DECISION SUPPORT ANALYSIS FOR A RENEWABLE ENERGY SYSTEM TO SUPPLY A GRID-CONNECTED COMMERCIAL BUILDING

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ABSTRACT

This thesis studies the integration of a solar concentrator photovoltaic array (CPV) system with a commercial building. Solar resource conversion, load characterization, power quality, and grid integration are the primary aspects addressed by the study. Local solar radiation and renewable energy source (RES) conversion data were used to determine a profile for annual energy production of the CPV, which uses a non-traditional method of solar energy conversion. The load was characterized by creating an annual profile for the building's power demand using a combination of historical monthly billing data and a week of detailed real-time power consumption data (real, reactive, and apparent). Various simulation approaches were considered to evaluate the integration of system components with the supply grid. Because of the high time resolution necessary for the study, which evaluates a number of parameters that traditional methods do not address, a custom analysis was performed, both in time segments and total project lifetime figures. This quantifies, at one-minute resolution, the energy produced by the RES, consumed by the building, and metered to and from the supply grid.

The study concludes that the CPV system will make a valuable contribution to the energy supply, it can pay for itself in energy savings over a number of years, and it provides a substantial environmental benefit by reducing pollutant emissions. Financial considerations are dependent upon a number of variables, including the panel quantity, buy/sell prices of grid energy, project lifetime, financing options, and renewable energy credit programs.

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LIST OF ACRONYMS AND ABBREVIATIONS

A	Amperes (amps) RMS
AC	Alternating Current
C&CC	Command & Control Center
CPV	Concentrator photovoltaic
CT	Current transformer
DC	Direct Current
DSS	Decision Support System
kWH	Kilowatt-hour
MWH	Megawatt-hour (1000 kWH)
NOAA	National Oceanic and Atmospheric Administration
P	Real (active) power
PV	Photovoltaic
Q	Reactive power
RES `	Renewable energy source/s
REC	Renewable energy credit/s
S	Complex power (|S| = Apparent power)
θ	Theta (power factor angle)
V	Volts RMS
W	Watts

CHAPTER 1
INTRODUCTION

As renewable energy sources (RES) gain popularity throughout the world, it becomes increasingly important to predict their value to a proposed electric power system that would include them. This allows energy customers to evaluate the technical feasibility, cost, benefit, and environmental factors in making a decision to integrate RES into their power supply. As evidenced by the questions that led to this thesis project, and the literature contributed by industry and academia on the topic, this is a valuable and timely course of study [1,2,3,10,13]. Many projects around the world are venturing to answer questions about how RES behave in hybrid systems and what the technical, financial, and environmental implications are for their inclusion.

The town of Playas, New Mexico is an isolated community served by a single electric utility feeder line from Columbus Electric Cooperative. This offers a unique opportunity to study the benefit and impact of various approaches to electricity supply and management of a microgrid and its components. Multiple projects are underway in Playas that are intended to provide such insight. The project discussed in this thesis is one such effort.

The system being studied in this case is a hybrid of renewable energy and grid power. The facility managers intend to connect one or more solar Concentrator Photovoltaic Array systems at or close to the utility feeder line into the town, and use it to replace a portion of the grid power being used from the utility to feed the microgrid.

Since a comprehensive study of the microgrid itself has not been performed, its load profile would be difficult to characterize with available data and is beyond the scope of this study. However, there is an intermediate option. The largest single electricity consumer in the microgrid is a commercial building, the Command and Control Center (C&CC). Historical power usage data is available for all electric loads in the town, but the C&CC is also being monitored in real time, in much greater detail. Real power, reactive power, apparent power, voltage, current, power factor, and associated phase angle are all being logged at one-minute intervals, providing time-series electricity usage data. Additionally, there are separate monitors for each electrical sub-panel in the building such that various categories of load types within the building can be characterized separately.

This offers the opportunity to characterize the C&CC energy usage in much more detail than any other component of the microgrid. Therefore, the project outlined here will evaluate the interconnection of the solar array with the C&CC building. This will generate a sample model for how the RES on site can be utilized by a load that is characterized in one-minute resolution with enough detail to meaningfully evaluate the short term characteristics. If or when such load characterization is available for the remainder of the microgrid it could replace the C&CC profile in the analysis for a new evaluation of the entire town.

The thesis work encompasses several stages. Starting with the *Background* chapter, relevant scientific literature on the topic will be explored to illustrate the relevance and industry context of the study. Additional background in the scientific principles that govern the topics covered in this thesis are provided in that section.

Decision support tools will also be evaluated to make a final choice on the analysis method.

The *Methodology* chapter covers a comprehensive description of the project's design, procedures, and analysis. This work is broken into five sections.

1. Description of the proposed system
2. Load characterization to determine the energy usage of the C&CC
3. Renewable energy source characterization to determine the energy resource on-site and predict electricity generation using the desired solar CPV collection system
4. Grid integration analysis and system analysis using a combination of off-the-shelf and custom-made computational tools
5. System characterization and feasibility analysis to determine the system's energy use impact, environmental impact, cost, and earning/savings potential

Stage 1 introduces the system and its composition. Stages 2 and 3 characterize the physical components of the system. Stage 4 performs the analysis computations and outputs the results. Stage 5 evaluates the financial and environmental factors to assist in the overall system analysis.

Stage 2 investigates the energy usage of the C&CC building load. This is the load characterization stage. It involves introductory work to gather data on the load components and learn how and when they will operate in an effort to fully characterize the power load and how it will change over time. This provides a theoretical description of the power needs at the site that is based on historical data. Several years of monthly power utility bills, along with one full week of power consumption measurements made at one-minute resolution are be used to create the theoretical energy usage projections.

Stage 3 investigates the renewable energy conversion equipment and its performance at the installation location. This is the source characterization stage. It considers the use of one or more 25 kW concentrated photovoltaic solar array systems manufactured by Emcore. System performance data and specifications, along with meteorological data for the installation and test sites are combined to calculate the expected energy harvested on-site.

Stage 4 addresses the decision support analysis used to characterize the load, grid and RES interaction. It involves modeling of the system and simulation to determine how the desired components will perform and interact with each other. Power factor analysis of the load and source/s are performed to determine how to best characterize the load for maximum accuracy in the simulation process and/or to determine the consumption correction factor necessary in the case that the load is assumed to have an ideal power factor of 1.0 in the analysis process. The necessity of transient analysis for load and source power dynamics will be discussed as it relates to potential need for transient suppression components. Finally, analysis tools are utilized to create a time series profile of the interaction between load, RES, and grid energy. This provides a combined picture of how much power will be needed from (and net metered back to) the utility's electric grid. The analysis will also provide financial projections for the system over the chosen time span, and computation of pollutant emissions over that time. This information will be used to characterize financial and environmental impacts and benefits of using RES for this application.

Stage 5 evaluates the physical components against financial and environmental factors to assist in the overall system analysis. It will consider the big picture perspective of the previous three stages and make feasibility conclusions based on the results. This portion will involve consideration of economics, environmental impact, and overall energy usage of the building and its energy system.

Finally, the project is summarized in the *Conclusion* chapter where results and implications are put into the context of their greater meaning. Future direction of this work will also be discussed in the closing.

In a sense, this project is comprised of an effort to create a large amount of viable data from a very small amount of information. It turns out that, with a few key sets of experimental and historical data, the rest can be calculated, interpolated, and/or estimated with acceptable accuracy. While attempting to minimize large assumptions and focus on certainties that develop quality predictions, this project aims to provide decision analysis of the proposed system that will be not only useful to the end user, but will do so with reasonable certainty of the expected performance.

CHAPTER 2
BACKGROUND

2.1 Literature Review

As evidenced by the variety of research being conducted in the field, renewable energy is a popular topic. Upon consideration of this project's goals, a selection of previous work in the field was investigated. Relevant literature falls into a number of topic areas, including sustainable decision making in the energy context, decision support systems (DSS), and technical resources.

Sustainable decision making is one of the clear motivators for the exploration of renewable energy systems. Useful research on the topic goes back many years. An exploration of this history was provided by Hersh [1]. This paper also introduces the concept of the decision support systems and the role they play, both in the cultural context and as a technical tool. Integrating renewable energy sources into the power supply is a complex issue. There are social, environmental, financial, and technical implications with which to contend through all phases of the project. Many projects have utilized decision support systems in an effort to characterize, consider, and ultimately pass judgment on the systems with regard to these factors.

Of specific interest to this project is the study of other projects that have utilized RES systems in remote areas, to feed particular loads (especially when they are integrated with grid-connected loads) , or in other circumstances where the source was not simply connected to an infinite grid. One highly useful example was a project for a grid-connected large hotel in Australia by Dalton, et al [2]. It offers a particularly concise summary of how decision support analysis was used to evaluate possible options, costs and benefits, and draw conclusions.

The most intensive portion of the literature search was investigating the options for the decision support system. There are a number of existing tools that are widely used for this purpose, and the paper by Georgilakis [3] was extremely useful by describing the benefits, drawbacks, and recommended applications of each of the most popular existing packages. The two main options worth considering are both free software packages developed by leading energy institutions. HOMER was created by the National Renewable Energy Laboratory (NREL) and is the most frequently mentioned in literature on the DSS topic. The user manual and quick start guide were a great help in evaluating HOMER as a DSS option [4, 5], as was the software itself which was installed for experimentation and to gain familiarity with its capabilities [6]. Another option is Hybrid2 which is managed jointly by the NREL and the Renewable Energy Research Lab (RERL) at the University of Massachusetts, Amherst. The user manual [7] was a key resource, and the software [8] was also installed for evaluation. These resources helped to confirm the assertions made in the Georgilakis paper [3] that HOMER is more of a logistical and financial simulation tool whereas Hybrid2 is more of a technical analysis tool.

Many papers on the DSS topic refer to these two software packages, mostly to HOMER, in their investigations of DSS options. Of particular interest were a number of projects that used HOMER as their primary analysis tool. An Australian project, by Dalton et al [2], that aims to reduce the environmental impact of operating a Hotel was mentioned earlier. A case study in Sri Lanka which explores RES hybrid systems that include gensets to serve a remote load was co-authored by Gilver and Lilienthal [9]. Lilienthal is one of the prime movers responsible for the HOMER legacy. The Khan [10] project in Newfoundland used HOMER to evaluate a RES system designed to relieve load on a diesel generator.

While the previously mentioned software packages are popular options for decision support analysis, many researchers have created their own custom solutions. One such example was constructed to evaluate a remote power system in Taiwan, by Yue and Yang [11]. There were two helpful papers on the topic of creating DSS solutions by Keller et al [12], and Karki and Billington [13], which were consulted to investigate the complexities of creating a homegrown solution.

Other literature was useful for a number of technical considerations. Several focused on creating and/or locating solar profile data for use in solar energy conversion predictions and were useful to gain understanding of solar radiation and how it relates to PV electrical conversion [14, 15]. Amador and Dominguez [16] focused on the use of geographic information as a source of data for decision support analysis. A paper by Karki and Billington [17] on evaluating the cost/reliability implications was also consulted. Finally, a number of papers were helpful in understanding the need for, complexities of, and options available to implement energy storage on site. General storage issues for RES systems are covered by Youli et al [18], and a particular focus on lead-acid batteries, the most commonly available and affordable form of energy storage, is covered by Manwell and McGowan [19]. Galvin and Chan [20], investigated storage possibilities along with options for transient suppression, an important aspect of energy systems that is largely neglected for RES studies. It explored the possibility of using capacitors as combined energy storage and transient suppression devices.

2.2 Technical Concerns

A number of technical issues have come to bear in this project. When evaluating the supply of power to the load, it is necessary to attend to several characteristics beyond simple magnitudes. The dynamics of transient events, along with other parameters such as frequency and power factor, will influence how the system operates and need to be understood before the system can be adequately evaluated. Much of what is covered in this section is based upon prior knowledge of power systems. These concepts are explained suitably in various texts, including the book by Glover et al [21] which was used as a reference during this project.

2.2.1 Power Balance

Power balance is the concept of matching power provided to power required by the load. The conservation of energy law dictates that power consumed (load power) will always equal the power generated (source power) in the system, minus losses. This will balance itself, regardless of the system design, due to the laws of physics. However, this does not always occur with desirable results. When there is a mismatch in source and load power magnitude, other parameters will suffer non-ideal conditions (voltage may rise or drop, frequency may deviate, etc). It is therefore necessary to plan a system such that power will balance with constructive results, and energy flows most advantageously to meet design preferences and minimize the chance of conditions that may damage equipment or result in inadequate power quality. Ideally, the system would have available all the power it needs and be able to store surplus power locally, or deliver it back to the grid for distribution to other loads, and do so with optimal power quality.

Photovoltaic (PV) solar energy conversion sources at the site will be used to take maximum advantage of renewable resources, specifically the Emcore CPV array. Grid power will be used to provide any deficit not generated by renewable production, and to buffer transient events. As such, the grid power will likely act to offset any deficit or surplus in the power balance between local generation and load.

Storing energy locally would normally act to offset as much surplus remainder in the power balance as possible. Storage at the installation site was not under consideration at the time of this study, so it was not included as a system component. Rather than storing energy on-site, surplus power will be sent back to the grid via net metering. Wasting the surplus and/or allowing it to dissipate destructively are obviously worth avoiding. Computational analysis will allow us to determine how much energy would be available for storage on site were it to be considered in the future.

The system design will manage these priorities, attempting to make best use of all energy that it handles, according to priority factors set forth in the design.

2.2.2 Time Dynamics & Transients

Converting alternative forms of energy to electricity on-site is inherently dynamic. Due to momentary, hourly, daily, seasonal, and annual fluctuations in sunlight, PV production will naturally vary over time. Additionally, the load will vary with time as electricity usage changes and the system switches between its operational modes. Although this behavior is dynamic, we will still consider the nominal mode to be steady-state, but we will characterize it over time to compare the power generated and load demand. These two quantities are compared in the simulation to characterize the surplus and deficit power over time, thus representing energy that will be generated and metered to and from the grid.

Sudden changes in the load characteristics tend to pull the system out of steady state and into transient state until the system re-stabilizes. Generally these are short term events that upset the nominal power curves, causing positive or negative impulses in current, voltage and/or power at points in the system. Examples of such events include (but are not limited to) the starting of a motor or dramatic changes in its speed, sudden powering on/off or connection or disconnection of a load, or transients passed into the system from the grid caused by external phenomena.

It is the initial design intent that time dynamics of production and load will be managed as much as possible by storing and retrieving energy from the grid. The PV system also has an integrated power management component that may offer some transient suppression capabilities. It is common practice, when analyzing systems much smaller in magnitude than the grid, to treat the grid as an infinite bus, able to absorb transients and power quality fluctuations of its smaller counterparts. As such, this study will assume that fluctuations in excess of the local system's compensation capabilities will likely be absorbed by the grid connection. If the load characterization and associated calculations suggest that this is not a realistic assumption then steps can be taken to identify other options. It will do this by determining peak values for voltage, and power to determine if the load has historically endured transients that appear on minute-interval data. Currently that is the limitation of the data collection system. It is possible, if not likely, that transient events could occur in the system that do not appear in such data, in which case it would be beyond the capabilities of this study to consider. If compensation were needed, it would likely come in the form of capacitors which can provide the peak current necessary to start a motor, and the stabilizing low-pass filter effect to smooth out other extremely short-term variations. The tricky part of transient compensation would then be choosing appropriate components and deciding where to put them. As discussed in the Background section, Galvin and Chan [20] provide an interesting exploration of this topic.

2.2.3 Power Quality

There are a number of subtleties in power production and consumption that reach beyond simple considerations of the magnitudes involved. To this point, power has been discussed only with concern for its magnitude, and the magnitude of voltage and current as well. It is also necessary to take a closer look at the relationship between the voltage and current waveforms (power factor), the frequency of AC in the system, and how these two considerations can impact each other and their subcomponents.

Frequency

Frequency is generally considered to be a constant in an electrical system, but it does vary enough to be significant when considering major components of a power delivery system. Power utilities manage the frequency on the grid such that it is closely matched at all points, within a tolerance. Small autonomous systems either generate their own frequency, whereas semi-autonomous systems with grid connections, such as the one under consideration here, generally match the frequency of locally produced energy to the frequency on the grid. Typically the inverter/grid interface component performs this task, as is the case with the CPV system used in this study. But frequency can be affected by certain anomalies. When the nominal voltage is outside specifications, it is possible for the frequency to deviate, and excessive power factors can cause the same effect. One common cause of this problem is when the system is operating at a sub-spec power factor. Together the voltage, frequency, and power factor affect each other as one of the more subtle forms of power balance. Additionally, frequency is significant as a mathematical component on which other power quality characteristics are dependent.

The data collection equipment being used to monitor power at the C&CC load is capable of collecting frequency data. However, the data collected shows exactly 60 Hz at all times. Either the frequency at this point in the system is actually that stable, or the sensors do not have the capability to measure smaller fluctuations (or the resolution to display it), or both. In either case, sufficient frequency data is not available in order to consider this as a variable in the analysis. As such, for this study, frequency will be assumed at a constant 60 Hz or 377 radians per second.

Power Factor

Power factor characterizes the phase relationship between the voltage and current waveforms. Under ideal conditions, the sinusoidal waveforms of the voltage and current are in phase with each other. This happens only when a load is purely resistive, having no capacitive or inductive components, or when non-ideal impedances are compensated with additional components to achieve the same effect. Different types of sources and loads tend to push and pull the current and voltage out of phase. Capacitive systems cause the current to lead the voltage, and inductive systems cause the current to lag behind the voltage. Compensation components (in the form of inductors or, more commonly, capacitors) can be added to the system to offset these tendencies.

Evaluation of the C&CC load power factor determines how much reactive power will result from the load characteristics. Literature on this topic tends to ignore this characteristic by assuming that the load power factor will either be ideal or compensated to behave as such. Since this study includes data that can be used to calculate the power factor of the load, we have the capability to evaluate this aspect as a variable in the system rather than assuming it will be ideal.

