Using Thermal Energy Storage to Increase Photovoltaic Penetration at Arizona State University's Tempe Campus

by

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ABSTRACT

This thesis examines using thermal energy storage as a demand side management tool for air-conditioning loads with the goal of increasing photovoltaic penetration. It uses Arizona State University (ASU) as a case study. The analysis is completed with a modeling approach using typical meteorological year (TMY) data, along with ASU's historical load data. Sustainability, greenhouse gas emissions, carbon neutrality, and photovoltaic (PV) penetration are all considered along with potential economic impacts.

By extrapolating the air-conditioning load profile from the existing data sets, it can be ensured that cooling demands can be met at all times under the new management method. Using this cooling demand data, it is possible to determine how much energy is required to meet these needs. Then, modeling the PV arrays, the thermal energy storage (TES), and the chillers, the maximum PV penetration in the future state can be determined.

Using this approach, it has been determined that ASU can increase their solar PV resources by a factor of 3.460, which would amount to a PV penetration of approximately 48%.

This paper is dedicated to my wonderful, loving wife Anna Wietrak. Without her this work would have been impossible. She has held me up and encouraged me at every step. Her love and support have carried me through and enabled me to chase my dreams.

ACKNOWLEDGMENTS

First, I want to thank Aymeric Maros and Natasa Vulic for their help in getting this project off the ground. I think there help and encouragement is appreciated more than either of them know. I'd also like Chris Gahan for taking the time to show me first hand all of the facilities that I have been studying and reading about. Donald Turner saved me countless hours of work by helping me to obtain the historical data I needed. Thank you to Matt Fraser and Stuart Bowden for serving on my committee. Last, but certainly not least, I'd like to thank Christiana Honsberg for her support throughout the year that I have been working on my thesis. She gave me the opportunity to join QESST and enabled me to take advantage of this amazing opportunity. I am extremely grateful to all of you.

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CHAPTER 1: INTRODUCTION

Over the past several decades, renewable resources have been a major focus of research. The United Nations (U.N.) has added “Affordable and Clean Energy” as one of their 17 Sustainable Development Goals to be accomplished by 2030 [1]. With the increases in greenhouse gas (GHG) emissions and political conflicts attributed to fossil fuel resources, it is clear that clean renewable energy sources are the way of the future. Some researchers believe that it is possible to convert the current grid to using 100% renewables by the year 2030 [1], [2]. Still, it is widely debated whether this is economically or logistically feasible [3], and what the asset mix should be in such a future state energy portfolio, but when implemented with strong sustainability methods, this will help to ensure political, economic, and environmental security both domestically and internationally.

Figure 1 shows atmospheric CO_2 has been increasing every year since 1958. This is just one of many GHG’s being released into the atmosphere. These GHG emissions are considered by many to be a major cause of global warming [4], [5]. Humans have known about these dangers since 1896 when Svante Arrhenius calculated the effects of doubling atmospheric CO_2 concentration. He accurately predicted that doubling CO_2 would increase global temperatures by approximately 5°C [6].

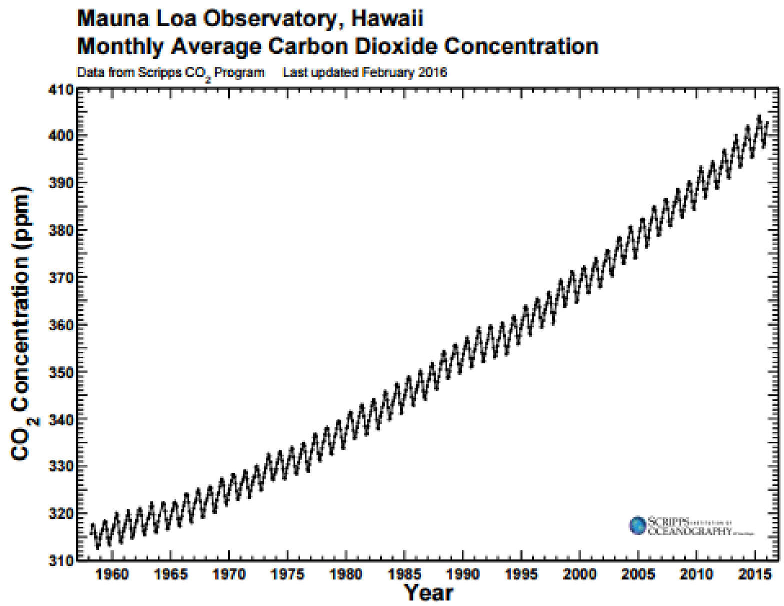

Figure 1: Atmospheric CO2 Concentration since 1958 [4]

A large portion of the energy that our society consumes is from electricity. As electric cars become more popular and more cost effective, that percentage will increase. As you can see in Figure 2, a significant amount of the energy we consume in the United States is used in residential and commercial settings. Moreover, the primary source for this energy is from fossil fuels [7]. Fossil fuels are a significant contributor to the GHG emissions that are leading to global warming.

