Economic feasibility analysis of photovoltaic installations in the Las Vegas Valley

Rinly Joseph

University of Nevada, Las Vegas

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ECONOMIC FEASIBILITY ANALYSIS OF
PHOTOVOLTAIC INSTALLATIONS
IN THE LAS VEGAS VALLEY

by

Rinly Joseph

Bachelor of Technology
University of Kerala, India
1988

A thesis submitted in partial fulfillment
of the requirements for the degree of

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in

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Economic Feasibility Analysis of Photovoltaic Installations in the Las Vegas Valley

by

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This thesis presents a new tool for performing an economic feasibility study of Photovoltaic (PV) power generation for Demand Side Management (DSM) as well as for a stand-alone system. The proposed analytical equations are capable of accommodating the constant changes in the system parameters due to the advances in new technologies and changes in electric utility industry. An economic feasibility study is conducted for photovoltaic systems in both suburban areas and in remote locations using actual data collected by Nevada Power Company (NPC). With the present cost and cell efficiency, the study shows that the cost of the panels will have to be reduced before PV installation becomes feasible in the Las Vegas Valley. However, remote locations are feasible options if the line extension costs are high. The expressions developed are valuable when estimating future parameter values that result in an economic PV installation, and when making decisions on DSM and “green power” pricing.
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LIST OF SYMBOLS

A - Number of panels required
B - Cost/panel
C - Cost of inverter assembly
D - Cost/battery
E - Number of batteries required
F - Installation cost/panel
G - Installation cost for accessories [batteries, inverter, etc.]
H - Efficiency of solar panel
I - VA rating of panel
J - AH rating of batteries
K - Number of hours of useful sunlight/average day
L - Efficiency of battery
M - Cost of backup generation/VA
N - Efficiency of inverter
O - Life of solar panels in years
P - Estimated peak demand in VA
Q - Peak Ampere rating of the battery
R - Voltage rating of the battery
S - Interest rate
T - Social approval factor
U - Distance from nearest available power
V - Line extension cost/ft
W - Estimated average demand (VA)/hr
X - Utility generation charge/kWh
Y - Utility transmission charge/kWh
Z - Utility distribution charge/kWh
ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

The increased concern over global warming caused by the greenhouse gases led electric utilities around the globe to look for alternate sources for power generation. Meanwhile, coal fired generating plants are coming under attack by environmental groups and getting approval to build new hydro-electric or nuclear power plants is becoming more and more difficult in the recent years. These issues are leaving utilities with no other choice than to look into environmentally-friendly renewable energy sources including wind, geothermal, solar, and biomass.

Renewable energy technologies have several advantages. These include (a) a fuel source that is either free or relatively inexpensive, (b) project construction lead time can be significantly shorter than those of traditional power plants, (c) capacity can be increased incrementally to better match load growth, and (d) they are environmentally cleaner than fossil fuels. Consequently, many regulatory agencies are requiring utilities to invest in renewable energy technologies in order to plan effectively for the future. In 1997, the Nevada Assembly passed Bill No. 366, which requires utilities in Nevada to produce a minimum of 1% of the power demand using renewable sources of energy. This amounts to around 50MW by the year 2010.
Solar power is considered by many utilities as the most promising among renewable energy resources. Around 925 W/m² of radiation is available on the earth’s surface when the sun is at zenith [1]. Locally, data collected by NPC’s solar monitoring station using a Rotating Shadowband Pyrometer shows that normal insolation varies from 80 kWh/m² in January to 300 kWh/m² in July. This makes Southern Nevada a prime location for solar power generation.

Photovoltaic (PV) energy technology employs a solid-state device to directly convert sunlight into electricity. PV cells represent one of the most benign forms of electricity generation available because they comprise stand-alone systems with no fuel or cooling requirements and no environmental emissions or noise, and have proven to be a viable option for the production of modest amount of electrical power. While both grid-connected and stand-alone PV systems have been producing power in the United States since the late 1960’s, their wide application was limited due to the high production cost of the crystalline semiconductor cells itself. Recent technology improvements have reduced PV generation cost from $1.50/ kWh in 1980 to a range of $0.30-$0.40/kWh in 1993 [2]. In 1992, the total PV generation around the world was approximately 60 MW [2] and is expected to increase sharply.

While research for more efficient cells is being conducted in national labs and other institutions, utility engineers have been developing different tools for the analysis of PV systems as a Supply Side Management (SSM) option or as a Distributed Generation option. Most recent articles focus on viability and feasibility of PV generation by utilities [3]-[7].
In this thesis, a tool which will help the utility customer evaluate the feasibility of a PV installation, predict the number of years it will take to revenue justify a PV installation, and make educated decisions when participating in the utilities DSM programs and ‘green power’ options is developed.

First, a brief review of various cell technologies is presented in Chapter 2. This includes a brief history of solar cell development, solar radiation, conversion efficiency, temperature and radiation effects on PV cells and device configuration. Chapter 3 covers DSM and interface with the utility system. The main issues discussed are safety of utility crews and power quality concerns. In Chapter 4 the analytical equations for feasibility analysis are developed. These expressions take into account all parameters associated with a PV system. Some of these include, cost per panel, efficiency of solar panels, number of hours of useful sunlight, life of solar panels, estimated peak demand of the load, interest rate, and social approval factor.

Chapter 5 presents the data collected from Nevada Power Company installation in the Las Vegas area. This data was used to derive many of the present values of various parameters used in the analytical equations. The Las Vegas Valley receives around 11:30 hours of useful sunlight on an average day throughout the year, and the average efficiency of the cells are only around 38% of their rating during these hours. In Chapter 6, an economic analysis of the feasibility of PV installations is conducted using the analytical equations developed in Chapter 4 and the data presented in Chapter 5. The analysis shows that cost per panel has to come down for PV installations to become feasible in the Las Vegas area. The study also shows that any installation will become
feasible if it needs more than a certain length of power line extension. Such a critical distance can easily be calculated for a fixed load. The Thesis ends with Chapter 7 which concludes the work presented.
CHAPTER 2

PHOTOVOLTAIC TECHNOLOGY

This Chapter gives a brief introduction to the photovoltaic (PV) technology, solar radiation, ideal conversion efficiency, temperature-radiation effects, and different device configurations. The solar cell was first developed by Chapin, Fuller, and Pearson in 1954 using a diffused silicon p-n junction [1]. Today, solar cells are made using various device configurations employing single-crystal, poly-crystal, and amorphous thin-film structures.

