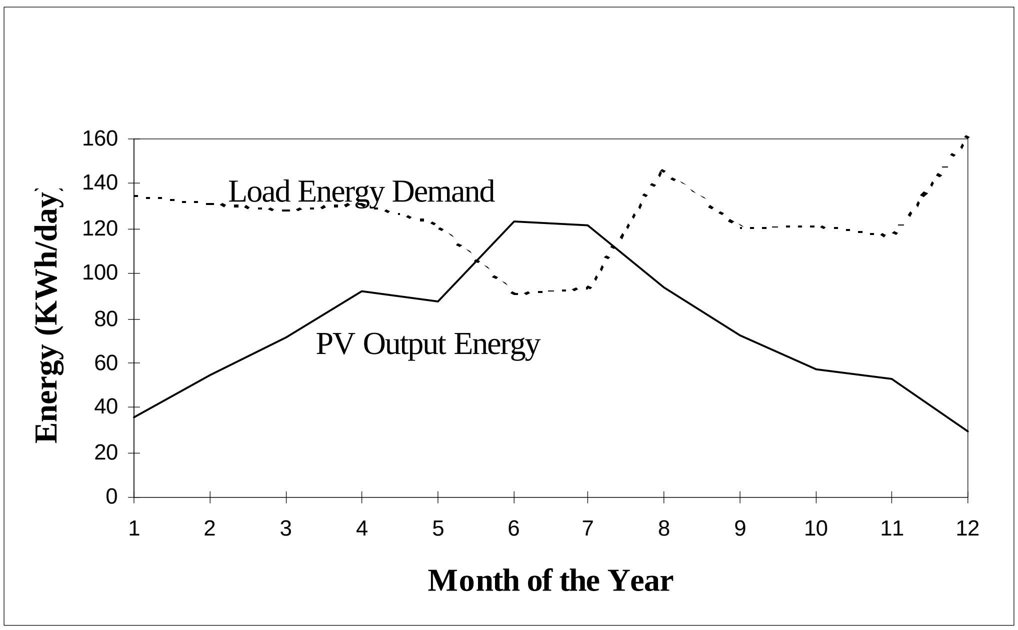

Figure 7.5. Annual PV Output Energy and Annual Load Energy Demand

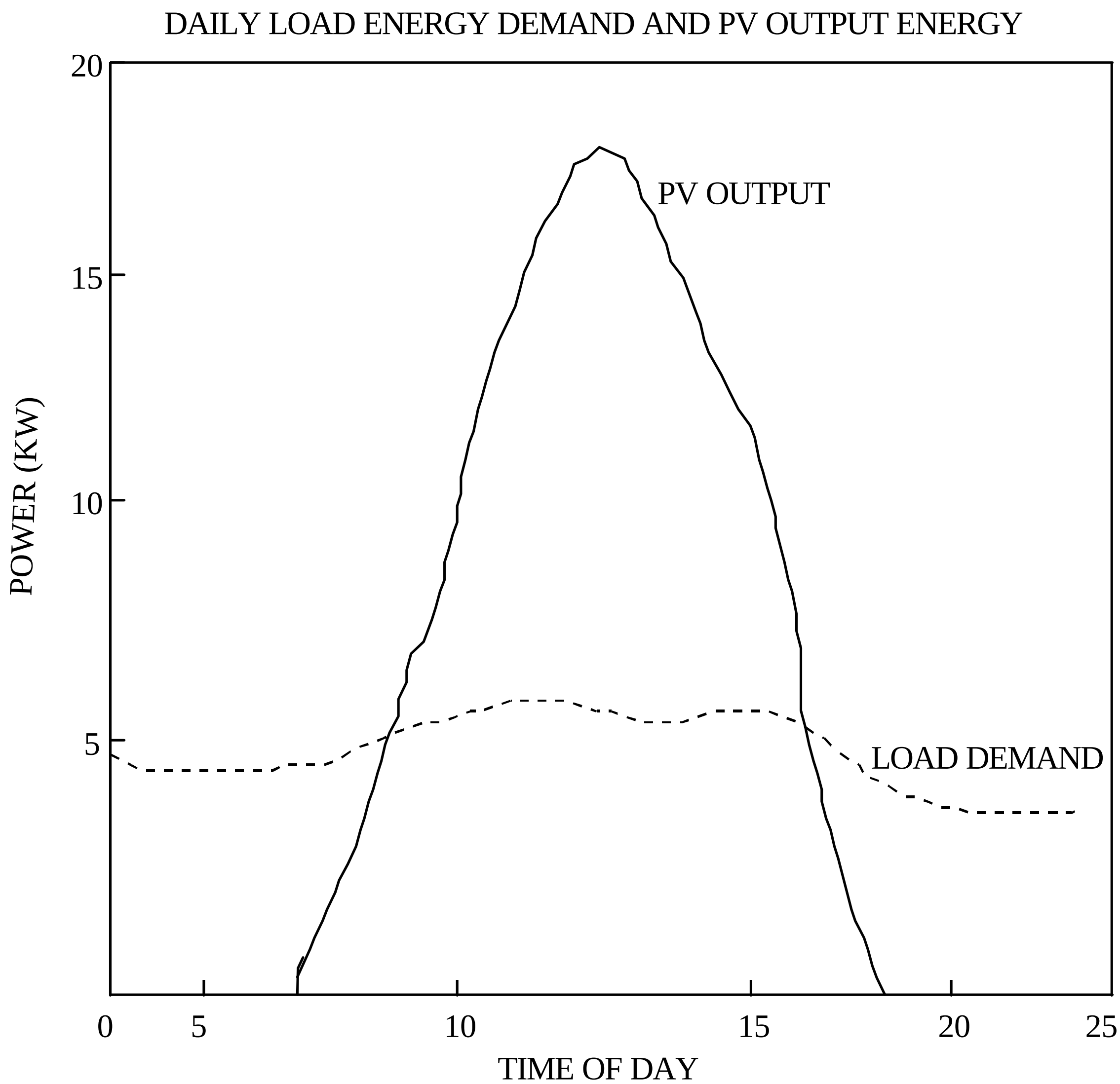

Figure 7.6. Daily PV Output Energy and Daily Load Energy Demand

Table 7.22. Storage Requirements For PV System

STORAGE REQUIREMENTS	
COLDEST 24-HOUR TEMPERATURE	-15 Deg
CAPACITY CORRECTION FACTOR	80 %
DEPTH OF DISCHARGE	60 %
SYSTEM AVAILABILITY	95 %
DAYS OF AUTONOMY DESIRED	18 Days
BATTERY CAPACITY	4688 Ah
INDIVIDUAL BATTERY CAPACITY	180 Ah
NOMINAL BATTERY VOLTAGE	6 V
NUMBER OF BATTERIES IN PARALLEL	26
NUMBER OF BATTERIES IN SERIES	20
TOTAL NUMBER OF BATTERIES	520

Table 7.23. PV System Cost

PHOTOVOLTAIC SYSTEM COST ANALYSIS	
EXPECTED LIFETIME OF SYSTEM	25 Years
MODULE COST	$ 144000.00
SUPPORT STRUCTURE COST	$ 10800.00
POWER CONDITIONER COST	$ 54000.00
BATTERY BANK COST	$ 98800.00
CONTROL ROOM COST	$ 14400.00
WIRING MATERIALS COST	$ 7200.00
DESIGN & INSTALLATION COST	$ 28800.00
LAND AREA COST	$ 21600.00
INSURANCE PREMIUM	$ 4000.00
OPERATION & MAINTENANCE	$ 4000.00
PRICE ESCALATION RATE	20.0 %
TAX OR DEPRECIATION CREDIT DEDUCTED	33.0 %
SALVAGE VALUE	$ 40000.00
TOTAL PV SYSTEM COST	$ 413169.92

Table 7.24 Present Value and Benefits For PV System

PHOTOVOLTAIC SYSTEM PRESENT VALUE ANALYSIS

EXPECTED LIFETIME OF SYSTEM	25 Years
TOTAL PV SYSTEM COST	$ 413169.92
LOAN DOWN PAYMENT	$ 206584.96
YEARS TO PAYOFF LOAN	15 Years