Also, "fossil fuels are finite: Incapable of growth or reproduction at a rate meaningful to humans, therefore, they are irreplaceable and non-renewable [8]." This means, by definition, that they are unsustainable. Newer, sustainable energy sources must be found for human society to maintain itself – hence the interest in renewable resources.

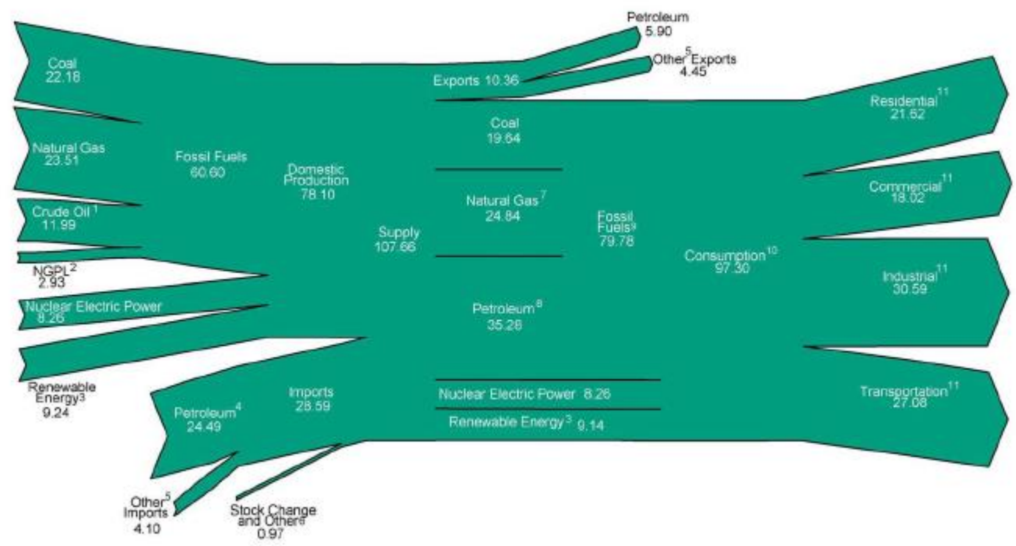

Figure 2: 2011 Energy Flow Diagram Measured in Quadrillions of BTUs [7]

Some of the most commonly considered renewable energy sources are solar photovoltaics (PV), concentrated solar, wind, hydro, geo-thermal and bio-fuels [2]. Each of these sources is considered to be sustainable. It is clear that none of these sources can solve the problem on its own. It will be a mixture of these resources that help us to stop emitting GHGs. One key indicator in the process of increasing renewables is PV penetration.

PV penetration is the percentage of energy that comes from PV resources. This helps to determine how much power will be available, and what actions need to be taken during different times of year, and under varying weather conditions. As discussed above, PV is a green, sustainable energy resource, so increasing penetration is one indicator in the process of making the grid more sustainable.

This paper is an examination of both the ASU electric utility system, and heating, air-conditioning and ventilation (HVAC) system, and the ability to use these systems to increase PV penetration with thermal energy storage (TES). It is a continuation of the research presented in [9]. Modeling the ASU system, using typical meteorological year (TMY) data to predict generation patterns, and comparing it to historical load data allows a method of TES management which enables a significant increase in PV penetration. This method uses air-conditioning chillers to charge TES during the day. By moving the chiller load to coincide with PV generation, it allows significant increases in PV penetration.

Increasing PV penetration has some potential negative side effects. The most famous of these is the "duck curve," which can be seen in Figure 3. This can cause overgeneration risk, due to high ramping requirements during a very short period. This upward ramping is usually seen in the afternoon just as the sun sets. California Independent System Operator (CAISO) is predicting that this trend will be exacerbated as PV penetration increases [10].

One way to avoid this "duck curve" is to use energy storage. This allows energy to be saved that has been generated during a period of low demand, so it can be utilized during a period of high demand. As PV and wind penetration increase, storage becomes increasingly important [11]. The most well-known form of storage is batteries, which can be expensive. As its name implies, TES can also be used for storage. The proposed method of chiller and TES management will help to alleviate these problems, and avoid this "duck curve" effect.