At present, solar cells furnish the most important long-duration power supply for satellites and space vehicles. They have also been successfully employed in small-scale terrestrial applications. Recently, research and development of low-cost, flat-panel solar cells, thin-film devices, concentrator systems, and many innovative concepts have led to significant proliferation of PV installations around the world.

2.1 Solar Radiation and Ideal Conversion Efficiency:

The radiative energy output from the sun derives from a nuclear fusion reaction. In every second, about $6 \times 10^{11}$ kg of $H_2$ is converted to He and emits around $4 \times 10^{30} \text{ J}$ as electromagnetic radiation [1]. The intensity of solar radiation in free space at the average
power is about 925 W/m² at the earth’s surface. The condition when sun is at 45° above the horizon represent a satisfactory energy-weighted average for terrestrial applications, with a total incident power of 844 W/m².

The conventional solar cell, a p-n junction, has a single bandgap $E_g$. When the cell is exposed to the solar spectrum, a photon with energy less than $E_g$ makes no contribution to the cell output. A photon with energy greater than $E_g$ contributes an energy $E_g$ to the cell output, and excess over $E_g$ is wasted as heat. Fig. 2.1 shows photovoltaic effect in a p-n junction solar cell Fig. 2.1(a) shows the absorption of light by the cell, and Fig. 2.1(b) shows the diffusion of electrons and holes to produce photocurrent. [8]

**Fig. 2.1: Photovoltaic effect in a p-n junction solar cell: (a) absorption of light by the cell, (b) diffusion of electrons and holes to produce photocurrent.**

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2.2 Manufacturing of Solar Cells:

For terrestrial applications, both flat-plate and concentrator solar cell systems are used. Solar cells are manufactured using the Edge-defined Film-fed Growth (EFG) technique, the Ribbon-to-Ribbon process, and the Dendrite-Web process. Polycrystalline silicon on ceramic or on metallurgical-grade silicon is also used to reduce substrate cost. Thin-film CdS solar cells as well as amorphous Si solar cells are also important candidates for flat-plate systems [1].

Solar cells consists of a shallow p-n junction formed on the surface (by diffusion), a front ohmic contact stripe and fingers, a back ohmic contact that covers the entire back surface, and an antireflection coating on the front surface.

2.3 Temperature and Radiation Effects:

As the temperature increases, the diffusion lengths in Si and GaAs will increase and the short-circuit current density ($J_{sc}$) increases. However, output voltage ($V_{oc}$) will rapidly decrease because of the exponential dependence of the saturation current on temperature. The overall effect causes a reduction of efficiency as temperature increases [1] in contrast to popular belief.

For satellite applications, the high-energy particle radiation in outer space produces defects in semiconductors thus resulting in a reduction in solar cell power output. To improve the radiation tolerance, Lithium has been incorporated into the solar cells. The Li can diffuse and combine with radiation-induced point defects.
2.4 Device Configurations:

Many solar cell configurations have been proposed for achieving higher conversion efficiency. Some of the most common ones are briefly discussed below [1]:

2.4.1 Back Surface Field Solar Cell (BSF):

The BSF solar cell has shown much larger output voltage than conventional cells. The back of the cell has a very heavily doped region adjacent to the contact, instead of containing just a metallic ohmic contact.

2.4.2 Violet Cell:

The violet cell is fabricated with reduced surface doping concentration and smaller junction depth. This greatly improves the response at high photon energies. The violet cell has a much higher response in the violet region, a fact from which the cell’s name is derived.

2.4.3 Textured Cell:

The textured cell has pyramidal surfaces produced by anisotropic etching of <100> oriented Si surface. Light incident on the side of a pyramid will be reflected onto another pyramid instead of being lost. The reflectivity of bare Si is reduced from about 35% for flat surfaces to around 20% for textured surface. An air mass 0 condition (in space for satellites) conversion efficiency over 15% has been obtained from textured cell.
2.4.4 V-groove Multi-junction Solar Cell:

The V-groove Multi-junction cell is also produced by anisotropical etching of \(<100>\) oriented Si surface. This cell consists of many individual \(p^{-n-n^-}\) (or \(p^-p^-n^-\)) diode elements connected in series. The trapezoidal shape of the diode elements is defined by anisotropically etching \(<100>\) Si through a thermally grown silicon dioxide layer. The V-groove Multijunction cell has a fundamental collection efficiency (i.e., the ratio of the number of photons that are absorbed to the number that enter a semiconductor with \(hv > E_g\)) greater than 93% and has a conversion efficiency greater than 20%.

2.4.5 Tandem-Junction Solar Cell:

The Tandem-Junction cell combines the concept of back-surface-field cell and textured cell. The device behaves as a bipolar transistor with an uncontacted front \(n^-\) emitter. This cell has an efficiency above 20%.

2.4.6 Vertical-Junction Solar Cell:

The Vertical-Junction cell has both the junction and the metallization perpendicular to the cell surface. The diffusions and metal contacts are embedded in deeply etched grooves normal to the surface, formed by anisotropic etching of \(<110>\) silicon. This cell has a conversion efficiency of 15%.

2.4.7 Hectrojunction Solar Cell:

The Hectrojunction cell has junctions formed between two semiconductors with different energy gaps. The advantages of this cell over conventional cells include (a)
enhanced short-wavelength spectral response, (b) lower series resistance, and (c) high radiation tolerance. The projected conversion efficiency of this cell under normal conditions is over 30%.

2.4.8 Schotty-Barrier Cells:

The advantages of the Schotty-Barrier cell over conventional cells include (a) low-temperature processing, (b) adaptability to polycrystalline and thin-film solar cells, (c) high radiation resistance, and (d) high-current output. Its maximum conversion efficiency is about 25%.

2.4.9 Thin-Film Solar Cells:

In thin-film solar cells, the active semiconductor layers are polycrystalline or disordered films that have been deposited or formed on electrically active or passive substrates, such as glass, plastic, ceramic, metal, graphite or metallurgical silicon. The active layer is deposited by vapor growth, evaporation plasma, and plating.