As stated, power factor characterizes the phase relationship between the current and voltage waveforms. The angular phase shift (θ) is calculated as the difference between the voltage phase and the current phase. Power factor is the cosine of that phase shift and is annotated as leading or lagging to describe whether the current leads or lags the voltage. The mathematical result is a positive number between zero and one. A result of one is the ideal that occurs when taking the cosine of zero, representing the case of zero phase shift between voltage and current, which occurs for a purely resistive load with no reactive component. A result of zero occurs when we take the cosine of a positive or negative 90° phase shift, which represents the case of either purely capacitive load (leading) or purely inductive load (lagging) respectively. Industry commonly expresses these decimal numbers in percentage form by multiplying the cosine result by 100.

This phase relationship can also be determined by evaluating real, reactive, and apparent power if the data is available, as in the case of this project. Real power (P) is the resistive component while reactive power (Q) represents the component determined by inductance or capacitance of the load. Complex power (S) is the resulting total power which is the sum of the real and reactive components. Together they make a triangle of vectors, shown in Figure 1, that lies in a coordinate plane with a horizontal “real” axis representing the real component and a the vertical imaginary axis (which quantifies the complex component). Real (active) power, P, is the base and shown here as a vector, although it is normally considered as a magnitude only because by definition it points along the real axis from the origin in the positive direction (there is no such thing as a negative resistance). Reactive power, Q, is the height, which is also normally considered as a magnitude because by definition it points parallel to the imaginary axis, either positive or negative. Complex power, S, is the hypotenuse that represents the sum of the P and Q vectors. The magnitude of S, |S|, represents the apparent power. The phase shift (θ) is the angle between S and P, measured where they meet at the origin. Following trigonometric identities we can express the cosine of θ as the ratio of real power to complex power magnitude (apparent power), or P/|S|. Similarly the tangent of θ is the ratio of reactive to real power, or Q/P

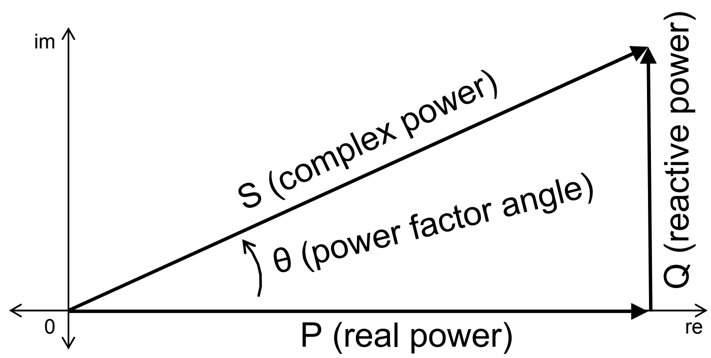

Figure 1: Power triangle for positive power factor angle

Figure 1 shows the power triangle for a positive phase angle, which is the result of current lagging voltage, and designates positive reactive power Q which is associated with inductive loads. In the case of a negative phase angle (current leading voltage) the vector Q would point downward, and the complex power vector S would point downward to meet it, indicating negative reactive power and a leading power factor, and thus a capacitive load.

With respect to the parameters of voltage, frequency, and power factor, system components are rated for a particular range in which they are capable of operating most safely and/or efficiently. When a system operates outside of the ideal power factor, additional current is exchanged between system components as a result of reactive power flow. In other words, more energy will be transferring between parts of the system than the real power measurements would suggest. In this case there is a reactive component which creates a complex power vector of greater magnitude than the real power alone. In the case that the power supply is not able to accommodate this behavior, it can be corrected by adding compensation components, usually capacitors, to the local system to offset the reactive components that are pulling the power factor away from the ideal. Power meters generally measure only real (active) power and do not necessarily notice the extra energy exchanged between reactive components, and as a result often do not record the full amount of energy exchanged. In this case system component ratings must be compatible with the total energy requirements so that they can accommodate the full complex power.

If we take power factor into consideration we can quantify the total energy exchanged by calculating the magnitude of S, or $|S|$. Based on the trigonometric relationship, the cosine of θ (power factor) equals $P/|S|$. Rearranging that algebraically we can see that the magnitude of S is the ratio of real power to power factor ($\cos\theta$) such that $|S| = P/\cos\theta$. The magnitude of real power represents the metered power, so to convert metered power to apparent power we divide it by the power factor. The resulting correction factor is the inverse of the power factor or 1/cos θ. This can be multiplied by the metered power measurement to determine a measure of the total power delivered to the load.

In the case of this study, there are several sub-panels being measured separately, but they all connect to the same feeder bus and billing meter upstream. Loads with components operating at different power factors, especially those with a mixture of leading and lagging, have the ability to compensate each other through a common node as reactive power flows between them. This diversity is what helps larger load networks operate at a more desirable power factor as a whole, and wider-spread grid systems become much more stable as a result. In these cases a small individual load on the system operating at a poor power factor has minimal impact on the whole. Because of this, care must be taken to sum the individual powers being measured for each sub-panel to account for that the reactive power flow at the main bus. It is expected that the power factor of the integrated load will be much closer to ideal than any of the subcomponents, because they have the ability to share reactive power through the main bus.

If this load operates at a low power factor as a whole, it is likely that the power utility feeder line will be able to handle the reactive power flow, as long as system components can accommodate the additional current to exchange reactive power with other loads on the grid. The low power factor situation becomes more difficult when a load is being serviced by a local generation source that does not have the benefit of the diversified grid with which to make reactive power exchange. With off-grid or islanded RES systems this becomes especially relevant because those sources need to exchange all of the load's reactive power, and must be designed for that capability.

CHAPTER 3
METHODOLOGY

The methodology of this project is broken into five segments: Physical system description, load characterization, source characterization, grid integration analysis, and system integration/feasibility analysis. This serves as both a chronological and logistical categorization of the project.

3.1 Physical System

3.1.1 Description

As mentioned previously, the site under study for this project is a commercial building in the small, isolated town of Playas New Mexico. A deserted former mining town, it was adopted by the New Mexico Institute of Mining and Technology to be used for a variety of training and research activities and the related support services necessary to sustain regular activity on site. One of the more heavily-used buildings in Playas is called the Command & Control Center. It is a commercial building that has served as classroom space, a mercantile store, and now as a logistical hub of operations. The building contains a variety of electrical loads, including heating and cooling (mostly rooftop units), a computer server center, office equipment, lighting, and appliances, among others.

Power feeding into the building is 3-phase at 208 Volts line-to-line. Downstream from the meter it goes through a main breaker panel where it is split to a number of sub-panels, which feed the individual branch circuits—some of which serve three-phase loads, and some serve single phase loads at 120 Volts (which is the line-to-neutral voltage of the three phase feeder, calculated by dividing the 208 V line-to-line voltage by the square root of three). Installed at main breaker panel location is a Multilin EPM4000 Sub Meter made by General Electric [22]. This meter uses a voltage probe on the three phases of supply power connection, and there is a current transformer (CT) installed on each phase conductor feeding each of the sub-panels. It has the capability to measure eight sets of three current transformers (one per phase for eight 3-phase circuits total), with six installed presently. The meter measures voltage and current, and computes a number of instantaneous power consumption quantities at one-minute resolution for each CT. Real power, reactive power, apparent power, voltage, current, power factor, phase angle are all being measured in real time. Along with its associated data tracking software, EnerVista, the system tracks and records these parameters, providing the time-series data that was used for this study.

The building's electricity comes from the Playas distribution network that originates at a local substation fed by a single high voltage supply line from Columbus Electric Cooperative. With this isolated configuration, Playas offers some unique possibilities for research of microgrids and power systems in isolated areas. The site managers plan to install one or more solar panels to connect to this microgrid, which was the impetus for this thesis project. Studying the entirety of the microgrid would be an interesting project indeed, but presently there is not a metering point at the town's main substation, so that project will have to wait for a later date. However, the Command & Control Center and associated electrical instrumentation offer another analysis option. As one of the larger electric consumers in the town, it would serve as a reasonable sample load for a grid-connected commercial building. Therefore, this project evaluates the integration of the solar equipment with the building's load directly.

The solar panel used in this study is an Emcore Concentrator Photovoltaic Array (CPV) system which is quite different from a traditional photovoltaic (PV) panel and therefore requires some special considerations. This product uses an array of Fresnel lenses to concentrate sunlight from a larger surface area to a collection of smaller PV cells. This makes better use of the PV cells as they are capable of converting energy at much higher intensity levels (up to 500 times the normal irradiance) than they would experience without the concentrating lenses [23, 24]. Therefore, a CPV panel converts sunlight to electricity much more efficiently by using only a small fraction of that surface area in PV cells. As with many traditional PV systems, the CPV uses a solar tracking system to ensure that it is always pointed directly at the sun for maximum electricity conversion. It also uses an inverter unit to convert from DC to AC and manage power quality parameters. Full details on the CPVs specs and operation are provided later in the Source Characterization section.

3.1.2 Operational Modes

Given the variety of combinations of loads and sources, there will be several possible operating modes for the integrated solar/grid power system.

A. Power deficit: Energy consumed by load exceeds energy generated by renewable sources. Supplemental energy would be provided by the grid.

B. Power surplus: Generated energy exceeds energy consumed by load. Surplus energy is stored, metered back to the grid, and/or dissipated as waste. In the case of this study, storage components are not included. Power balance analysis will determine if the system would benefit from storage capability.

C. Power equilibrium: This seemingly unlikely scenario would occur when energy generated matches the load exactly and no energy is consumed from or returned to the grid. Aside from momentary occurrences, the case when this mode might be achieved would be when storing excess energy locally in batteries or by other means. In this case all generated energy not being used by the load is channeled to the storage components. This is a commonly utilized option with RES systems but such components are not connected in this case, as explained previously.

3.2 Load Characterization

3.2.1 Historical and Time Series Data

A three-year history of electric utility bills for the entire town was cataloged previous to the commencement of this project. Consumption history for the C&CC building was extracted from this database to provide total consumption data for real power, and for evaluation of seasonal power usage trends. The goal was to understand how the building's electrical load changes over a year of operation such that this information could be combined with time series data collected by the GE Multilin/EnerVista meter over a recent single week. As seen in Figure 2 below, there does not appear to be a significant pattern to the differences in monthly consumption from year to year, aside from the marked increase for 2008 from August toward the end of the year, nearly equalizing with previous years by December. Whether this is an anomaly can be determined when 2009 data is available. From the time series data collected in November 2009, which will be discussed later in chapter, a slight increase over 2008 was indicated from the sample week.

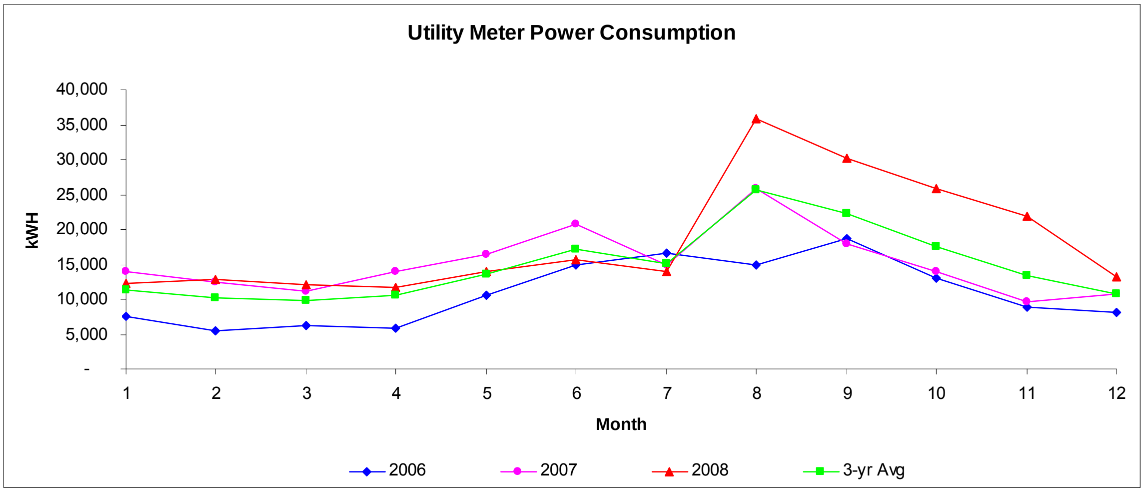

Figure 2: Monthly energy consumption based on utility meter readings

The time series data has much more detail than the simple monthly real power total found on the utility bills. It includes instantaneous readings of real, reactive, and apparent power at one-minute intervals, for each of the three phases, in addition to power factor and phase angle. Using this time series data to characterize each day of the week creates a weekly load consumption model that can be overlaid with the monthly real power consumption figures to create a projection of yearly consumption for these more detailed parameters.

Power to the building is 3-phase at 208V line-to-line. The real time data is collected at the main breaker panel with separate measurements for each sub-panel. Figures 3-5 below show the per-phase power consumption for real (P), reactive (Q), and apparent power (|S|) respectively. Instantaneous values are plotted, along with trend lines developed using a 60-minute moving average. Note that, with 1440 minutes per 24 hours, each vertical gridline marks a full day (starting and ending at 1800 hours Friday). The plots illustrate quite clearly the relationship between daytime weekday building occupancy and power consumption. On weekdays peak usage lasts approximately a half day, ending in the vicinity of 6:00 PM with a slightly earlier decline on Friday.

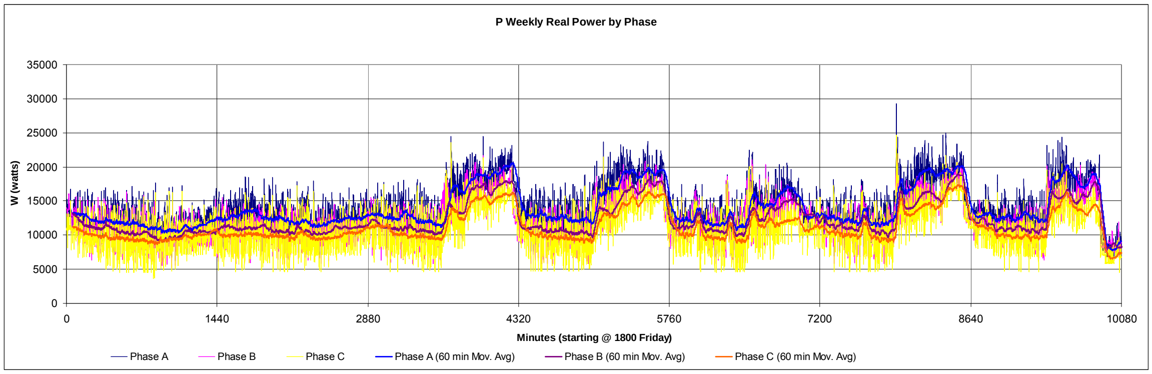

Figure 3: Weekly profile of real power, per phase

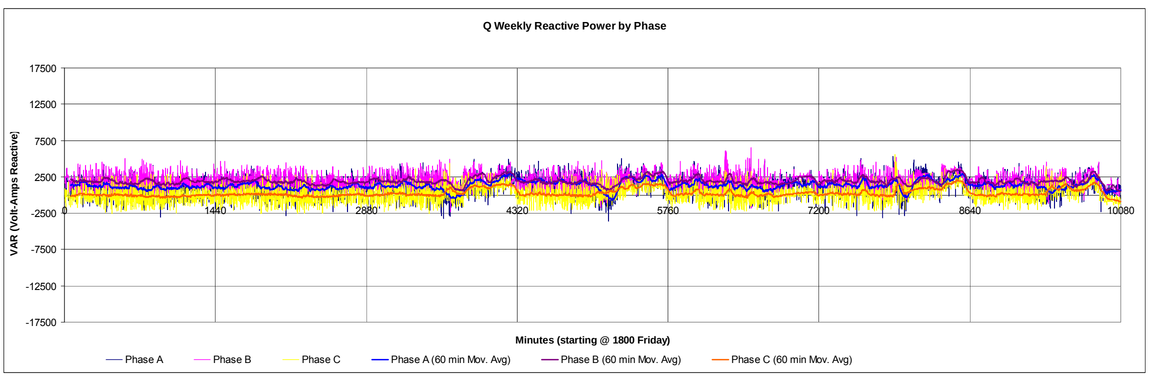

Figure 4: Weekly profile of reactive power, per phase

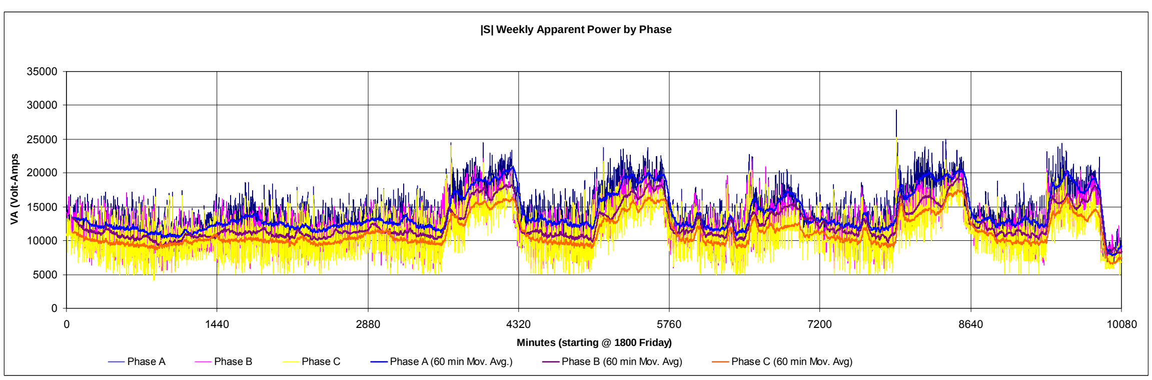

Figure 5: Weekly profile of apparent power, per phase

Looking more closely at the actual data, there are a number of anomalies worth considering. Note that the loads are not balanced across phases. The load on phase A is nearly always higher than phase B, followed by phase C. There was some curiosity about this phenomenon which was answered in part by confirming with the site engineer that the loads are as unbalanced as they appear in the data. In fact, upon infra-red inspection of the main conductors feeding the building, the phase A conductor was notably warmer than the others, indicating its larger current flow [28].