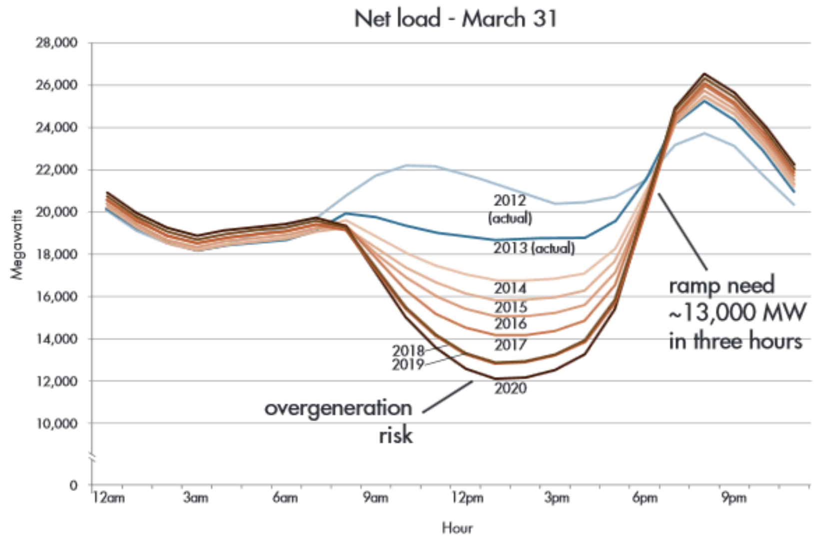

Figure 3: Duck Curve [10]

Arizona State University (ASU) is committed to achieving carbon neutrality for scope 1, 2 and non-transportation scope 3 emissions by 2025, and carbon neutral for scope 3 transportation emissions by 2035 [12], [13]. They have been recognized by U.S. News & World Report as the number one school for innovation in the United States, and this methodology will help maintain that status [14]. Their plan for achieving these aggressive goals is contingent largely on generating electricity, both on and off-site, from renewable energy facilities [12]. Due to ASU's desert location, and high number of sunny days, this on-site renewable energy primarily comes from solar PV.

ASU is a unique entity, due to its large amount of solar PV resources, availability of load and solar array data, and large TES system. Although it is unique in these respects, this research is scalable to other entities which employ TES, and will allow them to use the conclusions found here to increase their PV penetration. It is assumed that TES will allow entities to fully exploit their solar resources, and employ their TES as a form of demand side management (DSM). This DSM method allows an increase in PV penetration, but also acts as a method of load shifting, to move air-conditioning loads away from periods of peak demand, while also having the potential to act as a form of demand response. [15] argues that:

> "The introduction of demand management strategies, be it based on technological energy efficiency, consumer behavior changes or the introduction of dynamic demand side management technologies is crucial for the long-term sustainability of any region. These options will play a large role in the transition to sustainable energy systems by keeping demand at levels in which renewable energies can be used effectively to meet that demand."

The model of the ASU system and its implementation will be presented in chapter 6. First though, chapter 2 and 3 provide extensive background information on the systems that are used in the model. Chapter 4 defines the scope and limitations of the study. Chapter 5 details the current set-up of the electricity grid, HVAC system and PV resources at ASU. Chapter 7 and 8 are the results and conclusion sections.

This paper will explain how using TES can increase PV penetration and decrease ASU's carbon footprint. This will make ASU more sustainable, becoming more environmentally friendly and economically feasible. This methodology will also help ASU to continue to capitalize on their reputation as a sustainable and innovative institution.

CHAPTER 2: HVAC AND TES

It has been estimated that in commercial buildings, a large portion of their load profile can be attributed to air-conditioning loads. Estimates from [16] and [17] are as high as 60% to 70% during peak summer hours. With such a high percentage of energy being used on HVAC, even small, incremental efficiency and cost improvements can have a significant impact.

In a typical system for a commercial building, the air-conditioning process is performed in several steps. First, water is cooled in a water chiller. Next, the water is sent to an air handler, which may or may not be attached to the chiller. If the chiller and handler are separate, the separation distances can vary greatly.

The air handler consists of air filters and fans, along with a cooling coil. Then, water passes through the coil and the air is blown across it, which acts as a heat exchange. The cool air is then blown through the duct work into the building. Finally, once the water has gone through the cooling coil, it is usually returned via a closed loop system to the chiller to repeat the cycle. Due to the specific operating conditions of a particular system, the number and size of both water chillers and air handlers can vary. At ASU, they have 15 chillers and approximately one air-handler for each floor of each building.