Fig. 2.2 shows the schematic view of a thin-film Cu$_2$S-CdS solar cell. The main advantage of this is low cost. This has a conversion efficiency near 10%. [8]
Fig. 2.2 Thin-film Cu$_2$S-CdS solar cell: (a) schematic view and (b) the energy band diagram under thermal equilibrium [8].
CHAPTER 3

DEMAND SIDE MANAGEMENT & CIRCUIT DIAGRAM

In order to operate a utility system economically, one needs to manage the power generation using the Supply Side Management (SSM) technique or Demand Side Management (DSM) technique. Demand Side Management is more attractive to utilities than Supply Side Management due the absence of huge capital investments for transmission facilities. In the case of solar power, the economic feasibility of DSM is much higher due to the cost involved in the transmission line installation compared to SSM. After transmission rates are unbundled from utility rates, due to deregulation. SSM will become even less attractive.

DSM is the practice of actively involving the customer in managing the utilities load growth. Examples of such practice include the utilization of customers generation capacity to meet peak load, or as simple as requesting customers to cut down on their load during an emergency situation. In particular, the local utility company (NPC) utilizes the generation facilities of casinos, and remotely controlling the air-conditioning load of participating residential customers during system peaks. NPC is also requesting that the Public Utility Commission to allow shared-metering (two-way sale of power) for customers with solar power generation on their property. The main benefits of DSM are:
(a) capital and operating cost savings, (b) reduced emissions, and (c) improved reliability of the electricity supply.

While considering DSM, utilities should evaluate mainly three issues, the safety of the utility crew, operation and protection of PV installation, and power quality control.

3.1 Safety of Utility Crew:

This is a major concern for linemen due to possible power feedback from the customer's generation while working on outages. Even though most of the Demand-Side-Generation is low voltage, utility transformers will step this voltage up to dangerous levels thus posing a major threat in the primary system. A solution to this problem is to install reverse flow control relays or built-in safety features in the inverter assembly in a floating system. The first option is not possible in shared-metering installations due to the very nature of the system.

Utilities will have to develop a very good coordination with its customers who participate in PV program. Development of a new safety procedures and retraining of the utility crew are also required once such a program is implemented.

3.2 Operation/Protection of PV installation:

The standard protection the inverter/charger of a PV installation includes the following [9]:
• **Grid Shorted:** During power outages from the utility's side, the inverter momentarily tries to power the entire neighborhood. This condition appears as a short circuit to the inverter and causes it to reach the over current protection settings and shuts off.

• **Grid Opens:** The inverter can tell when no current is being delivered to the grid and it will disconnect. This is used when a disconnect switch is opened or the power line which feeds the installation is cut. This protective system operates instantly.

• **Islanding:** This situation occurs when the grid has failed and the network that the inverter is powering requires a power level that the inverter can supply. The built-in islanding detection circuit checks grid condition at each 60Hz cycle. The inverter monitors the utility grid and waits for it to rise a couple of volts before it begins to invert again.

• **Over / Under Frequency:** This protection will trip the system if the frequency rises above 61.5 Hz or drops below 58.5 Hz.

• **Over / Under Voltage:** This is to protect the installation from over-voltage due to an open circuit or from under-voltage caused by short circuit or islanding. The normal upper & lower limit settings for a 120 V system are 132 V and 108 V respectively.

### 3.3 Power quality control:

In floating or shared-metering applications, the key to provide an effective interface between a PV system and the local electric utility is the power conditioning subsystem (PCS), shown in Fig. 3.1, which is a part of the overall PV system, shown in Fig. 3.2. The major power quality concerns include [10]:

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• The harmonic injection of a PV into the utility, and the impact of that injection.

• The technical and economic implications to the utility of the PV system's power factor, which can be impacted by PCS design.

• The potential for voltage flicker disturbances from PV systems. Such disturbances can be costly to the utility as well as annoying to its customers.

• The appropriate response of the PV system to dynamic utility conditions, particularly the potential for islanding. This is for the protection of the PCS as well as for utility system.

The National Photovoltaic Program has done very extensive research in improving the impact of PV system on power quality. A well-designed PV system should enjoy a long and trouble-free coexistence with an interconnected utility.

FIG. 3.1 TYPICAL INTERCONNECTION DIAGRAM WITH STATIC POWER CONVERTER POWER CONDITIONING SUBSYSTEM [11].

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3.3.1 Harmonics [15]:

Like any other static power converter, the PV inverter (which converts the generated DC power to AC) generates harmonic distortion. The amount of distortion level depends on the type of inverter used. The harmonics generated by the most common inverters, namely, square-wave and pulse-width-modulated inverters, are analyzed below.
a) Square-Wave Inverters:

A thyristor converter shown in Fig. 3.3(a) operates in an inverter mode when the DC side voltage \( V_d \) is negative, thus the power flows from the DC side to the AC side. This is accomplished when the delay angle of the thyristor firing \( \alpha \) is greater than 90 but less than 180 degrees. If \( L_d \) is large enough to assume constant DC current \( i_d \), the instantaneous voltages and currents are shown in Fig. 3.3(b). The control angle \( \alpha \) is continuously adjusted so that the average DC side voltage matches that of PV generated voltage.

![Inverter Circuit Diagram](image1)

![Waveforms Diagram](image2)

**Fig. 3.4:** (A) INVERTER & (B) WAVEFORMS
If thyristor commutation is ignored, then

\[ \alpha = \cos^{-1}(E_d / V_{do}), \]  

(3.1)

where \( V_{do} \) is the maximum average rectified voltage (with \( \alpha = 0 \)), i.e.,

\[ V_{do} = (2(2)^{1/2}V_s / \pi) \leq 0.9 \, V_s \]  

(3.2)

Herein, \( V_s \) is the rms value of the AC supply voltage. Note that the resulting AC side current is a square wave with an amplitude of \( I_d \) shifted by \( \alpha \) with respect to \( V_s \). The Fourier components of such a waveform are easily determined:

\[ I_{sn} = (2(2)^{1/2}I_d / \pi n), \quad n=1,3,5,... \]  

(3.3)

The resulting total harmonic distortion:

\[ \text{THD} = 100((I_s^2 - I_{sl}^2)^{1/2}) / I_{sl} \leq 48.5 \% \]  

(3.4)

is unacceptable according to the IEEE recommended standard for harmonics limits [16]. Therefore, harmonic filters need to be installed at the inverter terminals to filter out the large low-order harmonics. In addition, the lagging displacement power factor i.e., D.P.F, is often poor thus requiring power factor correction by shunt capacitors.