Also suspect was the fact that the power factors for some of the sub-panels were different from phase to phase. Considerable effort was expended to determine the reason for this phenomenon. Two of the sub-panels in question feed primarily rooftop heating/cooling units which one would expect to run at a more balanced per-phase power factor since the primary components within are three-phase blower and compressor motors. Further confusing matters, two of the phases were tracked with negative reactive power values while the other was positive. This raises two questions. Why are two of the phase power factors leading while the other is lagging? Secondly, why would such a load appear to be capacitive?

There appeared to be three possibilities. First, perhaps the load is actually unbalanced as shown in the data. Despite a thorough inspection of the unit's owner manual [25] and multiple contacts with the manufacturer, no information on this question was located. Second, perhaps there was a problem with the wiring of the data collection hardware. Since the site is distant and accessible only on special arrangement, a visit to the site was not possible. High-resolution photographs of the installation provided some reassurance that the wiring was correct. Furthermore, the EnerVista owner's manual provided some troubleshooting advice to determine whether the current transformers were installed backward. In this case the real power measurements would show negative values, but this was not the case for the data they were providing. Finally, there is the possibility that the load is compensated by some means on two phases and not the other. As evaluating this would require access to the site, in addition to the rooftop equipment itself, and a visit to the site could not be arranged on an adequate timeline, it was decided to move forward with the data and assume it was good, with the intent to confirm its quality at a later date for the sake of future data collection for other studies.

When summing the sub-panel powers together, as was the case for these figures, it can be observed that reactive power is relatively small in magnitude compared to the real power. In fact, reactive power seems to have minimal impact on the shape of the weekly load profile. Note how the Apparent power profile is much the same shape as real power. As discussed earlier, this is not the case for all of the sub-panels, in fact some have significant power factors as low as 0.64 (64%) from phase angles as high as 50°. But since all of these individual loads are connected to the same main panel, ostensibly they will share reactive power through the main buses (one per phase), and effectively compensate each other's power factor if there is enough diversity. Clearly that is the case in this building. When the real and reactive powers are summed together separately, and a total apparent power is generated for the entire bus as one (per-phase) node, the power factor looks very close to ideal. In fact, the worst per-minute power factor recorded in the sample week was 0.886. The average was 0.991 with a standard deviation of 0.00195. Since power systems typically require a minimum power factor of 0.95 or even 0.90, from this data it is clear that no power factor compensation will be necessary.

This is also apparent in Figure 6 below which shows the sum of the three phases for real power and reactive power. Instantaneous values are plotted, along with trend lines developed using a 60-minute moving average. To determine the total power needs for the building, all three phases are added together. The total per-minute power of each type was calculated for each phase and then the phases were added together.

On the graph it is clearly seen that the real power is of much greater magnitude than the reactive power, indicating that the apparent power and real power plots would be very similar. This further illustrates the previous discussion about their similarity due to the nearly-ideal power factor.

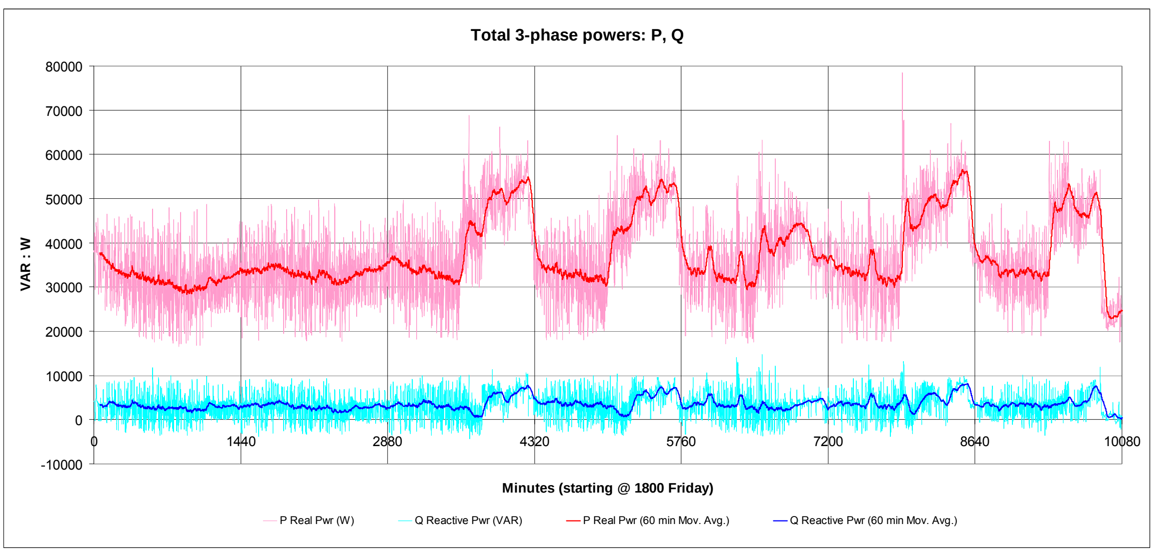

Figure 6: Weekly profile of power consumption from time series data

The total apparent power was used to provide the series of power consumption values for each minute of the week in the load profile data files. This became the basis for the total power consumption model used in the source/load power balance analysis.

3.2.2 Seasonal and Annual Variation

As there were incremental changes in the historical consumption data from year to year, it is reasonable to assume that future years would also experience similar change. The little data available for 2009 did not provide compelling evidence to steer the decision. This was considered by involved parties and it was agreed upon to sustain this assumption for the sake of simplicity, based on the expectation that the C&CC building's usage was expected to follow past trends, ignoring any dramatic change in climate. As such, it was decided to use a three-year average to provide the projected data for 2010, the year under study.

Cooling and heating portions of the total load also evolve with the seasons. As shown by the historical billing data in Figure 2, each month has its own typical consumption profile in comparison to other months. One would assume that the weather trends would have meaningful impact on this. As shown in Figure 7 below, median temperatures for nearby Hachita NM [26], which is of similar geography and located at similar elevation and latitude to Playas in the next valley to the east, show trends for warmer summer and cooler winter months, as expected. Comparing this plot to the consumption plot in Figure 2 allows for consideration of the potential impact of seasonal temperatures on the electric loads for heating and cooling. Consumption is higher during hot summer months than the cooler winter months. However, the consumption history does not appear to correlate directly with the historical temperature profile from year to year. More data on the building usage would be necessary to determine the nature of the fluctuations.

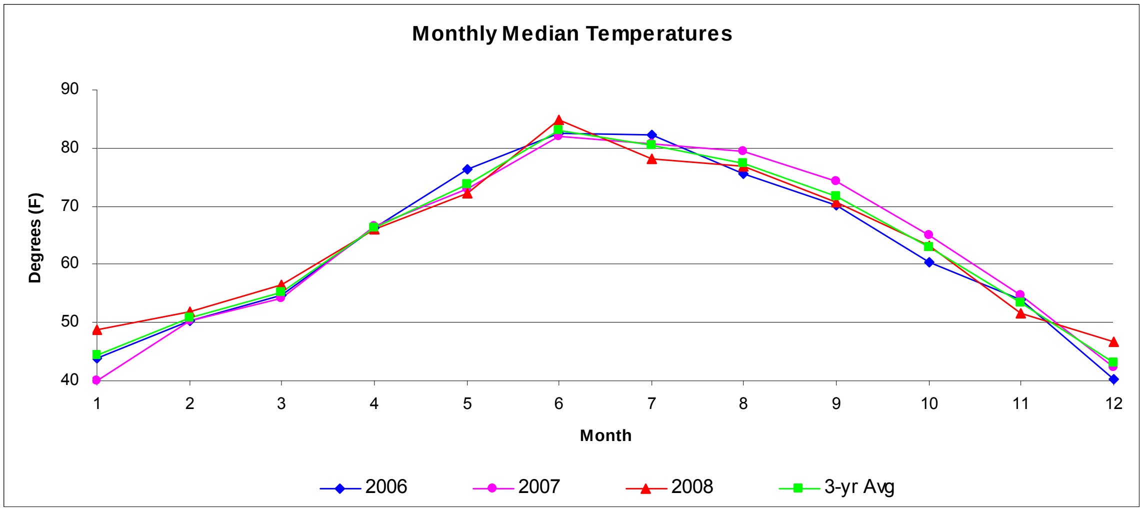

Figure 7: Monthly median temperatures at Hachita NM

The real time data currently being collected offers some insight into that trend because it meters individual sub-panels, some of which are dedicated to rooftop heating and cooling units. A look at these measurements reveals that the cooling and heating portions make up a substantial portion of the total load. This creates an interesting dilemma. The historical billing data does not provide sufficient information to determine what part of the day the energy was consumed. This would be possible with the time series data tracking performed by the Submeter, but it has been recording for less than a month.

When considering yearly, monthly, or even daily averages, this information is not as critical as when considering a RES whose generation capabilities are restricted to day-time operation such as the case with PV solar collectors. Furthermore, the load will vary based on the daily solar cycle. In warmer seasons the dominant portion of the climatic power load is consumed by cooling equipment which runs primarily during daylight hours. In cooler seasons, the dominant portion of the climatic power load is consumed by heating equipment which runs primarily at night, and likely with a substantially different power factor.

Given the importance of these dynamic interactions, power balance must be evaluated by the hour or even by the minute, in order to predict when the PV array will produce energy, and how much, and when the loads will be most active. For a truly accurate annual load profile, time series data would need to be collected over an entire year. However, time series data for this project is only available for one recent sample week, recorded in November, a relatively temperate month in southern New Mexico. It is expected that there is more balance between heating and cooling loads during this month than during the months of more extreme outdoor temperatures. Therefore, there is a good probability that the time series data does not provide adequate information to generate a comprehensive annual profile without making some assumptions. Therefore, the annual load profile will be based on the distribution of power usage throughout the sample week, repeating it for all 52 weeks of the year. It is expected that fluctuations of load timing throughout the year will vary with the weather of the seasons. Annual temperature trends for the period covered by the historical power bills differ by an average of 6%, so this may introduce one of the more significant sources of error in this study.

3.2.3 Projected Annual Load Profile

Combining the historical billing data with the week of detailed time series data creates a comprehensive annual consumption profile. The first step was to use the monthly real power metered figures from the bills to determine what proportion of a yearly energy load was consumed in each month. This would provide data for how to weigh each week in the annual profile relative to each other. The week of time series data was then analyzed to determine how much of a typical week's total apparent power consumption occurred during each minute of the week. This created a unit-less proportion figure for each of the 10080 minutes of the week that quantifies how much of the week's total power was consumed during each minute. Then, by using the real power proportional figures from the bills, each week was scaled to its appropriate portion of the annual expected total consumption for real power. In the end, by comparing those per-minute quantities to the source production for each minute, we are able to determine how much energy is used from (or returned to) the grid for any given minute of the year. Months have a variety of lengths, which results in three different numbers of minutes per month. For months with 31, 30, and 28 days there are 44640, 43200, and 40320 minutes, respectively.

The quantities computed per minute for a year are real power values, measured in kilowatts. They were originally determined using the apparent power values from the week of test data, but since the load was determined to have a power factor very close to ideal, as discussed previously, the result would have been within 1% if the real power values had been used instead.

3.3 Source Characterization

3.3.1 Solar Radiation and the CPV System

The basics of harnessing solar energy center around a transducer, the photovoltaic (PV) cell, which converts solar radiation into electricity. Solar radiation is measured in watts per square meter, and the exposure level at any particular location is dependent on the angle of the sun in the sky, atmospheric conditions, altitude, and other parameters [15]. Solar intensity at this project's installation site varies between zero (when the sun is not present in the sky) and upwards of 900 or even 1000 W/m^2 in some conditions [27]. Determining how much electricity a particular solar panel will convert is a function of its efficiency and the radiation to which it is exposed. Because of the lens array design, this panel design benefits negligibly from indirect sunlight, which conveniently simplifies the conversion projections by allowing for consideration of only the direct normal irradiance which is the sunlight component pointing directly along the path between the sun and the panel. Other irradiance values can therefore be ignored in the projection algorithm.

The Emcore Concentrator Photovoltaic Array (CPV) is a special type of PV panel. As mentioned earlier, it uses Fresnel lenses to concentrate a large exposure area to a much smaller PV cell, thus increasing the output of the cell to many times the normal for a non-concentrating panel. As seen in Figure 8 below, the panel is built from ten smaller arrays of approximately 200 cells each. Fairly large and heavy for a post-mounted panel, it measures 1814 cm (~60 feet) wide by 790 cm (~26 feet) tall. It weighs 8620 kg (~19,000 pounds—nearly ten tons). The panel has sun tracking control software to ensure that it is perpendicularly exposed to maximum direct sunlight at all times. Extreme precision is necessary for optimal electricity production. A deviation of as little as one degree from the ideal angle can degrade production by up to fifteen percent. The trajectory it follows is programmed using astronomical data. Periodically it also runs an accuracy-check procedure where it adjusts the panel's angle while monitoring power output to determine whether it is actually pointing in the most advantageous direction. Unfortunately that data is not used to correct the tracking path if it is not ideal. The array includes a power electronics system to manage AC inversion and other parameters for optimal power output [24].

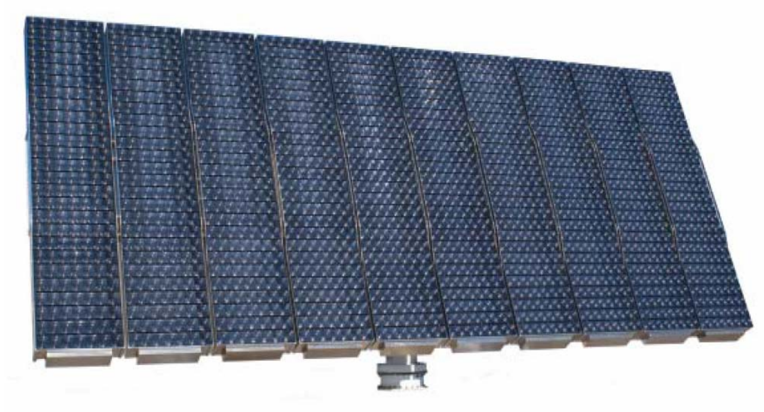

Figure 8: Emcore Concentrator Photovoltaic Array [24]

3.3.2 CPV Characterization

Rated maximum power output for the CPV under standard operating conditions is 25 kW. According to the specification sheet this is temperature dependent, but calculations on the data provided for the temperature extremes at the installation site suggest a maximum power loss of 2% (at 122° F) and even lower loss at more common temperatures (1.2% at 104° F and 0.4% at 50° F) [24]. Consideration of the spec sheet data is good for a brief introduction to the unit, but there is a better source of that information for the purposes of this project. A performance test of a sample unit was executed in Albuquerque which provides experimental data for local performance.

A data set was provided by the Playas site team that cataloged the power output of the CPV panel for the daylight hours of September 4, 2008 [28]. The data is highly detailed with three to four samples per minute, as shown in Figure 9 below.

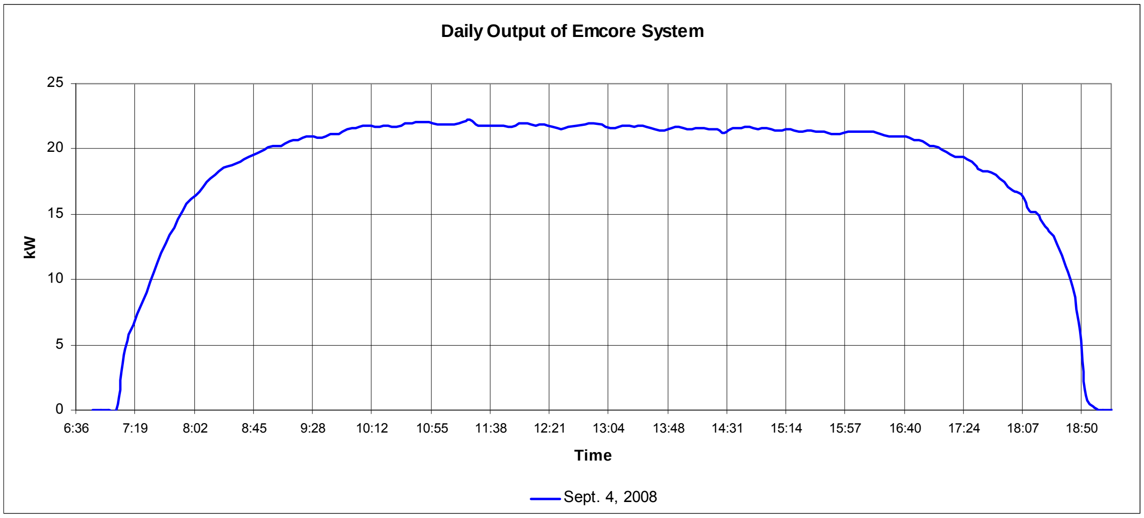

Figure 9: Daily CPV output profile based on experimental data from 9/4/2008

Albuquerque-specific solar irradiation data is available from the National Oceanic and Atmospheric Administration (NOAA) ISIS database [29]. Measurements were recorded by the National Weather Service office at the Albuquerque airport. This data is in three-minute resolution and shown in Figure 10 below which illustrates the solar profile for that day.