LOAN DISCOUNT RATE	12.00 %
LOAN PRICE ESCALATION RATE	20.00 %
LOAN UNIFORM PRESENT WORTH	27.22
PRESENT ELECTRICITY COST	$ 0.10
ELECTRICITY PRICE ESCALATION RATE	20.00 %

ANNUAL LOAN PAYMENTS ($)	PRESENT VALUE ($)	NET PRESENT VALUE ($)
30331.68	320426.78	-6192.75

7.7 Discussion on PV System Design

This section of the research discusses results obtained using the PVONE program to design a photovoltaic system. The three PV systems that have been designed are based on the maximum, average, and minimum daily load demand and on the average daily insolation. As discussed earlier, sizing a PV system based on the maximum daily insolation results in a smaller system. Alternatively, sizing the system based on the minimum daily insolation results in a much larger system that may be too costly to implement. It is for this reason, all the systems designed above were based on the average daily insolation.

7.7.1 Arco Solar M55 PV Module

The module chosen to size all PV systems designed above, is Arco Solar M55 photovoltaic module. This module was chosen because of its durability and ability to withstand the most extreme weather conditions and continue to perform efficiently. The overriding factor for selecting this module, is its high efficiency of 12.42 percent and available multi-year performance data collected at the Virginia Tech Solar Test Facility.