When including thyristor commutation, the source inductance causes an additional voltage drop,

\[ \Delta V_d = (2wL_dI_d) / \pi \]  

(3.5)

Then \( \alpha \) should be adjusted such that

\[ E_d = 0.9V_s \cos(\alpha) - (2/\pi)wL_dI_d \]  

(3.6)

The resulting input current has essentially a trapezoidal waveform and its displacement power factor can be approximated by

\[ \text{D.P.F} = \cos(180-\alpha-(1/2)\mu), \]  

(3.7)
where $\mu$ is the commutation angle which depends on the stiffness of the AC source. The rms value of the resulting fundamental current can be obtained by equating the power on the AC and DC sides:

$$V_s I_{st} (\text{D.P.F}) = E_d I_d$$  \hspace{1cm} (3.8)

Using (3.6) and (3.7) yields

$$I_{st} = \frac{(0.9 V_s I_d \cos(\alpha) - (2/\pi)wL_s I_d^2)/(V_s \cos(180-\alpha-(\mu/2)))}{(3.9)}$$

The harmonic components can be derived by decomposing the trapezoidal current wave-shape into its Fourier components. Commutation is found to not only improve the displacement power factor, but also reduce the harmonic content. But the resulting total harmonic distortion is still unacceptable (near 35%) even for the largest practical value of commutation angle of 20 degrees. Thus harmonic filters and power factor correction capacitors are still required for square-wave inverters.

b) PWM Inverters:

PWM inverters basically suppresses the hard-to-filter low-order harmonics by turning on and off the static switches several times in each cycle. Both analog and digital methods can be used to generate the switch turn-on signals required to implement this PWM method. One common analog process generates a triangular waveform with frequency $f_s$ and an inverted sinusoidal waveform at fundamental frequency $f_0$ as shown in Fig. 3.4. A pulse is initiated at the intersection of the sinusoid with the negative slope part of the triangular wave. This pulse is terminated when the sinusoid intersects with the
positive slope part of the triangular wave. The logic must be such that the polarity of the inverter output is reversed for each half cycle.

Ideally, the result is a complete suppression of the low-order harmonics. Higher-order harmonic components occur at

\[ n = 2kr \pm 1, \quad (3.10) \]

where 'r' is an integer and 'k' is the number of pulses per half cycle. The advantage of PWM inverters is that these are high-order harmonics can be suppressed more easily and more economically by filtering elements.

Once the pulse firing angles and their duration are determined, an exact Fourier analysis can be conducted to determine the exact harmonic content. However, such a task tend to be tedious and lengthy, especially at high carrier frequency \( f_c \). An approximate analysis can be done by impulse representations as follows:

Let the discrete pulse width be defined by

\[ t_p = m \sin(2\pi f_c t) \frac{T}{2k} \quad (3.11) \]

where the pulse initial times

\[ t_i = \frac{T}{2k}(i + 0.5), \quad i = 0, 1, 2, \ldots (k-1) \quad (3.12) \]

and 'm' is the amplitude modulation ratio. Due to the quarter-wave symmetry, the coefficients of the Fourier series can be found by evaluating equation (3.13)

\[ V_n = \frac{4}{T} \int_{-T/2}^{T/2} E_p \delta(t) \sin(2\pi f_c t) \, dt \quad (3.13) \]

Substitution of (3.11) in (3.13) results in

\[ V_n = \frac{3mE_p}{k} \sum_{i=0}^{k-1} \sin(2\pi f_c t_i) \sin(2\pi n f_c t_i) \quad (3.14) \]
To illustrate the accuracy of the above method, let \( m=0.2, E_d=120 \, V \) and \( k=5 \).

Table I below shows the exact coefficients and those predicted by (3.14). Note that the results differ only very slightly.

**Table I: Lowest Order Harmonic Components of PWM Waveform.**

<table>
<thead>
<tr>
<th>Coefficient ( V_n )</th>
<th>Value (FFT)</th>
<th>Value (Eqn. 14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_1 )</td>
<td>23.98</td>
<td>24</td>
</tr>
<tr>
<td>( V_3 )</td>
<td>0.03</td>
<td>0</td>
</tr>
<tr>
<td>( V_5 )</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>( V_7 )</td>
<td>0.19</td>
<td>0</td>
</tr>
<tr>
<td>( V_9 )</td>
<td>23.05</td>
<td>24</td>
</tr>
<tr>
<td>( V_{11} )</td>
<td>-22.68</td>
<td>-24</td>
</tr>
<tr>
<td>( V_{13} )</td>
<td>0.60</td>
<td>0</td>
</tr>
<tr>
<td>( V_{15} )</td>
<td>0.21</td>
<td>0</td>
</tr>
</tbody>
</table>

**Fig. 3.5: PWM Waveforms**

---

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CHAPTER 4

ECONOMIC FEASIBILITY EQUATION

In this Chapter a series of analytical equations for feasibility analysis of PV installations are developed. Since all parameters involved in a PV installation are considered as variables in these equations, they are capable of accommodating future changes in the utility industry as well as technological developments in PV devices.

4.1 Main Factors:

The main factors involved in the feasibility study of Photovoltaic installations are:

(a) cost of installation of PV cells ($C_{\text{inst}}$),
(b) energy generated by the PV cells ($PV_{\text{op}}$),
(c) battery storage,
(d) utility rate ($U_{\text{rate}}$),
(e) life of PV cells,
(f) cost savings from Solar Power ($C_{\text{pvst}}$),
(g) distribution line extension cost, and
(h) cost of backup generation.

These factors are derived using the various symbols defined on page (iii).