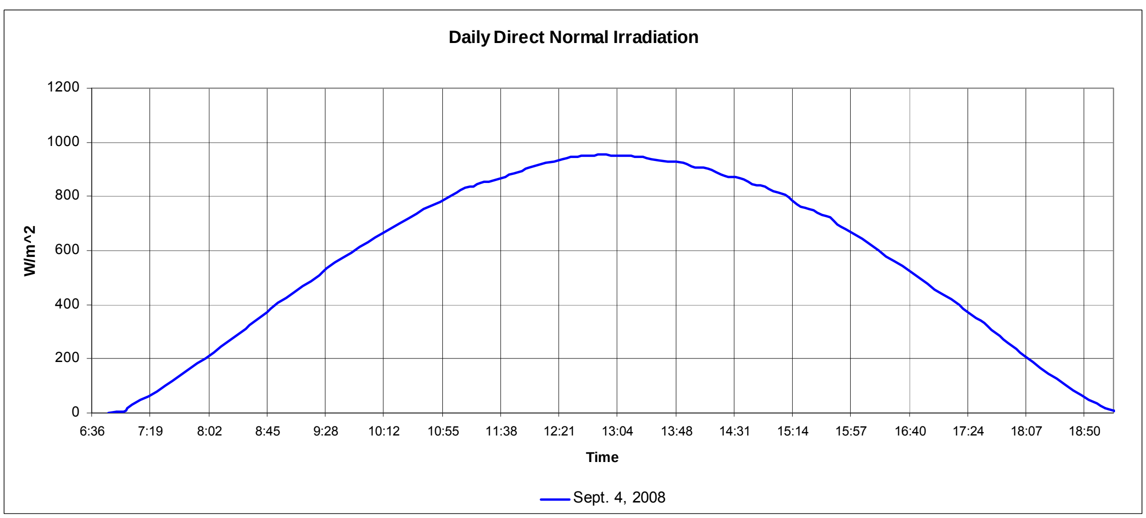

Figure 10: ISIS solar irradiation profile for Albuquerque NM on 9/4/2008

Samples were taken from both the CPVs measured power output and the ISIS solar database at 6-minute intervals in an attempt to replicate the resolution of the Playas area solar data. These two parameters were then plotted over the course of that day in Figure 11 below. It can be observed that the rising and falling of the sun follows nearly the same line. In an effort to characterize the panel with a single line, the average of the plots for the rising and falling sun was generated and plotted.

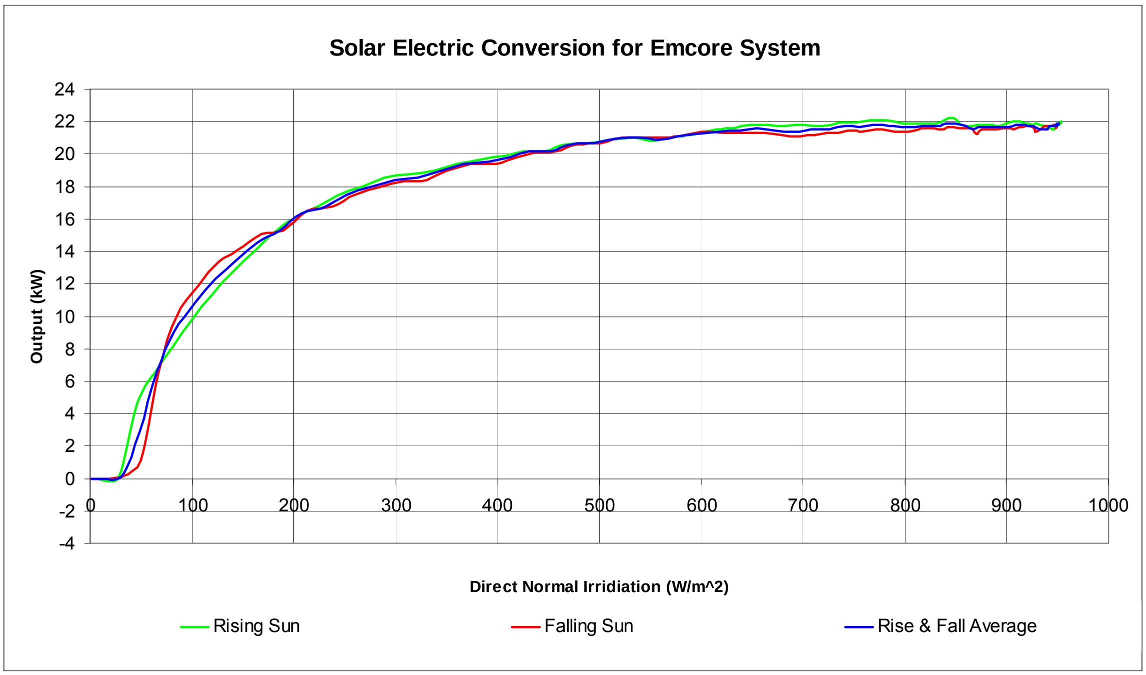

Figure 11: Electric conversion profile for CPV panel

Two polynomials were then generated using the least-squares method to approximate that production curve—one in Microsoft Excel, and the other in MATLAB. Both were 6^{th} order functions. One of these polynomials would be used with solar irradiation data to calculate the expected power output of the CPV panel. The MATLAB program is shown below.

```
data = csvread ('SolarVsPowerOutputData.csv');
x = data(:,1);
y = data(:,2);
polyfit (x,y,6)
```

The results generated by the program, shown below, are the coefficients of the polynomial in the following form, where the independent variable x is the solar intensity and the dependent variable Y is the CPV power output.

$$Y = Ax^6 + Bx^5 + Cx^4 + Dx^3 + Ex^2 + Fx + G$$

```
A = 382.4216e-018
B = -924.5694e-015
C = 616.3000e-012
D = 138.0168e-009
E = -332.3873e-006
F = 144.5586e-003
G = -1.5323e+000
```

Both polynomial curves were plotted on the graph as well as seen in Figure 12 below. Excel can calculate polynomial fits up to the sixth-order. MATLAB can plot higher-order polynomials with the Polyfit function [30], but experimentation with various orders resulted in a best fit at the sixth order. Higher order polynomials fit the curved portions quite well, but had unsuitable anomalies in the flattening horizontal portion. The sixth-order polynomials generated by both tools are so similar that they print precisely on top of each other on the plot. Since Matlab was to be used for the characterization calculations later, its polynomial was chosen for the job to simplify the computations.

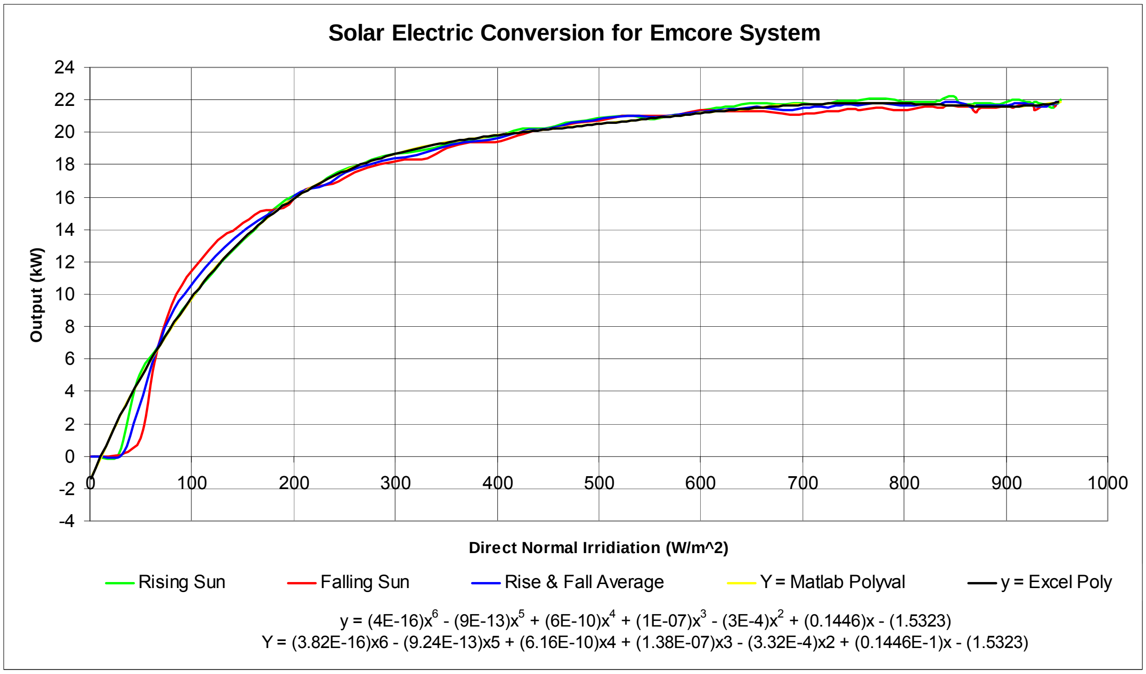

Figure 12: Electric conversion profile with polynomials

A close look at the plot reveals a complication with the polynomial approximation. The function appears to have difficulty estimating the tight curves near the bottom of the power output range, near zero. The resulting dip below the zero power axis creates a formidable problem with the data generated by the polynomial. Negative values for power production will make it appear as though the panel is consuming electricity at low sun exposure levels when in reality it is neither consuming nor generating. Since the power balance between generation and consumption is the entire purpose of this experiment, such anomalies would certainly prove problematic. A simple fix for this problem was implemented. The data generated by the polynomial was filtered to change any negative values to zeros (which only happened at times of very low, or zero, sunlight exposure).

As alluded to above, the polynomial was used to create a time series of power production values for every sixth minute of the day. Using the Matlab polyval function, each sample of the solar irradiation was plugged into the polynomial to calculate the expected power output for he panel. The program is shown below. It opens the solar data file, plugs each value into the polynomial to evaluate the output power value, then stores the pair of values into a new results file.

```
x = csvread ('SolarDataForSampleDay.csv');
P = [382.4216e-018, -924.5694e-015, 616.3000e-012,
138.0168e-009, -332.3873e-006, 144.5586e-003,
-1.5323e+000];
y = polyval (P,x);
results=[x,y];
csvwrite ('ResultsForSampleDay.csv',results)
```

The resulting CSV file, became the CPV source power parameterization data. In an effort to test the validity of the theoretical power production profile, the theoretical data was plotted on the same graph as the original experimental production plot, as seen in Figure 13 below. Note how the calculated plot correlates nicely to the experimental plot, with the added benefit of some smoothing as well. This validates the accuracy of the polynomial used, allowing for its continued application in the annual source profiling process described in the next section.

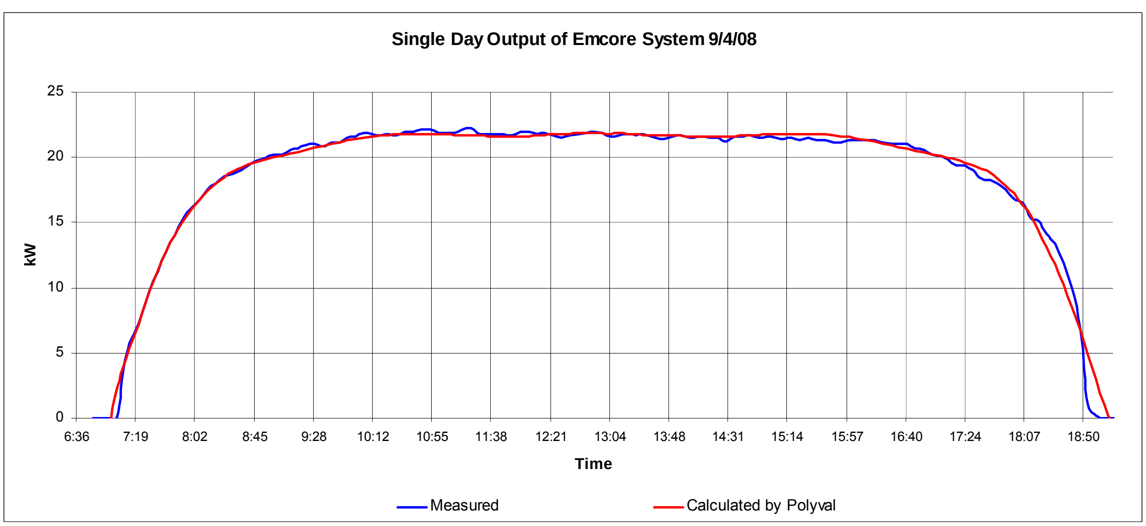

Figure 13: Single day CPV power output: experimental and theoretical values

3.3.3 Solar Irradiation Profile for the Installation Site

Estimating conversion of solar energy to electricity is dependent upon the pattern of solar radiation at the installation site. There are sources of geographical information available that can predict the sun's trajectory and provide solar intensity projections. One such example considered for this study is the Bird Clear Sky Model developed by the Solar Energy Research Institute (SERI) [31, 32]. This spreadsheet-based tool calculates the solar radiation projections based on a number of user-defined parameters such as geographical coordinates, altitude (by using the nominal atmospheric pressure), moisture (indicated by the total moisture in a vertical column), and others. The solar data was compiled using as many of these parameters as possible using various geographical information sources [33, 34], and utilizing the provided defaults for parameters that were not readily available. The computed results were saved for later comparison against other options. The problem with using this calculator is that it provides an estimation of clear-sky radiation and does not offer any simulation of weather patterns that are sure to impact real-world conditions at the site. While New Mexico is a predominantly sunny state with more than 300 days of sunshine per year, assuming the site would experience no solar-compromising weather at all would likely introduce a substantial source of error in the analysis.

Because of such concerns, the solar radiation information would ideally come from historical data collected at the location where the CPV array would be installed. Unfortunately no such local data was available for this study. However, there are a number of databases that catalog such information for a variety of sites across the USA and elsewhere. The ideal sample site would be as close to the installation site as possible, and share maximum similarity in daily solar trajectory.

Closest available solar profile

Two locations relatively similar to the installation site were identified using the Cooperative Network for Renewable Resource Measurements (CONFRRM) database [27]. Both of the chosen sites (seen in Figure 14 below) were within reasonable proximity to the installation site, one located 173 km to the northeast in Las Cruces, NM, and the other 201 km to the east in El Paso, TX [35, 36]. Both collection sites are similar to the Playas elevation of 1371 meters, at 1201 and 1219 meters, respectively. A key indicator for a site with similar solar exposure is latitude. Drawing a vector from Playas to each potential data collection site, the Las Cruces site's latitude displacement component points 24 km north of Playas, whereas the El Paso site is 8 km south, suggesting it would have a more similar solar profile.

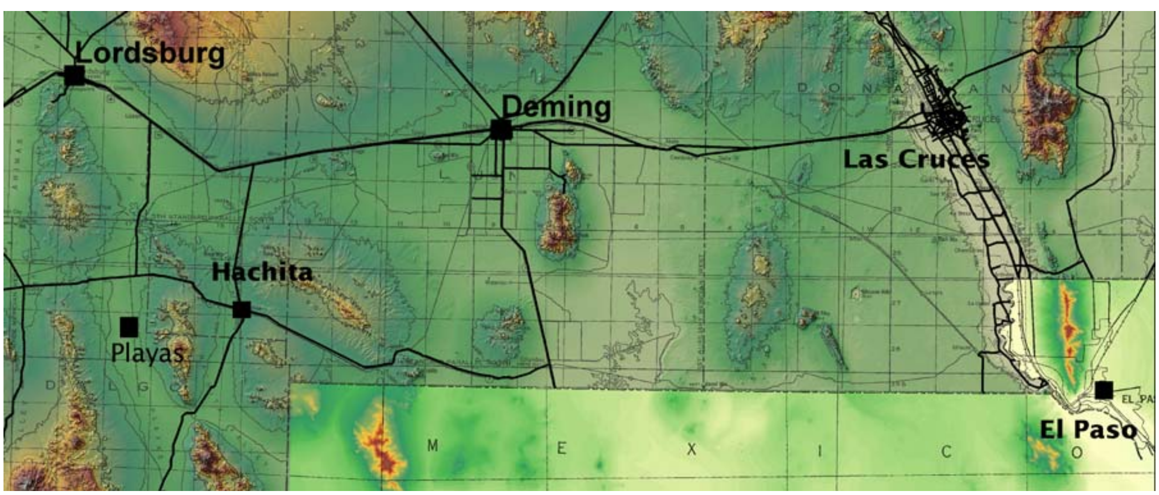

Figure 14: Map of Playas NM region [37]

Validating usage of closest data

Assuming that a closer latitude match would result in a more similar day length, astronomical data from the National Oceanic and Atmospheric Administration (NOAA) was considered. The NOAA sunrise and sunset calculator [38] was used to determine the times of sunrise and sunset at Playas and the two other locations. This information was used to compute the length of the day at each site on four sample dates spread throughout 1999, the one full year that historical data was available for both sites. The summer and winter solstices and vernal and autumnal equinoxes were chosen as comparison dates since they offer both the extreme cases of day/night proportion and the equilibrium points, and they are distributed evenly throughout the solar calendar.

Compared to the data for Playas, the Las Cruces site had matching day length for the equinoxes and a difference of +2 minutes and -2 minutes for the summer and winter solstices respectively. The El Paso data had matching lengths for both solstices and the autumnal equinox, with a +1 minute difference on the vernal equinox. By this comparison it appears that either choice would be reasonably similar to the Playas site. Las Cruces had larger deviations, but since one is positive and the other equally negative, they would likely offset each other over the course of the year. The El Paso site deviated on only one comparison day, and by only one minute, but the unbalanced nature suggests it might be slightly less comparable despite the smaller difference. In either case, the sample sites had worst-case day length differences of less than a half percent of the total day length. The Bird Clear-sky Model irradiation results were equal to or slightly higher than either site, confirming that, with occasional cloudiness, the site data was realistic.

The Las Cruces data was ultimately chosen as the best comparison. Its day length deviation had a balanced offset, and it was located closer to the Playas site. Furthermore, there was an additional swaying factor. The data collected in Las Cruces included additional measurements for wind speed and direction, which the El Paso data did not. These parameters were not specifically needed for this study, but if later work were to be done on this project, or at the same site, that might be able to take advantage of the extra data, its availability could be advantageous.