7.7.2 Photovoltaic Array

The results for all three PV array characteristics were obtained by running block 9 of the PVONE program. The number of modules increases as the load energy demand increases. The array area also increases as the load energy demand increases. After the number of modules was determined, the designer must decide on how to configure the system. That is, the number of sub-arrays, the number of modules in parallel and the number of modules in series will depend on the designer. Based on the designer’s specifications, the program will determine the sub-array ratings and the PV system characteristics. The output frequency is based on the type of loads that will be served by the system. The open-circuit voltage of the array is the open-circuit voltage of the module multiplied by the number of modules in series. The short-circuit current is the array short-circuit current of the module multiplied by the number of modules in series. The output voltage of the array is the open-circuit voltage multiplied by a factor of 1.25 and the output current of the array is the short-circuit current multiplied by a factor of 1.5. Multiplying by these factors will allow the designer to specify the correct power conditioning unit and also allow for some growth in load demand for the system.

7.7.3 Energy Output

After the PV array characteristics were determined, the annual energy output of the array was determined and then compared to annual load energy demand. When the system was sized based on the maximum daily load, the size of the PV array determined was able to supply the load energy demand from March through August with excess energy stored in the battery system. When the load demand is a minimum the PV output energy is a maximum and this was observed in June and July. From October through February, the PV system is deficient in meeting the total monthly load demand. This does not mean that the system will not be able to meet the load demand for some days. There will be days during these months that the system will meet the daily load energy demand and even have excess energy to store in the batteries. The annual energy output of the system satisfied the annual load energy demand. When the PV system was designed based on the average daily load, the system was able to meet the load energy demand from May through August with the excess energy was stored in the battery system. From October through April, the PV system was deficient in meeting the load energy demand. When the PV system was sized based on the minimum daily load, the system designed was capable of meeting the load demand only in June and July, the months with the lowest load energy demand and highest energy outputs. The system designed was deficient for the rest of the months. The numerical comparison of the annual PV output energy and the annual load energy demand is shown on Tables B-1, B-2, and B-3 in appendix B.

Another comparison was made between the daily load energy demand and the daily PV output energy. The daily PV output was obtained for a day expected to have very low insolation and compared to the load energy demand for all the systems designed. From the graphs obtained, only when the system is sized based on the maximum daily load, does the PV output energy satisfy the daily load energy demand. The PV output energy shown is the output energy obtained from the system between sunrise and sunset, while the daily load energy demand is from midnight through 11:00 pm.

7.7.4 Storage Requirements

The size of the storage depends on the size of the system. The system sized based on the maximum daily load has the largest storage since it produces much more excess energy than the systems sized based on the average and minimum daily load. The days of autonomy for all three systems designed was 18 days. This means the system will be able to withstand a stretch of poor weather for 18 days. Days of autonomy is normally referred to as system autonomy. The battery used in this analysis is GC12V200B lead acid batteries. This battery was chosen because it is maintenance free and best suitable for PV applications with long life. The battery is rated at 6 volts and 180 Amp hours capacity at a 20 hour rate. This means when the battery is fully charged, it can deliver a current of 9 Amps for 20 hours.

7.7.5 Economic Analysis

For a stand-alone system, the components with the largest cost are the modules, the battery bank and the power conditioning unit. For the systems that have been designed by the PVONE program, the modules account for about 40% of the total cost, the battery bank for about 20% of the total cost and the power conditioning unit accounts for about 15 % of the total cost. The remaining twenty-five percent was distributed as follows, 8% for design, labor and installation, 6% for land area, 4% for control room, 3% for support structure, 2% for wiring materials, 1% for insurance and 1% for operation and maintenance. The salvage value which is a negative cost and does not constitute part of the overall cost was estimated at 10% of the total cost. These percentage values are all within the recommended range for PV systems in North America. The expected lifetime of all the PV systems was 25 years. Present day PV systems are expected to have a lifetime of about 30 years. Note that because the system designed based on the maximum daily load has more modules, larger storage and larger power conditioning units,

its total cost is higher than the total cost of systems designed based on either the average or minimum daily load. Based on the total costs of the systems, the loan down payment was estimated at 50 percent of the total cost and the number of years required to pay off the loan was 15 years. The economic conditions assumed were the same for all three systems designed. The interest that was paid for all three systems, was 10.12 percent of the total cost. To see if the system designed had any benefits over their lifetime, the net present value was calculated. The net present value is obtained by subtracting the total cost from the system benefits. A positive net present value means that the systems will pay for themselves over their lifetime if all the criteria chosen are correct. If the net present value is negative which was the case when the minimum daily load was used to design the system, it is an indication that one or more unfavorable conditions exist for the system that has been designed. It may mean that some of the system components are too expensive, the interest rate is too high, the tax incentives are not favorable or the location suffers from insufficient sunlight. In order for the system to be beneficial at the location, certain design or cost criteria must be changed. Sometimes a combination of both design and cost criteria will have to change.