4.1 a) Cost of Installation for Solar Panels:

This is a function of number panels required ($A$), cost/panel ($B$), cost of inverter assembly ($C$), cost/battery ($D$), number of batteries required ($E$), installation cost/panel ($F$), and installation cost for accessories ($G$).
\[ C_{pvinst} = (A\times B) + C + (D\times E) + (A\times F) + G. \]  \hspace{1cm} (1)

4.1 b) Energy Generated by PV Cells:

This depends on the number of panels (A), efficiency of the panels (H), rating of the panel (I), and average number of useful hours of operation per day (K).

\[ PV_{op}/\text{day} = A\times H\times I\times K/1000 \text{ kWh}. \] \hspace{1cm} (2)

4.1 c) Number of Batteries Needed:

The storage capacity of the battery installation has to be more than the energy required by the load during the night hours, \( E\times R\times J\times L\times N > W\times (24-K) \). Hence,

\[ E > (W\times (24-K))/(R\times J\times L\times N) \] \hspace{1cm} (3)

Where (W) is the estimated average demand per hour, (R) is the voltage rating of batteries, (J) is the ampere-hour rating of batteries, (L) is the efficiency of batteries, and (N) is the efficiency of the inverter. Furthermore, the battery installation should be able to handle peak load requirements (P); i.e.,

\[ E > P/(R\times Q\times L\times N). \] \hspace{1cm} (4)

where (Q) is the peak ampere rating of the battery.

4.1 d) Utility Rate:

Due to the deregulation of electrical utilities, the present rates will be replaced with an activity-based rate in the near future. The unbundled rate \( U_{rate} \) will include separate charges for generation (X), transmission (Y), and distribution (Z), i.e.,
4.1 e) Life of PV Cell:

This is the operating life of a PV installation (O) since PV cells represent the major item in an installation. The manufacturer warranty is a very good base for calculating the life expectancy of a PV cell. Most of the commercially available panels have warranty for 20 years. Hence, 20 years is considered as the life of an installation in this study.

4.1 f) Cost Savings from Solar Power:

Cost savings (C_{pvsav}) per day is the product of energy produced in (2) and the utility rate in (5), since this gives the cost of utility power saved by a PV installation:

\[ C_{pvsav/day} = (X+Y+Z)*(A*H*I*K)/1000 \]  

(6)

Recently, Nevada Power Company conducted a survey among its customers to find the willingness to buy "green power" at a higher rate. The response was very encouraging from the supporters of "green power". If one uses the social approval factor (T), which is the ratio between the cost of "green power" utility customers are willing to pay and the cost of conventional power, the resulting cost saving is:

\[ C_{pvsav/day} = (X+Y+Z)*((A*H*I*K)/1000)*T \]  

(7)

Then, the cost savings in one year yields:

\[ C_{pvsav/year} = (X+Y+Z)*((A*H*I*K)/1000)*T*365 \]  

(8)
Assuming that the utility rate is going to stay the same during the life of a PV installation, the “present worth” [12] of the cost savings during the life of an installation is calculated by:

\[ C_{pv sav} = C_{pv sav/year} \times \frac{((1+S)^{10}-1)}{S(1+S)^{10}} \]

\[ = \frac{((X+Y+Z) \times (A+H+I+K)/1000) \times T \times 365}{((1+S)^{10}-1)/S(1+S)^{10}} \]  

(9)

where (S) is the interest rate for a home equity loan.

4.1 g) Distribution Line Extension Cost:

\( L_{ext} \) is the cost the utility charges to bring power to the site from the nearest available source. This could be a new line extension or upgrading of an existing line. This includes the cost of 1-1/0 cable, trenching, backfilling, and transformer. The average cost of line extension/ft. (V) in Las Vegas is $20/ft. \( L_{ext} \) is simply defined by \( L_{ext} = U \times V \), where (U) is the distance from the nearest available power and (V) is the line extension cost per linear foot.

4.1 h) Cost of Backup Generation:

This is the cost to assure the reliability of a stand-alone system. This includes propane generator and control system. At present, the cost of backup generation is around $0.12/VA and is defined as \( G_{back} = (M \times P) \), where (M) is the cost of backup generation per VA.

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4.2 Economic Feasibility Equation:

The economic feasibility equation can be derived by developing the relationship between the cost of installation and cost savings from the installation during the life of the PV system, i.e., \( C_{\text{pv,sav}} > C_{\text{pv,inst}} \) \hspace{1cm} (10)

Substituting (1) and (9) in (10) yields,

\[
\left( \frac{(X+Y+Z)(A*H*I*K)}{1000} \right) \left( T \times 365 \right) \left( \frac{(1+S)^9 - 1}{S(1+S)^9} \right) > \]

\[
(A*B) + C + (D*E) + (A*F) + G \hspace{1cm} (11)
\]

One can also develop the number of years to recover the cost of installation (\( N_{\text{yrs}} \)) from these factors:

\[
N_{\text{yrs}} = \frac{C_{\text{pv,inst}}}{C_{\text{pv,sav}}/\text{year}}.
\]

By substituting (1) and (8) in the above expression, one finds

\[
N_{\text{yrs}} = \frac{(A*B) + C + (D*E) + (A*F) + G}{(X+Y+Z)\left( \frac{(A*H*I*K)}{1000} \right) \left( T \times 365 \right)} \hspace{1cm} (12)
\]

4.2.1 Installation in Developed Areas:

City customers normally don’t require long distribution line extension to bring utility power to the site. There are two kinds of installations in cities; those with and without battery storage for night uses:

4.2.1 a) With Battery Storage for Night Use

These are stand-alone installations which need battery backup for night. Here the feasibility equation (11) can be used; with (E) satisfying constraints (3) and (4).
4.2.1 b) Without Battery Storage:

In this case, the power generated by the PV system can be sold back to the utility during the day and utility power is utilized at night. Therefore, there is no need for battery storage system. Hence, one has to modify (11) by chopping the (D*E) term:

\[ (((X+Y+Z)*(A*H*I*K)/1000)*T*365)* ((1+S)^0-1)/S(1+S)^0) > (A*B)+C+(A*F)+G \]  

(13)

4.2.2 PV Installations in Remote Locations:

Remote locations often need long distribution line extensions or costly system upgrades, and have very little chance for refunds from the utility or future attachment fees from another customer. These line extension costs \( L_{\text{ext}} \) could run into thousands of Dollars and vary according to the distance from the nearest available power. Furthermore, generator backup is also required in these installations for assuring system reliability.