The data came in the form of comma-separated value (CSV) files, one per month, for the year 1999 which was the most recent year that there was data for every month. There are several solar measurements included in the data but, as mentioned earlier, only the direct normal irradiance is relevant for the design of solar panel in use for this project. Measurements were taken every five minutes for the entire year. Ten of the monthly files were fully complete, but the months of January and July were missing a total of three periods of approximately 62, 72, and 96 hours. The CSV files from January 2000 and July 1998 were used to replace missing data for the same dates and times in 1999. The choice of a single year for this data is not ideal. It likely would have been better to use some combination of years to minimize the impact of a particular year's weather trends, but data for locations this close to the isolated installation site is hard to come by and the available data sets have limited time coverage. Regardless, it was assumed that data which incorporates at least some kind of weather impact would be better than the Bird calculator that assumes 100% sunshine every day.

3.3.4 Projected Annual Solar Source Profile

The first step in creating the annual conversion projections was to get the solar data into the same resolution as the load data. The load data was at one-minute resolution which was worth preserving for maximum accuracy in the dynamic source/load interaction in the power balance profile. Therefore, rather than averaging the load data from one to five minute resolution, the solar data was expanded from five to one minute resolution. The intermediate data was interpolated a linear progression between existing values. This provided a smoother transition between known values than the stepped progression that would have resulted from repeating each value five times.

Similar to the characterization process for the CPV panel mentioned earlier, the same polynomial equation was used to create a time series of power production values for every minute of the year. Using the Matlab Polyval function, each month's solar irradiation CSV file was opened, each value was plugged into the polynomial which generated a power output figure for that irradiation value, and the resulting data was stored in a new CSV file.

The resulting files became the CPV source power parameterization data for the entire year. They are the same sizes as their corresponding monthly load profile files so that computations can be performed on them in pairs during the analysis stage, as explained in the next section.

3.4 Analysis

3.4.1 Overview

There are four main functions of the overall analysis:

A. Perform the calculations and plots necessary for technical characterization of the inputs, which in this case are the system components and variables that affect them. This has already been performed and described above. The Emcore CPV source and C&CC building load are characterized to one-minute resolution for an entire year.

B. Compute the interaction of the components and display the results. This is where a mathematical engine is applied to the data inputs to determine the power balance between source and load for each minute of the year, and the results are displayed in a clear format for the user to review, along with other considerations such as financial and environmental factors. This will be performed three times to calculate results for the integration of one, two, or three CPV panels.

C. Allow the user to adjust parameters and observe the resulting effects. In this portion the user will be able to adjust constants and recalculate various values that relate to the energy costs, net metering and renewable energy credit programs, project term and financing options. The results will update accordingly so the user can evaluate the implications of various parameters.

D. Provide meaningful information to assist the user in evaluating the various options and making system design choices.

3.4.2 Tools

Now that the needs have been defined, and much of the preparation work has been completed, it is necessary to evaluate the possible options for the decision support analysis tool(s) that will be most advantageous for this application. As discussed previously, there are two leading contenders among the existing simulation packages, plus the remaining third option to create one from scratch. However, since so much work has already been done to characterize the load and source, some of the difficult analysis, for which the existing tools are typically helpful, will not need to be performed. In fact, since that is a major component of what those packages do, it is safe to say that much of their capability will not need to be utilized. Furthermore there are some other factors that make the existing choices less attractive.

First of all, both HOMER and Hybrid2 are meant to characterize a system from the ground up and help the user make choices between various types and quantities of system components. This project differs in that it aims to evaluate a particular system setup (albeit at three different quantities of the same source). Secondly, the existing packages favor the use of traditional PV equipment. The CPV array behaves quite differently, so traditional PV conversion profiles used by existing software packages can not be expected to characterize the CPV accurately. HOMER offers the capability to provide custom characterizations for wind turbines and other energy sources, but the PV source module does not offer much beyond simple specifications found only on traditional PV panels Therefore, it would be very difficult to customize it to this application.

Additionally, the data compiled for this project is in much greater detail than those programs typically handle. HOMER is built around using and generating data at one-hour resolution. Clearly it is meant for looking at the bigger picture of performance over years or decades. This study is aimed at understanding the performance of the system on a per-minute basis.

Finally, the energy industry currently offers a variety of renewable energy programs that consumers can take advantage of. Some of these involve net metering at an even exchange, others buy and sell electricity from the consumer at different rates, and some also offer to buy renewable energy credits from customers that generate and use their own electricity. (Yes, it is possible to get paid for electricity that never goes into the grid.) PNM, the largest power utility in New Mexico offers one such program [39]. Existing tools have the capability to handle the first two of these examples, but no available option was found that could accommodate the third possibility of including renewable energy credit income into the financial projections for the system.

While these issues do not necessarily indicate shortcomings in the existing tools, they do suggest an incompatibility with the goals and needs of this study. Therefore it is prudent to consider a custom solution that is more directed toward the specifics of the work being conducted. Since characterization of the source and load has already been performed, a large portion of the simulation tool's task is already completed. The remaining parts would be to perform the power balance analysis and summarize the input and output data in an interactive interface, which is not necessarily the largest part of the project. MATLAB and Microsoft Excel have already been used extensively in the study so far, and offer highly convenient mathematical tools that can be used to perform the remainder of the analysis tasks. Furthermore, the data being used is already in formats that were created by these programs, and the principle investigator in the study is adequately proficient in both to use them effectively and efficiently. It is therefore a fairly straightforward decision to create a custom analysis tool for this application.

3.4.3 Computation

Analysis of the power system actually involves relatively simple calculations. The difficulty lies in the sheer quantity of data. The source and load profiles are characterized at one-minute resolution, which is of great benefit to the detail level of the study. However, there are 525,500 minutes in a year. Dealing with data files that contain more than a half million values is relatively cumbersome. The upper limit for rows in an Excel file is 65,000. It is possible to create CSV files larger than that, but the problem of how to view them conveniently would remain. Despite the added convenience that would be gained by using a single data file for each (source and load) profile, it was determined such large files would be overly difficult to manage. The chosen solution was to keep the data organized by month, which meant that there would be 24 files in total for the input data (12 each for source and load), and twelve files for the output. Actually a total of 36 output files would be generated because the simulation was run three times to simulate one, two, and three connected CPV panels. While the logistics were time consuming, the files were of manageable size and error checking remained relatively simple.

The monthly source data and load data contained various quantities of values depending on the length of the month. These quantities were used as a check to be sure each file was the proper length and that when computed the source and load data array sizes matched appropriately. This also helped to ensure that the proper files were being used for each computational step. Furthermore, the output file sizes were correlated to the input file sizes as an additional indicator of properly matched data arrays.

The fundamental calculation involved is to perform a power balance check for each minute of the year. Essentially this means that the source power was subtracted from the load power on a minute-by-minute basis. A positive result indicates that the load power demand is larger than the power coming from the source and results in that quantity of power being drawn from the electric utility grid, which is referred to in this study as "deficit power." A negative result indicates that the source is producing more power than the load is consuming. This is "surplus power" that could be stored on site if such components were included in the system. Since that is not the case for this project, the extra energy will be net metered back to the grid. In cases where the purchase and sale price of net metered energy is the same, this can be thought of as ‘storing’ the electricity on the grid for later retrieval. The energy is not actually being stored, but the net effect is the same. In reality it is being deposited into the grid for immediate use elsewhere, and when an equivalent amount of new energy is used from the grid later it is thought of as being retrieved.

To preserve the per-minute dynamic, these positive and negative values could not simply be added up over time to determine the total amount of power used from the grid. Instead the positive and negative values would need to be added independently to generate separate total watt-minute values for deficit and surplus energy (later converted to kWH). Maintaining the separation is important because it allows the analysis stage to evaluate the earning potential for the surplus energy, to calculate possible renewable energy credits, and to determine how much timing mismatch there is between when power is being generated and when it is being consumed.

With these constraints in mind, a MATLAB program was written to perform the computation. It is remarkably simple. It first loads each monthly data input file into a 1xN array of values where N is the number of minutes in the month (lines 1 and 2 of the program below). It multiplies each row in the source file by the corresponding row in the load file (line 3 below). Finally it writes the result to a new power balance output data file (line 4 below). This shows the program as run for the month of January, as indicated by the “01” designator at the end of each file name.

```
1 source = csvread('SourceDataMonth01.csv');
2 load = csvread('LoadDataMonth01.csv');
3 powerbalance = load – 1*source;
4 csvwrite('PowerBalanceDataMonth01.csv',powerbalance);
```

The program was run twelve times, changing the month designator numbers each time, to generate the full year of power balance data. It was then run twelve additional times with the same process but using a value of 2 instead of a 1 in line three, where the source array is multiplied by a constant, to characterize the case where there are two CPV panels connected to the system. Finally this process was repeated again for the case of three connected panels. The programs each ran for about two seconds. Certainly the logistical management of the many files created was more cumbersome than running the program itself. Future projects using this kind of analysis would likely benefit from efforts to automate some or all of this process.

3.4.4 Actual vs. Predicted Value Check

As a method of validating the solar data profile used, which was from 1999 (utilized because it was a complete year of data where other sites lacked such detail for a complete year), a sample week was chosen from the data set to compare to more recent 2009 solar data from Weather Underground [40] taken in nearby Deming NM. This check was performed at five-minute resolution. Expected power output from the CPV panel was calculated using both solar data sets from the week that the detailed load measurements were taken, as a relevant time period, and plotted in Figure 15 below.

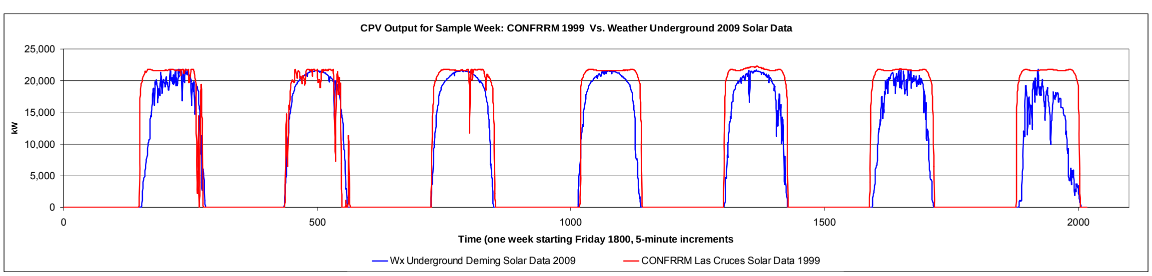

Figure 15: Expected CPV power output comparison

Correlation is relatively close, however the 1999 data appears to have faster rise/fall times. It is unknown whether the 2009 Deming data represents direct normal radiation (which is what the 1999 Las Cruces data uses) or some other measure. From the sloped profile it is suspected that it may represent radiation on a horizontal panel rather than direct radiation. Deming is located at approximately the same longitude as the location where the Las Cruces data was collected, so the north/south displacement likely has little impact. In the absence of any information about the Deming data collection instrumentation setup or calibration, this can serve only as a rough comparison.

As a check on the load profiling system used in the analysis, a plot was generated that compares the actual week of real time data to the profile generated by the load characterization process for the same week. Figure 16 below includes both plots on the same graph.

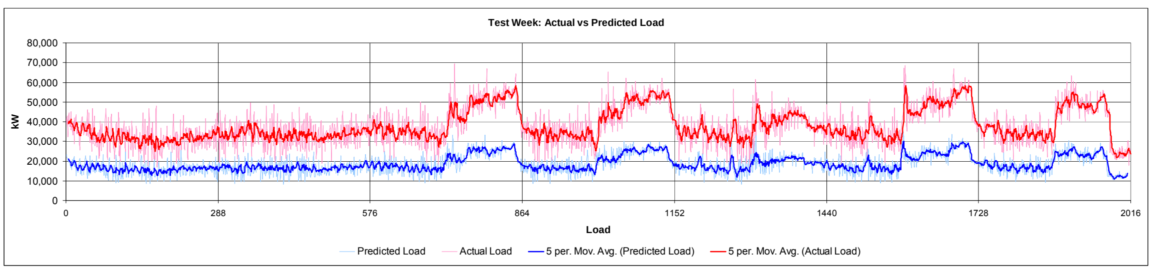

Figure 16: Load comparison: Actual vs. profile

The point of this comparison is to determine if the prediction for the test week matches in shape to the original data, which should confirm that the load profiling process was accurate. We are primarily interested in the change in load because the magnitude was assumed to match the 3-year average of the historical billing data. As seen in the plot, the curves correlate closely in shape which indicates success in the characterization of the change in load over time. Clearly the actual test week's load was of higher magnitude, and until more recent data can be assembled it is unknown if that is a general trend or not.

Another data check of interest involves comparing the power balance plots (again, for the test week) of the profiled source and load data against the actual source and load data. This generates a plot for the week of profile data using with the profiled solar source from 1999 in Las Cruces, and a separate plot for the actual load data using the 2009 solar data from Deming. These are plotted in Figures 17-18 below.

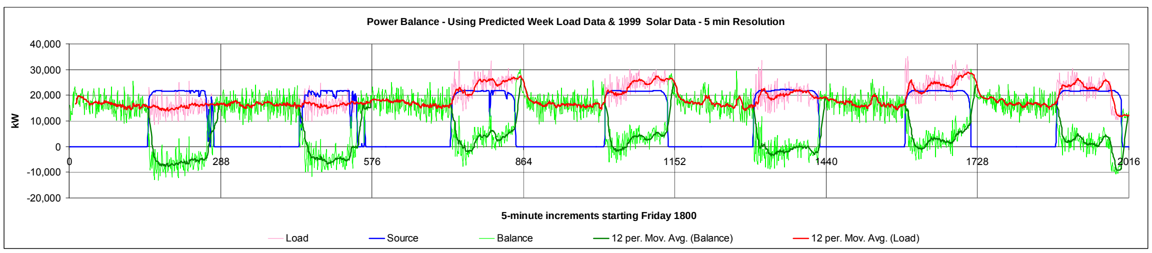

Figure 17: Power balance for profiled data sets

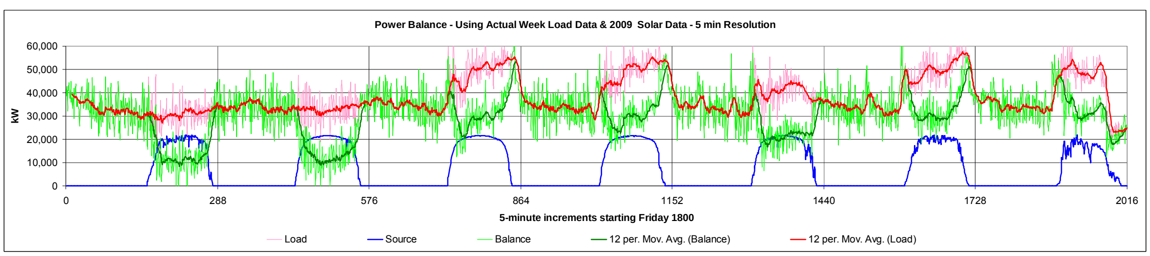

Figure 18: Power balance for actual data sets

More on the power balance analysis can be found in section 3.5 where the analysis results are discussed. For now this offers an opportunity for a first glimpse of how the load and source will interact. Figure 17 shows some periods of negative power balance values. These are times when the source is producing more than the load is consuming, thereby generating a surplus. Figure 18 shows that when the load is always greater than the source power, there is no surplus energy available for storage or net metering back to the grid. These dynamics will be discussed more thoroughly later.

3.4.5 Results Interface

While that all may seem like a straightforward exercise, the substantial portion of the analysis is processing that power balance data and presenting it in a meaningful format. The user needs to be able to read and understand the output data, and its implications. Furthermore, the financial and environmental calculations still need to be made in a way that allows for user adjustment of relevant constants. Microsoft Excel was chosen as the interface for this since it offers a convenient user interface with the computational tools necessary to present the information in a mathematically interactive format. In other words, the user will be able to enter the user-adjustable parameters, and the interface will recalculate the results based on that input. This mathematically capable interface can also be used as an effective data verification and error calculation tool.

A three-page spreadsheet was developed to perform this group of functions, one page per panel quantity (representing one, two and three connected CPV panels). Months of the year are represented in columns and the data and calculations are represented in rows. Refer to Figure 19 below for a selection from the spreadsheet. Certain months have been omitted in an effort to fit a reasonable portion of the sheet onto the page. Full-page panel prints of the spreadsheet's three pages can be found in the Appendix of this thesis.