Then the feasibility equation for this case becomes;

\[ (C_{\text{pvsav}} + L_{\text{ext}}) - (G_{\text{back}} + C_{\text{pvinst}}) > 0 \]  

(14)

4.2.2 a) With Battery Storage and Generator Backup:

PV installations require backup generation and battery to maintain reliability if the utility grid is not available. Therefore the feasibility equation can be derived by expanding equation (14)
\[ (((X+Y+Z)*(A*H*I*K)/1000)*T*365)* (((1+S)°-1)/S(1+S)°) + (V*U) > (M*P) + (A*B)+C+(D*E)+(A*F)+G \] (15)

Note that the feasibility of these installations is directly proportional to the length of line extension and inversely proportional to the load.

4.2.2 b) Without Battery Storage and Backup Generation:

The main purpose of these facilities are to defer utility system upgrade for new loads or system improvements. These sites can utilize the shared-metering plan, explained earlier, with utility grid available for system reliability. Such installations don’t require any battery or generator backup. Here, the feasibility equation becomes:

\[ (((X+Y+Z)*(A*H*I*K)/1000)*T*365)* (((1+S)°-1)/S(1+S)°) + (V*U) > (A*B)+C+(A*F)+G \] (16)

Utilities can determine the minimum amount of line extension a PV system can justify from this expression, i.e., the minimum cost of line extension

\[ (L_{\text{ext, min}}) = (V*U) = ((A*B)+C+(A*F)+G) - (((X+Y+Z)*(A*H*I*K)/1000)*T*365)* (((1+S)°-1)/S(1+S)°) \] (17)

So if one knows the estimated peak demand of the installation which will provide the number of panels and accessories needed, the minimum length of line extension to justify such an installation can be calculated. Similarly, one can also find out the maximum size of an installation which can replace a costly upgrade from the above equation.
4.3 Other Applications:

4.3.1 Average Generation by the Installation ($A_{ave}$):

This gives the average production by a PV installation during a 24 hour period.

$$A_{ave} = \frac{A \cdot H \cdot I \cdot K \cdot L \cdot N}{24} \text{ Watts} \quad (18)$$

4.3.1 Number of PV Panels Needed (A):

Number of PV panels (A) can be calculated using the following equation and is a valuable tool during design of an installation.

$$A = \frac{W \cdot 24}{H \cdot I \cdot K \cdot L \cdot N} \quad (19)$$
CHAPTER 5

NPC DATA COLLECTION

The data presented in this Chapter are from solar installations of Nevada Power Company (NPC) at several locations in Las Vegas. Nevada Power Company facilities include residential roof-top shared-metered installations, residential stand-alone installations and commercial installations floating on the utility grid.

5.1 PV Sites:

The installations visited during this study are listed below according to their installation type:

- **5.1.1 Blue Diamond Site**, is located along Blue Diamond Road, approximately 9 miles west of I-15. With 24 modules, the peak output of this facility is 1.54 kW.

- **5.1.2 Kyle Canyon Site**, is located along Kyle Canyon Road, approximately 1.5 miles west of US-95. The peak generating capacity of this facility is 1.48 kW with the help of 28 modules.

- **5.1.3 Lee Canyon Site**, is located in Lee Canyon at Camp Lady of Snows. The PV system array is comprised of two 18 module subarrays mounted on fixed aluminum
• **5.1.4 Caroll Street Site**, is located west of Pecos Road (between Las Vegas Boulevard and Carey Avenue). The rated capacity of this installation is 4.1 kW.

• **5.1.5 Brown Circle Site**, is located north of Alta Drive (west of Rancho Drive.) The rated capacity of this installation is 4.1 kW.

• **5.1.6 Canoga Avenue Site**, is located west of Pecos Road (between Las Vegas Boulevard and Carey Avenue.) The rated capacity of this installation is 4.1 kW.

• **5.1.7 Heather Avenue Site**, is located west of Pecos Road (between Las Vegas Boulevard and Carey Avenue.) The rated capacity of this installation is 4.1 kW.

• **5.1.8 UNLV Site**, is located on the University of Nevada Las Vegas (UNLV) campus. The installed capacity of this station is 18 kW. This provides 3-phase power to the student recreation building using 90 panels.

The first three sites are stand-alone systems with battery and generator back up and were installed to offset huge line extension cost. Next four site are floating systems with no backup since they are located in developed area. They were installed as experimental stations to reduce system upgrade. The UNLV site is a commercial installation floating on utility grid.

For illustration purposes, the Fig. 5.1 and 5.2 show a roof-top stand-alone installation and typical inverter, battery & generator assembly, respectively.
Fig. 5.1 A TYPICAL ROOF-TOP INSTALLATION (LEE CANYON SITE).

Fig. 5.2 TYPICAL INVERTER, BATTERY & GENERATOR ASSEMBLY.
5.2 NPC Data:

The average daily output of the Carol Street site and Brown Circle site were recorded for 6 months (Feb '97 to July '97). Measured data is shown in Appendix (I-IV) and summarized in Fig. 5.3 & 5.4. This data was used to calculate the parameters contained in previous equations.

5.3 Parameter Values:

In this section, the values of all parameters used for the feasibility analysis are derived from the collected data. This will allow an accurate feasibility analysis of PV installations in Las Vegas area since NPC sites are located in various parts of the valley. These values reflect the current technology and utility rates. Therefore, the results of this data shows only the present conditions:

• Using equation (19) one can derive the number of PV panels (A) required for an installation. It is estimated that a stand-alone system with 4 kVA estimated peak demand requires 122 panels to support the load completely. For shared-metering facilities, one could design a system with fewer panels.

• The cost per panel (B) of common poly-crystalline photovoltaic modules (model # SES-P60) is $339.00 in the wholesale market [13].

• The cost of the inverter assembly (C) is around $1.00 per VA rating of the inverter.

• The cost per battery (D) is approximately $ 50.00 for the installations discussed [14].

• The number of batteries required (E) can be calculated using equations (3) & (4). The installation presented in this analysis requires 39 batteries.
### Fig. 5.3: Recorded Data from Carol Street Site

<table>
<thead>
<tr>
<th>Month</th>
<th>Total KW</th>
<th>Ave o/p / day</th>
<th>Hrs of ops / day</th>
<th>Peak o/p</th>
<th>Ave o/p per operating hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>214.6</td>
<td>13.41</td>
<td>10</td>
<td>2.48</td>
<td>1.34</td>
</tr>
<tr>
<td>March</td>
<td>501.31</td>
<td>16.17</td>
<td>11</td>
<td>2.69</td>
<td>1.47</td>
</tr>
<tr>
<td>April</td>
<td>554.07</td>
<td>18.47</td>
<td>12</td>
<td>3.08</td>
<td>1.54</td>
</tr>
<tr>
<td>May</td>
<td>584.02</td>
<td>18.83</td>
<td>12</td>
<td>2.82</td>
<td>1.57</td>
</tr>
<tr>
<td>June</td>
<td>591.58</td>
<td>19.06</td>
<td>13</td>
<td>3.01</td>
<td>1.47</td>
</tr>
<tr>
<td>July</td>
<td>292.3</td>
<td>19.49</td>
<td>13</td>
<td>2.45</td>
<td>1.50</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>16.45</td>
<td>11.5</td>
<td></td>
<td>1.42</td>
</tr>
</tbody>
</table>

Peak eff: (system) % 75.12
Ave eff: during operation (system) % 34.64
Inverter eff: % 90

### Fig. 5.4: Recorded Data From Brown Street Site

<table>
<thead>
<tr>
<th>Month</th>
<th>Total KW</th>
<th>Ave o/p / day</th>
<th>Hrs of ops / day</th>
<th>Peak o/p</th>
<th>Ave o/p per operating hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>161.51</td>
<td>14.68</td>
<td>10</td>
<td>2.72</td>
<td>1.47</td>
</tr>
<tr>
<td>March</td>
<td>552.6</td>
<td>17.83</td>
<td>11</td>
<td>2.79</td>
<td>1.62</td>
</tr>
<tr>
<td>April</td>
<td>547.76</td>
<td>18.26</td>
<td>12</td>
<td>3.04</td>
<td>1.52</td>
</tr>
<tr>
<td>May</td>
<td>491.29</td>
<td>15.85</td>
<td>12</td>
<td>2.40</td>
<td>1.32</td>
</tr>
<tr>
<td>June</td>
<td>470.24</td>
<td>15.67</td>
<td>12</td>
<td>2.51</td>
<td>1.31</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>15.175</td>
<td>11</td>
<td></td>
<td>1.39</td>
</tr>
</tbody>
</table>

Peak eff: (system) % 74.15
Ave eff: during operation (system) % 33.83
Inverter eff: % 90

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• Installation cost per panel (F) is estimated to be $30.00.

• Cost for the installation of accessories (G) is $500.

• Average efficiency during operating hours (H): This is the ratio between the average output during the useful hours of operation and the rated output of the cell. For all practical purposes, this is the panel efficiency at a particular location. The data shows that the average efficiency is 38.04% in the Las Vegas Valley. The efficiency of the panels when they were generating maximum power was found to be 83.47% to its rating (7% conversion efficiency).

• The panel presented has a rated output (I) of 60 VA, 17.1 Volts and 3.5 Amps.

• Ampere-Hour rating of batteries (J) used is 50 AH.

• Average hours of useful sunlight in Las Vegas area (K): The data shows that on an average day, Las Vegas receives 11.5 hours of useful sunlight.

• The efficiency of the batteries (L) available in the market is around 80%.

• The market value of backup generation (M) is $0.12/VA.

• The efficiency for the inverter (N) is assumed to be 90%

• The manufacturers offer 20 year warranty for the panels (O).

• Estimated Peak Demand (P) for a 1500 sq. ft. home is around 4.000 VA in Las Vegas.

• Peak Ampere rating of the battery (Q) used is 85 A.

• Voltage rating of the battery (R) used in the calculations is 12 Volts.

• Current interest rate (S) is 8.5% for a home equity loan, which is the most popular financing for home improvement investments.
• Social approval factor (T) is the premium customers are willing to pay for “Green Power”. In a recent survey, it was shown that Las Vegas customers are willing to pay $0.10 for “green power”. This results in a social approval factor of 1.66.

• Distance from the nearest available power (U) is assumed as 3.000 ft. for calculation purposes.

• Estimated value of line extension (V) (1-1/0 direct buried cable including trench and transformer) is $20.00 per foot.

• Estimated Average Demand (W) during summer months for a 1,500 sq. ft. home is approximately EPD/3 that is 1,333 VA. This value was determined from NPC billing history.

• Current utility rate in Las Vegas (U_{rate}), (X+Y+Z) is $0.06/kWh.
CHAPTER 6

FEASIBILITY STUDY USING NPC DATA

In this Chapter, an economic feasibility analysis of a PV installation in the Las Vegas area is conducted. The data collected from the Local installations discussed in Chapter 5, the feasibility equations derived in Chapter 4, and a 1,500 sq. ft. home with an estimated peak demand of 4,000 VA is used as a load in this study.

The calculations using NPC data are shown in Fig. 6.5, and the results of the study are discussed below:

6.1 Installations in Developed Areas:

6.1 a) With Battery Storage for Night Use:

- 122 panels and 39 batteries are required to fully support the load (rated capacity = 7315 VA).
- Cost of installation = $51,050
- Cost savings from solar power = $11,075
- Therefore, this is not a feasible option with the present cost of PV cells.
6.1 b) Without Battery Storage:

- In this arrangement, the utility will buy-back power from the customer. However, the maximum buy-back is limited to the amount of customer load. Therefore the maximum number of panels the installation can have are limited to 122.

- Cost of installation for a 122 panel facility = $49,121

- Cost savings from solar power = $11,075

- Therefore, this is not a feasible option either.

- Fig. 6.1 shows the relationship between the costs and number of panels. As one can see, smaller installations fare better than larger installations.

![Graph showing relationship between installation costs and number of panels.](image)

**Fig. (6.1) Relationship between installation costs and number of panels.**
6.2 PV Installations in Remote Locations:

6.2 a) With battery storage and generator backup:

- 122 panels and 33 batteries are required to fully support the load (rated capacity = 7,315 VA).
- Generator must be able to completely supply the load during outages. This will require a 4,000 VA generator.
- Cost of installation = $51,530
- Cost savings from solar power = $11,075
- Line extension cost saved (3000 ft.) = $60,000
- This is a feasible installation, and saves around $19,545 during the life of the installation.
- Fig. 6.2 shows the relationship between the distance from the nearest available power and cost. For a 1,500 sq. ft. home, the PV system becomes a feasible option after 2,000 ft. of line extension.