Jan	Jul	Sept	Oct	Nov	Dec	Total	W-min
676,254,094	912,030,161	1,341,673,436	1,058,903,202	802,093,729	644,611,520	10,632,437,358	Total Load Power
357,881,135	373,613,428	372,290,813	401,330,539	382,964,902	290,548,766	4,623,308,886	Total Source Power
395,403,928	564,792,291	972,260,202	673,089,463	463,227,957	423,842,159	6,617,409,815	Debt used from grid
(77,030,977)	(26,375,592)	(2,877,623)	(15,516,728)	(44,099,077)	(69,779,413)	(608,281,347)	Surplus
280,850,158	347,237,836	369,413,190	385,813,810	338,865,825	220,769,353		Site-consumed RES
676,254,086	912,030,127	1,341,673,392	1,058,903,274	802,093,782	644,611,512	10,632,437,354	Load check
357,881,135	373,613,428	372,290,813	401,330,539	382,964,902	290,548,766	4,623,308,886	source check

Jan	Jul	Sept	Oct	Nov	Dec	Total	kWH
11,271	15,201	22,361	17,648	13,368	10,744	177,207	Total Load Power
5,965	6,227	6,205	6,689	6,383	4,842	77,055	Total Source Power
11,240	15,120	22,240	17,600	13,480	10,694	177,254	3-yr avg billed power
-0.27%	-0.53%	-0.55%	-0.27%	0.83%	-0.46%	0.03%	% error
6,590	9,413	16,204	11,218	7,720	7,064	110,290	Debt used from grid
(1,284)	(440)	(48)	(259)	(735)	(1,163)	(10,138)	Surplus
4,681	5,787	6,157	6,430	5,648	3,679	66,917	Site-consumed RES
11,271	15,201	22,361	17,648	13,368	10,744	177,207	Power check
5,965	6,227	6,205	6,689	6,383	4,842	77,055	Source Check
							Net Metering
5,306	8,974	16,156	10,960	6,985	5,901	100,152	Net kWH
5,965	6,227	6,205	6,689	6,383	4,842	77,055	Savings kWH
53%	41%	28%	38%	48%	45%	43%	kWH Savings %
							Financial
461	659	1,134	785	540	494	7,720	Cost kWH
(90)	(31)	(3)	(18)	(51)	(81)	(710)	Income kWH
(702)	(868)	(924)	(965)	(847)	(552)	(10,038)	Income RE Credits
(331)	(240)	207	(197)	(358)	(139)	**(3,027)**	**Net Annual Cost**
789	1,064	1,565	1,235	936	752	12,405	Grid cost w/o RES
1,120	1,304	1,358	1,433	1,294	891	**16,431**	**Savings $**
142%	123%	87%	116%	138%	118%	**124%**	**Savings %**
							Emissions kg
4,165	5,949	10,241	7,090	4,879	4,464	69,703	Carbon Dioxide
18	26	44	31	21	19	302	Sulfer Dioxide
9	13	22	15	10	9	148	Nitrogen Oxides
							Emissions w/o RES kg
7,123	9,607	14,132	11,154	8,449	6,790	111,995	Carbon Dioxide
31	42	61	48	37	29	486	Sulfer Dioxide
15	20	30	24	18	14	237	Nitrogen Oxides
							Savings kg (NoRES - Debt)
2,958	3,658	3,891	4,064	3,569	2,325	42,292	Carbon Dioxide
13	16	17	18	15	10	183	Sulfer Dioxide
6	8	8	9	8	5	90	Nitrogen Oxides
							Savings kg (all RES)
3,770	3,935	3,921	4,227	4,034	3,060	48,699	Carbon Dioxide
16	17	17	18	17	13	211	Sulfer Dioxide
8	8	8	9	9	6	103	Nitrogen Oxides
							Savings %
42%	38%	28%	36%	42%	34%	38%	w/o surplus RES
53%	41%	28%	38%	48%	45%	43%	considering all RES

From data files
Error checking
Converted from W-min
User constants

User Constants

Energy cost	
$/kWH	
0.07	Purchase electricley
0.07	Sell back electricity
0.15	Renewalbe Energy Credits

Emissions Released	
g/kWH	
632	
2.74	
1.34	

Financial Analysis

$	250,000.00	RES Total cost
$	250,000.00	Principal Investment
$	-	Financed amount
	7%	Interest Rate (annual %)
	120	Term (months)
	$0.00	Monthly Payment
$	-	Financed cost
$	-	Interest expense
$	1,200.00	Annual maintenance cost
$	**(1,828.82)**	**Annual total cost**
$	250,000.00	Total Capital Cost
	16	Payback period (years)
	20	System lifespan
$	248,090.21	Total lifetime cost w/o RES
$	213,461.62	Total lifetime cost w/ RES
$	34,628.58	Total life savings or (loss)
	14%	Total life savings or (loss)

Figure 19: Selection from analysis spreadsheet

The first effort was to extract the sums of positive and negative power balances from each monthly results file. The source and load power data for each month was also summed and entered in the spreadsheet to use for error-checking. These sums were performed separately within each data file and the values were pasted into the spreadsheet. Again, with this file management hassle, an automated process would have been a time saver. This data is found in the top box of the spreadsheet and comes in the form of watt-minutes, which is not a particularly useful unit. So, a separate section of the spreadsheet shows the same information converted into kilowatt-hours (kWH) which is the standard unit for power utility bills, and it is more user-friendly. This is the middle box on the sheet which contains most of the information that will interest the user.

In the middle box portion of the sheet, two important error-checking opportunities were exploited. The power utility bill data that was originally used to project the per-minute load profiles was retrieved. Each month's three-year average of total kilowatt hour consumption was entered directly into the spreadsheet in the *3-yr average billed power* row (highlighted in blue). Then, the theoretical sum of power consumed for that month (as calculated by the load profiling process and used in the power balance calculations) was compared to that original consumption value derived from the power bills and a percentage error was calculated in the *% error* row (highlighted in purple). This completes a critical loop of verifying whether each month's theoretical power consumption derived by the load profile matched the original data it was based upon. Error was extremely low, ranging from 0.0 to 0.83%. This helps to confirm that there were no obvious problems with the data processing that were used to create the monthly load profiles.

The source profiles already had some assurance of accuracy from the comparison made between the sample production day and the projected production computed by the polynomial calculations. However, as an additional check, one of the monthly sums was compared to an estimated month's worth of CPV production, based on the test day data. Roughly integrating the area under the Emcore daily production curve, and multiplying it by 30 days, results in a monthly estimate of 7000 kWH for the month of September (the same month as the one-day test was performed). Analysis results showed production of 6200 kWH, a difference of 13%. This comparison is very rough, however, because the estimate assumes the same solar irradiation for every day of the month, but the test was performed in the first week of September. Days get shorter as the month progresses, so the solar irradiation, and resulting power production, should decline accordingly. Also, the test location in Albuquerque has different solar, atmospheric, geographic and climatic conditions than the Playas installation location for which the source profile was built. Regardless, considering the variances in parameters which could easily cause that degree of error, it is sufficiently low to conclude that major problems with the source profile data are unlikely.

The remainder of the spreadsheet handles the calculation and display of energy dynamics, financial evaluation, and environmental factors that are based on the analysis results. The middle box contains all of the monthly information with totals in the right column. The bottom box contains the user inputs and the lifetime financial projections for the installation.

The center box is where most of the analysis is performed. Its top section covers the error checking mentioned above, in addition to some calculations of power supply and demand. Each column represents a month, so the figures mentioned to follow are monthly figures. *Debt used from the grid* is a total of all the positive power entries in the month's simulation results data. This represents the total kWH of electricity drawn from the grid. The next line *Surplus RES* is a sum of all the negative power entries in the month's simulation results data. This represents the total kWH of electricity that was generated and unused on site. This is energy that could be stored if such capacity were available in the system or, as in the case of this study, can be sold back to the utility via net metering (sometimes referred to as 'grid storage' as explained earlier). The next row, *Site-consumed RES* is the difference between total solar energy produced and the amount of that energy that was unused on site during that month. This represents the amount of energy that was produced and consumed on site that would not be reflected in the utility meter. This is relevant data because some utilities offer bonus credits for this figure—essentially they are purchasing renewable energy credits (REC) from the customer in an effort to increase the utility's percentage of renewable energy used on its network. There is a row further down in the spreadsheet where this is calculated, *Income REC Credits*, which multiplies that kWH figure by the user-provided per-kWH price paid by the REC program.

The next section of the center box is where net metering is calculated. The first row, *Net kWH* computes the difference between kWH drawn from and sent back to the grid. This is the net total energy purchased from the utility that month (assuming all surplus was net metered back to the grid). The next row *Savings kWH* is the difference between the total load power consumed and the energy purchased from the utility, thus representing the total amount of energy generated on site. This can be compared to the

Total RES power in the section above as a check, which matches identically for all months. This offers reassurance that the calculations are correct so far. Finally the *kWH Savings %* row indicates the percent reduction in kWH purchased from the utility as compared to not using any RES on site

The next section of the middle box begins the financial considerations. Starting with *Cost kWH* it determines the cost of all the debt power used from the grid. This is not the net kWH amount, rather it is the cost of all the energy drawn from the grid without considering what was sent back. This is calculated separately from the net to allow compensation for a difference in price between purchasing and selling power through the meter. Some utilities charge a retail rate for power delivered to the load that is higher than the wholesale rate at which they buy it back. Therefore, the next line, *Income kWH*, calculates the expected income from the kWH sent back to the utility, and *Income RE Credits* calculates the earning potential of site-consumed RES for cases where there are renewable energy credits available. The following *Net* row calculates the difference between the cost and income to determine the expected utility bill for that month. Next the cost of total power consumed by the load, *Grid Cost w/o RES* is calculated to illustrate what it would have cost to serve that load without any RES. Then a difference in cost is calculated (*Savings $)* and quantified by percent (*Savings %*). This figure is dependent upon the price per kWH of purchasing energy and of selling it back, and any renewable energy credits. All three of these prices are entered by the user in the bottom box.

The final portion of the middle box calculates the emissions figures for carbon dioxide, sulfur dioxide, and nitrogen oxides. The emissions per kWH are user constants that are determined by the way power delivered to that site is produced. HOMER uses a set of default values for this is the user does not specify [6], so for a sample case these theoretical values were used in for lack of better data from the utility. The first group of figures computes the total monthly emissions in kg that would result from generating the kWH listed in *Debt used from the grid* which incorporates energy generated and used on site but ignores net metered power. The next group performs the same calculation on the total power consumed by the load as an indication of emissions in the case where no RES are used. Savings of emissions are calculated as the difference between these two. The next group is a calculation of total emissions assuming that the energy was net metered back to the grid and replaced power that would have otherwise been generated by non-renewable means. The final group of calculations in the emissions section offers two ways to consider pollution reduction. The first case relates to emissions reduction as the result of power generated and used on site, the second relates to emissions reduction as a result of all RES power generated on site. Calculating both allows us to decide whether or not to consider the emissions reductions done on behalf of other customers on the grid by sending them energy cleanly produced by the RES.

Discussion so far on the middle box has referred exclusively to monthly figures. The column to the right of the monthly columns totals the monthly figures into an annual result.

The bottom box is where the user inputs are located, and where the remainder of the financial data is calculated. Here the user provides data for energy costs and emissions statistics, as mentioned previously. These values are hard-linked to the underlying sheets which do all the identical calculations for the cases of using two and three connected panels. It is worth noting that many power utilities have scaling rate structures that are dependent on various consumption thresholds. Since these structures vary from utility to utility and for the service size classification, it was decided to not attempt to incorporate those intricacies in this computational model. The proper rates can be estimated based on the monthly kWH consumption figures when the rate is entered by the user, as will be done for the sample scenario discussed in the next section on output analysis.

The remainder of this box contains a financial calculator for evaluating project lifetime figures. The user enters the up front capital cost including installation, the principle value and interest rate for any loan needed, annual maintenance costs, and life span of the equipment. In some cases significant tax deductions and/or credits are available to offset the capital costs of RES systems, but since they have relatively short term limits and vary greatly by locale and qualifications required, they were not included in this analysis. The spreadsheet calculates the cost of the financing, monthly payment amount, interest expense, and generates a total annual cost including electricity bills. A payback period is also calculated based on savings compared to a system without any RES, and lifetime cost and savings figures in dollars and percent for the RES-integrated system versus the grid-only system without RES. Capital costs, financing, and maintenance costs are entered separately on each sheet to allow for the difference in the cost for installing multiple CPV panels.

3.5 System Characterization and Output Evaluation

Evaluation of the output results is largely dependent upon the specific scenario that is being considered. Analysis results fall into the two categories of power usage and financial/environmental factors. Power usage figures are calculated before entering the spreadsheet, so this is not a dynamic component as with the financial section where user variables can be adjusted. These pertain to the financial aspects of the evaluation. The variety of user-chosen variables involved can quickly create a plethora of hypothetical options to consider. In an effort to simplify the explanation of what can be learned from the simulator's results, two sample scenarios will be used and evaluated for each of the three CPV panel quantity cases. One will assume even trade net metering and the other will add renewable energy credits to the parameters to illustrate their impact. The resulting output will be evaluated and relevant insights will be added to illuminate alternate possibilities when notable. Power issues will first be explored, after which the sample financial scenario will be proposed and analyzed.

As stated, the power figures are not influenced by the user-controlled variables so they will be inspected first. Throughout the remaining analysis, Sheet 1 will refer to the spreadsheet page that details the case where there is a single CPV panel installed, Sheets 2 and 3 will correspond to the cases of two and three connected panels respectively which are the second and third layered sheets in the spreadsheet. Please refer to the Appendix for reproductions of the sheets.

The motivating factor of this study was to determine how the load and source interact. On Sheet 1, using January as an example month, we can see that the total load power consumed is just over 11 MWH. The total RES power produced is just under 6 MWH. The resulting power used from the grid is not simply the difference between these two (approximately 5 MWH). Instead, because the CPV only produces electricity during daylight hours, and it is likely to produce either more or less than the total load at any given moment, the timing of production and consumption must be considered. A graph is be helpful in illustrating this concept. It would be impractical to attempt to show a plot of an entire year, or even a month or week, because the fluctuations would make the plot lines so dense in the space allowed that no discernable information would be apparent. A sample day, however, provides a good snapshot of the dynamics at work (Figures 20-23).

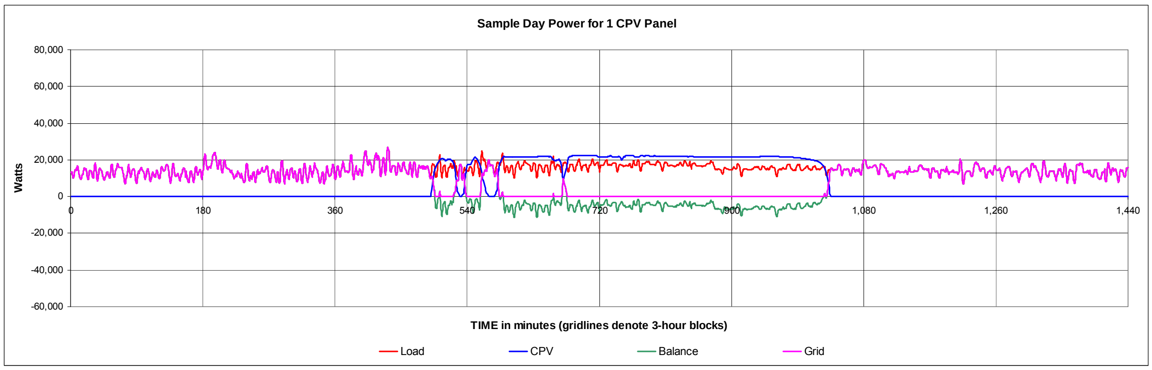

Figure 20: Power for 1 CPV panel from sample day

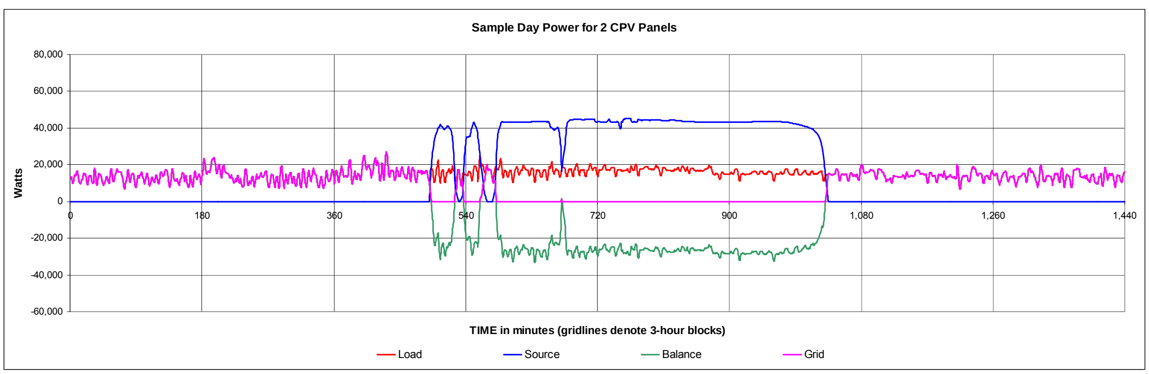

Figure 21: Power for 2 CPV panels from sample day

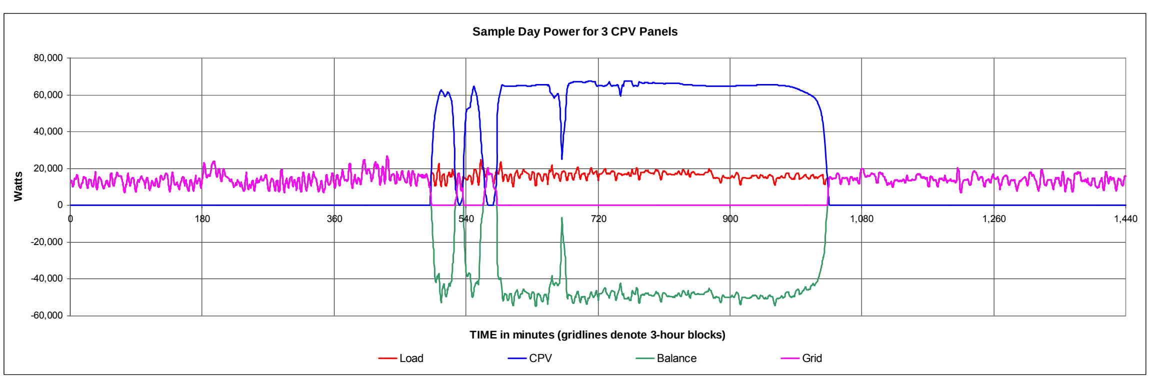

Figure 22: Power for 3 CPV panels from sample day

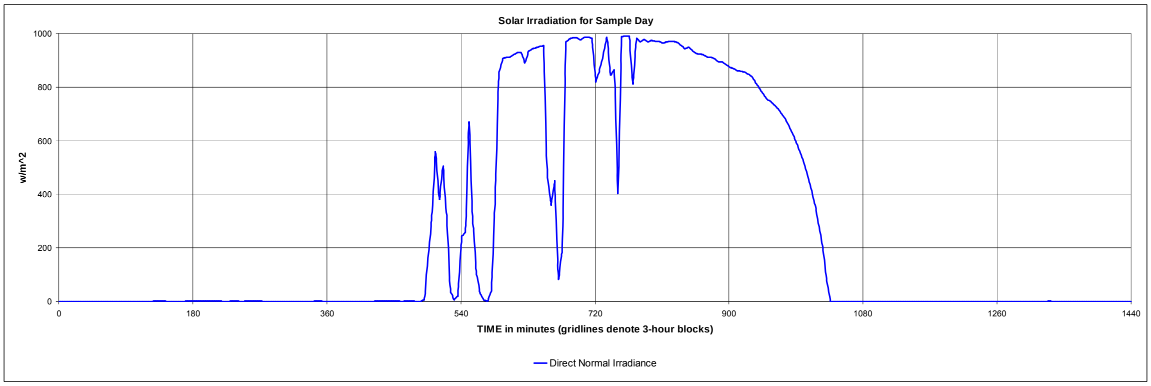

Figure 23: Solar irradiation from sample day

The daily profile of Figures 20-23 shows minutes with vertical gridlines indicating three hour blocks. Figure 23 is a plot of the day's solar intensity, included for reference, on which the mid-day low points likely indicate cloud cover. Figures 20-22 plot the power balance. In the early morning and night time hours the grid consumption, load, and power balance are all synchronized since they are all equal. Around 8:00 AM the blue CPV production quickly peaks as the sun rises. Dips in this plot most likely indicate cloud cover for short periods. It drops back to zero quickly as the sun sets around 5:00 PM.

On all three plots there are times where no grid energy is being utilized, as seen by the flat pink line on the zero axis. Not surprisingly, this occurs when the CPV is producing more energy than the load is consuming. The green line below the axis indicates the total quantity of surplus energy being generated but not consumed on site. Note that none of the simulated quantities of CPV panels create a situation when the grid connection is not utilized for at least a portion of the day. This is partly because the solar system can not generate electricity in the dark, and partly because surplus CPV energy is not stored locally. This explains how, at times—especially as shown on Sheets 2 and 3, power is still being purchased from the grid even though total daily production exceeds the total daily load. This indicates an opportunity to take advantage of net metering and/or storage. On-site storage will gain more advantage over net metering if the price paid for each kWH consumed from the grid is more expensive than the income received per kWH delivered to the grid. On an even exchange net metering arrangement, the storage components (and their expense) can be eliminated in preference of utilizing free "grid storage." In cases where renewable energy credits are available it will likely be more financially beneficial to store on-site, but the cost of the storage components will make that a more complex decision.

These power balance dynamics can be observed numerically on the spreadsheet in the top portion of the middle box. In the January column on Sheet 1, the 1284 kWH of surplus power results in a net consumption of 5306 kWH from the grid if net metering is utilized. This results in a kWH savings of 53% over what the usage would have been without RES connected. Similar observations can be made on Sheets 2 and 3 to find that surplus power increases without much reduction in the monthly grid power usage, as was attributed to night time loads not being served by the CPV.

The next section can be used to consider the costs of the energy management decisions described above. A price of 7¢ per kWH was used in this sample case which accounts for the 5.2¢ Large Power Service rate [41] per kWH in effect for the building, plus approximately $100 in additional costs, which amounts to roughly 1.8¢ per kWH for a month with January's usage. For months where usage is higher the per kWH share of the fixed costs would come down, but leaving the estimate at 7¢ provides a worst-case scenario to prevent overly optimistic figures. This example also assumes even exchange for net metering so the price is also set to 7¢ for the sellback rate. No renewable energy credits are assumed, but the specific benefit thereof will be mentioned when relevant.

The financial implications of net metering for this example are a savings of $418 for a single CPV, but increase to $835 and $1746 for two and three panels. However, the three panel system is operating in a theoretical state in that example, since the utility does not usually purchase the power back, but rather banks it for later use. In this scenario the banked power would accumulate faster than it can be withdrawn which does not generate income. In this case the system would likely be switched over to another program where the utility buys the power back at a lower wholesale rate. This situation does, however, highlight an opportunity to consider using more of the RES generated power on-site, perhaps to feed other nearby loads or feed it into the downstream microgrid of the town. But that is beyond the scope of consideration here. Regardless, care must be taken when using this spreadsheet, especially with multiple panels connected, to not rely on capital investment payback scenarios that would require the theoretical (and unlikely) state where the RES are making a profit. Again, buy-back figures that are set appropriately for those other programs, if available, can alleviate this concern.

Emissions figures call attention to the environmental impact of the RES system. Net metering and/or storing energy on site could, in this case, save 11,309 kg of carbon dioxide emissions for January (this is approximately the amount released by burning 1000 gallons of gasoline in a typical automobile). Other pollutants are quantified here as well. As mentioned earlier, these figures are based on the default values provided in the HOMER simulation software. Utilities do not appear eager to release emissions information since many variables impact these figures, they generally do not produce all of the power they sell, and they may not even be able to calculate it themselves.

The final, and perhaps most useful, portion of the output analysis involves the bottom box on the spreadsheet. This is where the lifetime cost/benefit analysis is calculated. With a retail price of $250,000 per CPV panel, including installation, there is a sizable capital investment required. The test case used that figure for each panel, except the two-panel system assumes a cost of $175,000 each, which reflects a discounted price paid for the pair being used in Playas. By these figures, the three-panel system price may seem disproportionately high, but it is unknown whether it could have been acquired at a discount so its price is left at normal retail. The example scenario also assumes 50% of the project cost would be financed at 7% interest over ten years. A twenty year life span was used as that is the minimum of the various numbers mentioned by sources consulted. Annual maintenance costs were roughly estimated at $100 per month for an annual expense of $1,200.

In all three panel quantity cases, the system fails to pay for itself with these figures. For a single panel the total lifetime cost is 87% higher than what the cost of electricity would have been without the use of RES. The two and three-panel systems cost 92% and 241% extra. It is also noteworthy that this has not accounted for the profitability problem discussed above.

With figures like this, one must consider what the primary motivation of the RES system is. In the case where it is desired to help a load use as little grid energy as possible, then the extra expense may be justifiable. If the intent was to reduce overall cost by integrating RES, then it is not likely to be helpful in this scenario. It is worth mentioning here that the price of three CPV panels could pay for half of the equipment and installation costs of a utility-scale wind turbine rated at 1.6 megawatts. It is common for these to generate about 1,000 kilowatts when operating, which is a scale of more than ten times the 75 kW rating of the trio of CPVs. Wind turbines come with their own set of logistical and regulatory challenges that are much more cumbersome than installing solar panels, so it's nowhere near a direct comparison, but it does offer some perspective.

There is another possible option that would provide a clear benefit. PNM, the largest electric utility in New Mexico offers some renewable energy credit programs that would definitely alter the outlook. These programs may also be available from utilities in other areas. Keeping with all the same assumptions as the previous example, and including a 15¢ REC paid to the customer for each kWH generated and used on site, we get very different results. In this case the single panel option comes within 6% of breaking even. Two panels saves 9% over grid-only, and the three-panel system is 139% higher than the grid-only cost. If financing expenses are eliminated then some cost savings start to appear, as seen in Figure 19, which shows a 14% lifetime savings for the single panel scenario. Two panels saves 36% and three costs 79% extra.

At a grid energy price of 7¢ per kWH these systems may have a hard time paying for themselves, especially without the REC benefit. Raising the rate to 10¢ and keeping the REC rate at 15¢ results in a 9% savings for one panel and 32% savings for two, and costs 58% extra for three panels, with 50% of the investment financed at 7%. Removing the financing option again looks better for the one and two-panel systems which save 23 and 52 percent respectively. The three-panel system is still losing money, costing just 16% more than grid power alone.

Considering these figures, it is easy to conclude that a three-panel system is not an advantageous option unless the customer is willing to pay extra for their clean energy or they can get better pricing. It generates power far in excess of what can be used on-site and thus becomes more of a miniature power plant rather than a local energy source. A two-panel system also looks to be less financially viable than a single in some cases depending on the financial inputs and whether the buyer can secure a discount as in the case of the Playas application. The single panel system does show promise in paying for itself more consistently, largely because it is more closely suited to the power needs of the building, and puts less demand on the payback potential of net metering options.

In cases where utility power is more expensive than these test figures, the possibilities look much more promising, especially if the up-front costs are financed at a lower interest rate, or less money is borrowed. If the load increases significantly above the three-year average assumed for this study (as may already be the case as shown in Figure 18), then more of the generated power would be used on-site and more panels may begin to appear viable, especially when revenue from renewable energy credits can be generated. Also, if quantity discounts are available, or if co-location of multiple panels incur lower installation costs, the figures could look better.

There are also situations where cost savings is not the primary deciding factor, and for those cases the CPV panel may be an attractive option, such as remote areas without grid connections, applications where there is minimal night time load such that less power needs to be purchased, or the simple cases where the customer is willing to pay what it costs to be green. The two-panel scenario, despite breaking even in only the most advantageous scenarios, will spare the planet of 92,000 kg of CO_2 emissions over its lifetime, which is an 87% reduction when compared to grid power alone. Perhaps the wise conclusion is that renewable energy simply costs more. This is assumed to be a contributing factor in the advent of governmental incentives in place to encourage people to undertake renewable energy projects.

CHAPTER 4
CONCLUSION

This project was successful in many ways. While it was not apparent at the outset, the load and source characterization process constituted the bulk of the work, and a significant part of its contribution. Much effort went into carefully considering as many options and variables as possible to make the best possible models for future power consumption by the load and generation by the renewable energy source/s.

Primarily, it involved the construction of large data sets for which there was little confirmed information to start with. Building wisely from know quantities, and interpolating, estimating, and calculating effectively, this project created impressive results. The source characterization was closely correlated with the test that was used to generate it, and the figures that came out after processing were in line with expectations. The load characterization was based on a small amount of data, a single week of detailed data from the data logging meter, combined with three years worth of very simple utility power bills with little more than a total monthly consumption number. It too generated results that closely correlated with expectations. The calculation engine demonstrated its accuracy as well.

Aside from the technical success, this project made a number of valuable contributions to the study of renewable energy systems. First of all, it provided the means to include renewable energy credits in the financial projections. This feature is not available in the popular existing simulation packages. There are some locales where this is a significant factor and by including it in this study a door was opened to bring greater attention to this consideration.

Characterization of the Concentrator Photovoltaic Array's output as a function of the solar irradiation is another important contribution. Whereas this information may be known to the manufacturer, it was not previously available to the user and researcher. As it is a non-traditional application of solar electricity production, modeling its conversion provides insight that other analysis tools could not.

A thorough study of the power quality issues involved was also included in this research, an aspect which is largely undocumented in the existing literature on the topic. For example, by not mentioning it, a great majority of the available studies that focus on integration of RES systems seem to assume that they will be dealing with an ideal power factor, a fully compensated load/source, or that they do not need to consider power factor at all. The respected off-the-shelf simulation tools used for RES system analysis also do not include provisions for calculating or compensating the power factor. While it was determined that power factor would not have a significant impact on the results for the project considered by this study, in the process it did determine the necessary considerations that would be applied in the non-ideal case. Having gone through the exercise of making the power factor determinations appears to be uncommon among similar projects.

The results indicate that, for the load considered, a single CPV panel can be a beneficial addition to the commercial building's energy system. Under various, but not all, conditions it will be able to pay for itself and create cost savings over its lifetime. However, results show that more panels do not add significant benefit in this situation, at the simulated energy usage level. While there are cases where it can, the RES systems under consideration in this study will not necessarily save the customer money, and more is not necessarily better when it comes to RES components. The financial components are based on a diverse set of variables that are difficult to work with in the hypothetical mode, so honing the input parameters to the specific installation situation is essential to making a financial feasibility determination. Regardless, whether the inclusion of the CPV panels in the power system will end up saving money in the long run is not necessarily the motivating factor of those who plan to build the system, so it is important to recognize the other benefits.

Future efforts to carry this work forward would include a number of procedural, improvements in addition to some additional features. For more convenient adaptation to other projects, or to incorporate additional data as it becomes available, such as more recent power bills and more real-time detailed power data, it would be useful to automate more of the data processing steps. A number of cumbersome file management components hinder the simulator's flexibility. There are software tools within MATLAB and elsewhere that could be implemented for an improved design. Adding the capability to accommodate tiered utility rate structures would eliminate an estimation stage that the user needs to compute manually. Also, the inclusion of tax credits and/or other incentives in the financial computations would be beneficial. As this was a project meant for a particular application, some constraints were treated as constants, but the dynamic nature of changing rates, policy, building usage, weather, and other factors, including the desire to apply it to other projects, offer compelling justification to revisit these topics if work were to continue.

In summary, it is clear that this project successfully completed a formidable task of accurately creating large data sets from limited starting information, for both the load and source. The computation engine provided useful results that can be used to make better decisions than would have been possible without the information it generated. It determined that the CPV system in question can be a viable option for the site considered. Additionally, it contributed insight on a number of topics not commonly addressed by previous work.

APPENDIX

Full-page printouts of the evaluation spreadsheet appear on the following pages. Spreadsheets for evaluation of one, two, and three CPV panels, respectively.

Master Summary ::: 1 Panel

W-min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	W-min
Total Load Power	676,254,094	612,000,000	594,652,595	630,046,927	617,413,092	1,028,637,998	912,030,181	1,523,718,645	1,341,673,438	1,058,903,202	802,068,729	664,611,530	10,632,437,358	Total Load Power
Total RES Power	357,861,135	346,350,300	367,774,270	403,779,150	470,051,768	429,915,175	373,613,428	406,606,622	372,290,813	401,330,539	362,966,932	280,548,768	4,623,303,898	Total Source Power
Debt used from grid	395,403,926	341,596,737	320,716,496	328,134,175	401,450,235	614,929,555	554,792,291	1,117,954,607	972,260,202	673,089,463	463,227,857	423,842,159	6,617,409,815	Debt used from grid
Surplus RES	(77,030,977)	(75,947,068)	(123,640,434)	(101,864,445)	(54,118,851)	(16,003,735)	(26,375,592)	(1,024,403)	(2,877,628)	(15,516,728)	(44,059,077)	(69,779,413)	(608,281,367)	Surplus
Site-consumed RES	280,850,158	270,403,232	264,133,835	301,914,705	415,932,937	413,908,441	347,237,836	405,784,219	369,413,180	385,813,810	338,685,825	220,769,355		Site-consumed RES
Load check	676,254,085	611,999,969	594,652,391	630,048,878	617,413,172	1,028,836,005	912,030,127	1,523,718,826	1,341,673,392	1,058,903,274	802,068,782	664,611,512	10,632,437,354	Load check
source check	357,861,135	346,350,300	367,774,270	403,779,150	470,051,768	429,915,175	373,613,428	406,606,622	372,290,813	401,330,539	362,966,932	280,548,768	4,623,303,898	source check

kWH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	kWH
Total Load Power	11,271	10,200	9,746	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,746	177,207	Total Load Power
Total RES Power	5,965	5,773	6,463	6,730	7,634	7,165	6,227	6,780	6,205	6,689	6,363	4,842	77,055	Total Source Power
3-yr avg billed power	11,340	10,200	9,800	10,480	13,640	17,160	15,120	25,600	22,240	17,600	13,480	10,696	177,254	3-yr avg billed power
% error	-0.27%	0.00%	0.54%	-0.20%	0.12%	0.07%	-0.53%	0.80%	-0.55%	-0.27%	0.83%	-0.46%	0.03%	% error
Debt used from grid	6,590	5,693	5,345	5,469	6,691	10,249	9,413	18,632	16,206	11,218	7,720	7,066	110,290	Debt used from grid
Surplus RES	(1,284)	(1,266)	(2,061)	(1,698)	(902)	(267)	(440)	(17)	(48)	(259)	(735)	(1,163)	(10,138)	Surplus
Site-consumed RES	4,681	4,507	4,402	5,032	6,932	6,898	5,787	6,763	6,157	6,430	5,646	3,679	66,917	Site-consumed RES
Load check	11,271	10,200	9,746	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,366	10,746	177,207	Power check
Source Check	5,965	5,773	6,463	6,730	7,634	7,165	6,227	6,780	6,205	6,689	6,363	4,842	77,055	Source Check
Net Metering														Net Metering
Net kWH	5,306	4,427	3,285	3,771	5,769	9,982	8,974	18,615	16,156	10,960	6,965	5,901	100,152	Net kWH
Savings kWH	5,965	5,773	6,463	6,730	7,634	7,165	6,227	6,780	6,205	6,689	6,363	4,842	77,055	Savings kWH
kWH Savings %	53%	57%	66%	64%	56%	42%	41%	27%	28%	38%	48%	45%	43%	kWH Savings %
Financial														Financial
Cost kWH	461	399	374	385	468	717	659	1,304	1,134	785	540	494	7,720	Cost kWH
Income kWH	(90)	(89)	(144)	(119)	(63)	(19)	(31)	(1)	(3)	(18)	(51)	(81)	(710)	Income kWH
Income RE Credits	-	-	-	-	-	-	-	-	-	-	-	-	-	Income RE Credits
Net	371	310	230	266	405	699	628	1,303	1,131	767	489	413	7,011	Net Annual Cost
Grid cost w/o RES	789	714	682	735	954	1,200	1,064	1,778	1,565	1,235	936	752	12,405	Grid cost w/o RES
Savings $	418	404	452	471	548	502	436	475	434	468	447	339	5,394	Savings $
Savings %	53%	57%	66%	64%	56%	42%	41%	27%	28%	38%	48%	45%	43%	Savings %
Emissions kg														Emissions kg
Carbon Dioxide (26)	4,165	3,598	3,378	3,456	4,229	6,477	5,949	11,776	10,241	7,090	4,879	4,466	69,703	Carbon Dioxide
Sulfur Dioxide	18	16	15	15	18	28	26	51	44	31	21	19	302	Sulfur Dioxide
Nitrogen Oxides	9	8	7	7	9	14	13	25	22	15	10	9	148	Nitrogen Oxides
Emissions w/o RES kg														Emissions w/o RES kg
Carbon Dioxide (20)	7,123	6,446	6,160	6,637	8,610	10,837	9,607	16,050	14,132	11,154	8,449	6,790	111,995	Carbon Dioxide
Sulfur Dioxide	31	28	27	29	37	47	42	70	61	48	37	29	486	Sulfur Dioxide
Nitrogen Oxides	15	14	13	14	18	23	20	34	30	24	18	14	237	Nitrogen Oxides
Savings kg (NoRES - Debt)														Savings kg (NoRES - Debt)
Carbon Dioxide	2,958	2,848	2,782	3,180	4,381	4,360	3,658	4,274	3,891	4,064	3,569	2,325	42,292	Carbon Dioxide
Sulfur Dioxide	13	12	12	14	19	19	16	19	17	18	15	10	183	Sulfur Dioxide
Nitrogen Oxides	6	6	6	7	9	9	8	9	8	9	8	5	90	Nitrogen Oxides
Savings kg (all RES)														Savings kg (all RES)
Carbon Dioxide (3.21)	3,770	3,648	4,085	4,253	4,951	4,528	3,935	4,285	3,921	4,227	4,094	3,060	48,699	Carbon Dioxide
Sulfur Dioxide	16	16	18	18	21	20	17	19	17	18	17	13	211	Sulfur Dioxide
Nitrogen Oxides	8	8	9	9	10	10	8	9	8	9	9	6	103	Nitrogen Oxides
Savings %														Savings %
w/o considering surplus RES	42%	44%	45%	48%	51%	40%	38%	27%	28%	36%	42%	34%	38%	w/o considering surplus RES
considering all RES	53%	57%	66%	64%	56%	42%	41%	27%	28%	38%	48%	45%	43%	considering all RES