6.2 b) Without Battery Storage and Backup Generation:

- Similar to the installations in developed locations, the maximum number of panels are limited to 122.
- Cost of installation for a 122 panel facility = $49,121
- Cost savings from solar power = $11,075
- Line extension cost saved (3000 ft.) = $60,000

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• This is also a feasible installation and saves around $21,954 during the life of the installation.

![Graph showing relationship between distance from nearest available power and cost.]

**Fig. 6.2 Relationship between distance from nearest available power and cost.**

From these results we can see that shared-metering facilities are more attractive than stand-alone systems due to the absence of backup requirement. Fig. 6.3 shows the relationship between cost of installation and savings as a function of PV cell cost. This plot predicts when an installation becomes feasible in the future. The cost per VA of PV cell has to come down to $0.35 to make an installation financially feasible in the local climate. Currently, the cost per VA of PV cell is around $5.50.
Using the feasibility equation, one can also predict the relationship between the line extension dollars saved by the utility and the installed capacity. For example, Fig. 6.4 shows that if the line extension cost is $60,000, one can build a facility with maximum of 200 panels, which will supply 4,500 VA system capacity. Consequently, it is a powerful tool for making decisions on system upgrade to remote locations.
Fig. 6.4 Relationship between line extension cost and number of panels.

![Graph](image)

Fig. 6.5: Feasibility Calculation Sheet
<table>
<thead>
<tr>
<th>Number of PV cells required</th>
<th>=</th>
<th>122</th>
<th>Total mounting cost</th>
<th>=</th>
<th>$4,157</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Batteries required</td>
<td>=</td>
<td>39</td>
<td>Total rated Capacity of the installation</td>
<td>=</td>
<td>7315 VA</td>
</tr>
</tbody>
</table>

**Installations in cities:**

<table>
<thead>
<tr>
<th>a) With battery storage:</th>
<th>Cost of installation of PV cells (Cpvinst)</th>
<th>=</th>
<th>$51,050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost savings from Solar Power (Cpvsav)</td>
<td>=</td>
<td>$11,075</td>
</tr>
<tr>
<td></td>
<td>Feasibility</td>
<td>=</td>
<td>No</td>
</tr>
<tr>
<td>b) Shared-Metering facility:</td>
<td>Cost of installation of PV cells (Cpvinst)</td>
<td>=</td>
<td>$49,121</td>
</tr>
<tr>
<td></td>
<td>Cost savings from Solar Power (Cpvsav)</td>
<td>=</td>
<td>$11,075</td>
</tr>
<tr>
<td></td>
<td>Feasibility</td>
<td>=</td>
<td>No</td>
</tr>
</tbody>
</table>

**Installations in remote locations:**

<table>
<thead>
<tr>
<th>a) With battery storage and Generator backup:</th>
<th>Cost of installation of PV cells (Cpvinst)</th>
<th>=</th>
<th>$51,530</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost savings from Solar Power (Cpvsav)</td>
<td>=</td>
<td>$11,075</td>
</tr>
<tr>
<td></td>
<td>Line Extension Cost</td>
<td>=</td>
<td>60000.00</td>
</tr>
<tr>
<td>b) Shared-Metering facility (to save system upgrade):</td>
<td>Cost of installation of PV cells (Cpvinst)</td>
<td>=</td>
<td>$49,121</td>
</tr>
<tr>
<td></td>
<td>Cost savings from Solar Power (Cpvsav)</td>
<td>=</td>
<td>$11,075</td>
</tr>
<tr>
<td></td>
<td>Line Extension Cost</td>
<td>=</td>
<td>60000.00</td>
</tr>
</tbody>
</table>

| Feasibility | = | Yes |

| Feasibility | = | Yes |

**Fig. 6.5: Feasibility Calculation Sheet (continued)**

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CHAPTER 7

CONCLUSIONS

This thesis presented an analytical tool to assist the utility customer in evaluating the feasibility of a PV installation and in making educated decisions for participating in the utility's Demand Side Management programs and "green power" options. This tool includes a series of mathematical expressions which take into account all parameters associated with a PV system. Since all the parameters involved in these equations are considered as variables, they are capable of accommodating future changes in the utility industry as well as any technological development.

The data collected from Nevada Power Company PV installation in the Las Vegas area was used to calculate the present values of all parameters. Then feasibility of PV installations under different configurations are evaluated, and various charts were plotted for analyzing the relationship between different variables and for exploring future possibilities.

The data shows that Southern Nevada receives enough solar radiation to make this a prime location for solar power generation. The area receives around 11:30 hours of useful sunlight on an average day, and existing PV panels convert this radiation at an average efficiency of 38% to its rating, (while the peak efficiency of the panels when they
that some of its customers are ready to pay a premium of 1.66 times than the power
generated by fossil fuel for the green power. The results of the economic feasibility study
shows that, in Las Vegas Valley, PV installations are far from feasible in developed areas
at present. These installation will be feasible if the cost per rated VA of the panel
becomes cheaper than $0.35. However, for a medium size home with a 4 kVA estimated
peak demand in an undeveloped area, PV installations are feasible if the site requires
more than 2,250 ft. of line extension. This tool can also be used to set goals for research
and development work on PV installations and make educated decisions regarding system
upgrades to remote locations.
REFERENCES


Fig. A.1: Carrol Street PV System February 1997 Average Daily Output

Fig. A.2: Carrol Street PV System March 1997 Average Daily Output
Fig. A.3: Carrol Street PV System April 1997 Average Daily Output

Fig. A.4: Carrol Street PV System May 1997 Average Daily Output

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Fig. A.5: Carrol Street PV System June 1997 Average Daily Output

Fig. A.6: Carrol Street PV System July 1997 Average Daily Output
Fig. A.7: Brown Street PV System February 1997 Average Daily Output

Fig. A.8: Brown Street PV System March 1997 Average Daily Output

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Fig. A.9: Brown Street PV System April 1997 Average Daily Output

Fig. A.10: Brown Street PV System May 1997 Average Daily Output
Fig. A.11: Brown Street PV System June 1997 Average Daily Output
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