From data files

Error checking

Converted from W-min

User constants

User Constants

Energy cost

$/kWH	
0.07	Purchase electricity
0.07	Sell back electricity
0	Renewable Energy Credits

Emissions Released

g/kWH
632
2.74
1.34

Financial Analysis

$	250,000.00	RES Total cost
$	125,000.00	Principal investment
$	125,000.00	Financed amount
	7%	Interest Rate (annual %)
	120	Term (months)
	$1,451.36	Monthly Payment
$	174,162.72	Financed cost
$	49,162.72	Interest expense
$	1,200.00	Annual maintenance cost
$	35,656.92	Annual total cost
$	399,162.72	Total Capital Cost
	55	Payback period (years)
	20	System lifespan
$	248,090.21	Total lifetime cost w/o RES
$	463,375.72	Total lifetime cost w/ RES
$	(215,285.51)	Total lifetime savings or (loss)
	-87%	Total lifetime savings or (loss)

Master Summary ::: 2 Panel

W-min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	W-min
Total Load Power	676,254,096	612,000,000	584,882,585	630,046,927	817,413,092	1,028,837,968	912,030,181	1,523,718,645	1,341,873,436	1,058,903,202	802,093,729	646,811,520	10,632,457,358	Total Load Power
Total RES Power	715,762,270	692,700,600	775,548,539	807,556,300	940,103,575	858,850,350	747,226,857	813,617,244	744,581,825	802,661,077	765,929,604	581,097,531	9,246,617,773	Total Source Power
Debt used from grid	383,030,166	330,228,283	313,548,160	315,712,532	359,988,345	488,145,677	496,619,712	830,964,358	744,508,175	561,128,174	426,415,449	413,499,465	5,665,786,484	Debt used from grid
Surplus RES	(422,538,330)	(410,928,931)	(504,242,313)	(493,222,008)	(482,678,580)	(318,158,031)	(331,816,368)	(120,862,709)	(147,416,347)	(304,885,940)	(390,251,491)	(349,985,395)	(4,277,086,474)	Surplus
Site-consumed RES	293,223,939	281,771,669	271,306,226	314,336,297	457,424,986	540,692,319	415,410,469	692,754,534	597,165,276	497,775,137	375,678,313	233,112,137		Site-consumed RES
Load check	676,254,106	611,999,952	584,852,376	630,046,829	817,413,331	1,028,837,986	912,030,175	1,523,718,892	1,341,673,453	1,058,903,312	802,093,762	646,611,601	10,632,457,763	Load check
source check	715,762,270	692,700,600	775,548,539	807,556,300	940,103,575	858,850,350	747,226,857	813,617,244	744,581,825	802,661,077	765,929,604	581,097,531	9,246,617,773	source check

kWH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	kWH
	-	-	-	-	-	-	-	-	-	-	-	-		
Total Load Power	11,271	10,200	9,748	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,744	177,207	Total Load Power
Total RES Power	11,929	11,545	12,926	13,459	15,668	14,331	12,454	13,560	12,410	13,378	12,765	9,685	154,110	Total Source Power
3-yr avg billed power	11,240	10,200	9,800	10,480	13,640	17,160	15,120	25,600	22,240	17,600	13,460	10,694	177,254	3-yr avg billed power
% error	-0.27%	0.00%	0.54%	-0.20%	0.12%	0.07%	-0.53%	0.80%	-0.55%	-0.27%	0.63%	-0.46%	0.03%	% error
Debt used from grid	6,384	5,504	5,226	5,262	6,000	8,136	8,277	13,849	12,408	9,352	7,107	6,892	94,398	Debt used from grid
Surplus RES	(7,042)	(6,849)	(8,404)	(8,220)	(8,045)	(5,319)	(5,530)	(2,014)	(2,457)	(5,081)	(6,504)	(5,833)	(71,299)	Surplus
Site-consumed RES	4,887	4,696	4,522	5,239	7,624	9,012	6,924	11,546	9,953	8,296	6,261	3,852	82,811	Site-consumed RES
Load check	11,271	10,200	9,748	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,744	177,207	Power check
Source Check	11,929	11,545	12,926	13,459	15,668	14,331	12,454	13,560	12,410	13,378	12,765	9,685	154,110	Source Check
Net Metering														Net Metering
Net kWH	(658)	(1,345)	(3,178)	(2,958)	(2,045)	2,817	2,747	11,835	9,952	4,271	603	1,059	23,097	Net kWH
Savings kWH	11,929	11,545	12,926	13,459	15,668	14,331	12,454	13,560	12,410	13,378	12,765	9,685	154,110	Savings kWH
kWH Savings %	106%	113%	133%	128%	115%	84%	82%	53%	55%	76%	95%	90%	87%	kWH Savings %
Financial														Financial
Cost kWH	447	385	366	368	420	570	579	969	869	655	497	482	6,606	Cost kWH
Income kWH	(493)	(479)	(588)	(575)	(563)	(372)	(387)	(141)	(172)	(356)	(455)	(408)	(4,991)	Income kWH
Income RE Credits	-	-	-	-	-	-	-	-	-	-	-	-	-	Income RE Credits
Net	(46)	(94)	(222)	(207)	(143)	197	192	828	697	299	42	74	1,617	Net Annual Cost
Grid cost w/o RES	789	714	682	735	954	1,200	1,064	1,778	1,565	1,235	936	752	12,405	Grid cost w/o RES
Savings $	835	808	905	942	1,097	1,003	872	949	869	936	894	678	10,788	Savings $
Savings %	106%	113%	133%	128%	115%	84%	82%	53%	55%	76%	95%	90%	87%	Savings %
Emissions kg														Emissions kg
Carbon Dioxide	4,035	3,476	3,303	3,328	3,792	5,142	5,231	8,753	7,842	5,911	4,492	4,356	59,659	Carbon Dioxide
Sulfer Dioxide	17	15	14	14	16	22	23	38	34	26	19	19	259	Sulfer Dioxide
Nitrogen Oxides	9	7	7	7	8	11	11	19	17	13	10	9	128	Nitrogen Oxides
Emissions w/o RES kg														Emissions w/o RES kg
Carbon Dioxide	7,123	6,446	6,160	6,637	8,610	10,837	9,607	16,050	14,132	11,156	8,449	6,790	111,995	Carbon Dioxide
Sulfer Dioxide	31	28	27	29	37	47	42	70	61	48	37	29	486	Sulfer Dioxide
Nitrogen Oxides	15	14	13	14	18	23	20	34	30	24	18	14	237	Nitrogen Oxides
Savings kg (NoRES - Debt)														Savings kg (NoRES - Debt)
Carbon Dioxide	3,089	2,968	2,858	3,311	4,818	5,695	4,376	7,297	6,290	5,246	3,957	2,434	52,336	Carbon Dioxide
Sulfer Dioxide	13	13	12	14	21	25	19	32	27	23	17	11	227	Sulfer Dioxide
Nitrogen Oxides	7	6	6	7	10	12	9	15	13	11	8	5	111	Nitrogen Oxides
Savings kg (all RES)														Savings kg (all RES)
Carbon Dioxide	7,539	7,296	8,169	8,506	9,902	9,057	7,871	8,570	7,843	8,455	8,068	6,121	97,396	Carbon Dioxide
Sulfer Dioxide	33	32	35	37	43	39	34	37	34	37	35	27	422	Sulfer Dioxide
Nitrogen Oxides	16	15	17	18	21	19	17	18	17	18	17	13	207	Nitrogen Oxides
Savings %														Savings %
w/o considering surplus RES	43%	46%	46%	50%	56%	53%	46%	45%	45%	47%	47%	36%	47%	w/o considering surplus RES
considering all RES	106%	113%	133%	128%	115%	84%	82%	53%	55%	76%	95%	90%	87%	considering all RES

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Error checking

Converted from W-min

User constants

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User Constants		Financial Analysis		
Energy cost			$ 350,000.00	RES Total cost
			$ 175,000.00	Principal investment
$/kWH			$ 175,000.00	Financed amount
0.07	Purchase electricity		7%	Interest Rate (annual %)
0.07	Sell back electricity		120	Term (months)
0	Renewable Energy Credits		$2,031.90	Monthly Payment
			$ 243,827.81	Financed cost
			$ 68,827.81	Interest expense
			$ 1,200.00	Annual maintenance cost
			$ 27,199.87	Annual total cost
Emissions Released			$ 418,827.81	Total Capital Cost
g/kWH			39	Payback period (years)
632			20	System lifespan
2.74			$ 248,090.21	Total lifetime cost w/o RES
1.34			$ 475,163.61	Total lifetime cost w/ RES
			$ (227,073.40)	Total lifetime savings or (loss)
			92%	Total lifetime savings or (loss)

Master Summary ::: 3 Panel

W-min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	W-min
Total Load Power	676,254,094	612,000,000	584,652,585	630,048,927	817,413,092	1,028,637,985	912,030,161	1,523,718,845	1,341,675,456	1,058,903,202	802,093,729	644,611,520	10,632,457,358	Total Load Power
Total RES Power	1,073,843,405	1,039,050,900	1,163,322,809	1,211,337,449	1,410,155,363	1,289,745,525	1,120,840,265	1,220,425,865	1,116,672,456	1,203,991,816	1,148,894,706	871,646,297	13,869,926,659	Total Source Power
Debtused from grid	380,106,721	327,375,834	311,209,774	311,612,479	369,290,169	479,429,748	489,475,571	783,445,732	721,771,062	557,691,613	424,361,100	410,659,015	5,553,428,016	Debt used from grid
Surplus RES	(777,495,034)	(754,426,799)	(889,880,215)	(892,901,114)	(949,032,215)	(740,337,318)	(698,285,695)	(480,152,748)	(496,970,051)	(702,780,053)	(771,162,050)	(637,698,723)	(8,790,917,014)	Surplus
Site-consumed RES	296,146,371	284,624,101	273,442,596	318,436,335	481,123,148	549,403,207	422,554,590	740,273,117	619,902,396	501,211,584	377,732,658	233,952,574		Site-consumed RES
Load check	676,254,092	611,999,935	584,652,387	630,048,814	817,413,337	1,028,637,853	912,030,161	1,523,718,849	1,341,675,450	1,058,903,377	802,093,756	644,611,589	10,632,457,661	Load check
source check	1,073,843,405	1,039,050,900	1,163,322,809	1,211,337,449	1,410,155,363	1,289,745,525	1,120,840,265	1,220,425,865	1,116,672,456	1,203,991,816	1,148,894,706	871,646,297	13,869,926,659	source check

kWH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	kWH
	-	-	-	-	-	-	-	-	-	-	-	-		
Total Load Power	11,271	10,200	9,748	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,744	177,207	Total Load Power
Total RES Power	17,894	17,318	19,389	20,189	23,503	21,496	18,681	20,340	18,615	20,067	19,148	14,527	231,165	Total Source Power
3-yr avg billed power	11,240	10,200	9,800	10,480	13,640	17,160	15,120	25,600	22,240	17,600	13,480	10,694	177,254	3yr avg billed power
% error	-0.27%	0.00%	0.56%	-0.20%	0.12%	0.07%	-0.53%	0.80%	-0.55%	-0.27%	0.83%	-0.46%	0.03%	% error
Debtused from grid	6,335	5,456	5,187	5,194	5,938	7,990	8,158	13,057	12,030	9,295	7,073	6,844	92,557	Debt used from grid
Surplus RES	(12,958)	(12,574)	(14,828)	(14,882)	(15,817)	(12,339)	(11,638)	(8,003)	(8,283)	(11,713)	(12,853)	(10,628)	(146,515)	Surplus
Site-consumed RES	4,936	4,744	4,561	5,307	7,685	9,157	7,043	12,338	10,332	8,354	6,296	3,899	84,650	Site-consumed RES
Load check	11,271	10,200	9,748	10,501	13,624	17,147	15,201	25,395	22,361	17,648	13,368	10,744	177,207	Power check
Source Check	17,894	17,318	19,389	20,189	23,503	21,496	18,681	20,340	18,615	20,067	19,148	14,527	231,165	Source Check
Net Metering														Net Metering
Net kWH	(6,623)	(7,118)	(9,641)	(9,688)	(9,879)	(4,349)	(3,480)	5,055	3,747	(2,418)	(5,780)	(3,784)	(53,958)	Net kWH
Savings kWH	17,894	17,318	19,389	20,189	23,503	21,496	18,681	20,340	18,615	20,067	19,148	14,527	231,165	Savings kWH
kWH Savings %	159%	170%	199%	192%	173%	125%	123%	80%	83%	114%	143%	135%	130%	kWH Savings %
Financial														Financial
Cost kWH	443	362	353	364	416	559	571	914	842	651	495	479	6,479	Cost kWH
Income kWH	(907)	(860)	(1,026)	(1,042)	(1,107)	(894)	(815)	(560)	(590)	(820)	(900)	(744)	(10,256)	Income kWH
Income RE Credits	-	-	-	-	-	-	-	-	-	-	-	-	-	Income RE Credits
Net	(464)	(498)	(673)	(678)	(692)	(304)	(244)	354	252	(169)	(405)	(265)	(3,777)	Net Annual Cost
Grid cost w/o RES	789	714	682	735	954	1,200	1,064	1,778	1,565	1,235	936	752	12,405	Grid cost w/o RES
Savings $	1,253	1,212	1,357	1,413	1,645	1,505	1,308	1,424	1,303	1,405	1,340	1,017	16,182	Savings $
Savings %	159%	170%	199%	192%	173%	125%	123%	80%	83%	114%	143%	135%	130%	Savings %
Emissions kg														Emissions kg
Carbon Dioxide	4,004	3,448	3,278	3,282	3,753	5,050	5,156	8,252	7,603	5,874	4,470	4,326	58,496	Carbon Dioxide
Sulfer Dioxide	17	15	14	14	16	22	22	36	33	25	19	19	254	Sulfer Dioxide
Nitrogen Oxides	8	7	7	7	8	11	11	17	16	12	9	9	124	Nitrogen Oxides
Emissions w/o RES kg														Emissions w/o RES kg
Carbon Dioxide	7,123	6,446	6,160	6,637	8,610	10,837	9,607	16,050	14,132	11,154	8,449	6,790	111,995	Carbon Dioxide
Sulfer Dioxide	31	28	27	29	37	47	42	70	61	48	37	29	486	Sulfer Dioxide
Nitrogen Oxides	15	14	13	14	18	23	20	34	30	24	18	14	237	Nitrogen Oxides
Savings kg (NoRES - Debt)														Savings kg (NoRES - Debt)
Carbon Dioxide	3,119	2,998	2,882	3,354	4,857	5,787	4,451	7,798	6,530	5,279	3,979	2,464	53,499	Carbon Dioxide
Sulfer Dioxide	14	13	12	15	21	25	19	34	28	23	17	11	232	Sulfer Dioxide
Nitrogen Oxides	7	6	6	7	10	12	9	17	14	11	8	5	113	Nitrogen Oxides
Savings kg (all RES)														Savings kg (all RES)
Carbon Dioxide	11,309	10,945	12,254	12,759	14,854	13,585	11,806	12,855	11,764	12,682	12,102	9,181	146,097	Carbon Dioxide
Sulfer Dioxide	49	47	53	55	64	59	51	56	51	55	52	40	633	Sulfer Dioxide
Nitrogen Oxides	24	23	26	27	31	29	25	27	25	27	26	19	310	Nitrogen Oxides
Savings %														Savings %
w/o considering surplus RES	44%	47%	47%	51%	56%	53%	46%	49%	46%	47%	47%	36%	48%	w/o considering surplus RES
considering all RES	159%	170%	199%	192%	173%	125%	123%	80%	83%	114%	143%	135%	130%	considering all RES

From data files
Error checking
Converted from W-min
User constants
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User Constants

Energy cost

$/kWH	
0.07	Purchase electricity
0.07	Sell back electricity
0	Renewable Energy Credits

Emissions Released

g/kWH
682
2.74
1.34

Financial Analysis

$	750,000.00	RES Total cost
$	375,000.00	Principal investment
$	375,000.00	Financed amount
	7%	Interest Rate (annual %)
	120	Term (months)
	$4,354.07	Monthly Payment
$	522,488.16	Financed cost
$	147,488.16	Interest expense
$	1,200.00	Annual maintenance cost
$	48,671.78	Annual total cost
$	897,488.16	Total Capital Cost
	55	Payback period (years)
	20	System lifespan
$	248,090.21	Total lifetime cost w/o RES
$	845,946.75	Total lifetime cost w/ RES
$	(597,856.54)	Total lifetime savings or (loss)
	-241%	Total lifetime savings or (loss)

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