Another element that may be used in the HVAC system is TES. TES has been employed around the world for several decades and is a common method of energy and cost savings for large commercial consumers in warmer climates. Typical TES operation consists of cooling your TES system when energy prices are at their lowest, usually at night. Then, during peak pricing periods, the TES cooling is used to run air-conditioning, to save electricity, and in-turn, money.

Despite losses (which are generally low) the overall process uses less energy than a system without TES. Due to decreased nighttime temperatures, chiller efficiency is generally increased when used with TES [16], [18]. In addition, while the chillers are charging the TES, they are running at, or near their optimal operating point, decreasing off-design operation time, which also increases efficiency [19].

As a result of purchasing electricity at night when prices are low, and utilizing the TES during peak load when prices are high, there is also a net monetary savings. It is estimated that "a TES system in a large commercial building can reduce the peak cooling load demand between 30 and 40% and the peak electrical demand between 10 and 20% [16]." Due to the fact that more expensive plants are used to generate power during peak loads, the decrease in consumption due to TES saves both the consumer and the supplier money. For this reason, many power companies will offer incentives to commercial customers who install TES systems [11]. There are several other methods of employing TES; for example, heating loads, and motor and generator efficiency gains. These techniques will not be discussed in this paper.

There are three main forms of TES used for air-conditioning loads. The first is a chilled water system (CWS), the second is ice storage, and the third is eutectic salt storage systems. Ice systems and CWS are both mature technologies which have been successfully implemented on a commercial scale, while the eutectic salt systems are mainly still in the research and development phase. Each of the systems has many similarities to the others, with a few intricacies that make them unique. ASU has a CWS system, so I will focus on this type of system and disregard the other two types.

In a CWS system large, insulated tanks of water are used as the TES. This is the most cost effective system for large systems (greater than 2,000 ton-hours), where land area is not an issue (which is the case at ASU). The water is stored in stratified layers within the tanks for later use to meet cooling demands [16]. Generally cold water is added during charging, and withdrawn during discharging from the bottom of the tank, with the corresponding warm water being replaced in the top layer of the tank. The return water is brought in at a low flow rate to avoid disrupting the stratification and mixing the layers [18].

The water for the CWS system is generally chilled using a conventional air-conditioning water chiller. This makes integrating TES into existing commercial air-conditioning systems relatively simple and cost effective [16]. This also makes it possible to use the same chiller equipment to simultaneously run your air-conditioning and charge your TES. This type of dual operation would not be possible with ice or eutectic salt systems.

In a future, smart-grid environment, TES has the potential to be a demand response tool. This means that during times of peak load, or during large spikes in demand, the water chillers could be shut off and the air-conditioning can continue to run from the TES system. This allows continued usage and operation without consuming electricity. This capability would require a significant amount of research into policy and incentives for both the supplier and consumer, which is out of the scope of this paper.

CHAPTER 3: SOLAR IRRADIANCE, ARRAY POWER OUTPUT, AND PV PENETRATION

The irradiance calculations within the model are made using typical meteorological year (TMY) data. The TMY data is maintained by the National Renewable Energy Lab (NREL) [20]. TMY data was used for generation modeling, and ASU's historical load data as the demand. TMY data was obtained from NREL's TMY3 data set, which was collected at Phoenix Sky Harbor Airport. Phoenix Sky Harbor Airport is approximately three miles from ASU's Tempe campus, which makes this an ideal dataset.

First, the position of the sun was calculated for every hour of the year. In order to do this, it was first required to calculate the hour angle (HRA), which adjusts for longitude, latitude and the time zone for the specific location. Equations 1 through 6 were used to calculate the HRA [21].

$$LSTM = 15° * \Delta T_{GMT} \tag{1}$$

$$B = \frac{360}{365}(d - 81) \tag{2}$$

$$EoT = 9.87\sin(2B) - 7.53\cos(B) - 1.5 * \sin(B) \tag{3}$$

$$TC = 4(Longitude - LSTM) + EoT \tag{4}$$

$$LST = LT + \frac{TC}{60} \tag{5}$$

$$HRA = 15°(LST - 12) \quad (6)$$

Where:

LSTM = Local Standard Time Meridian

d = Day of the Year

EoT = Equation of Time

TC = Time Correction Factor

LST = Local Solar Time

HRA = Hour Angle (in degrees)

Next, using this time adjusted data, it is then possible to calculate the sun's position for each hour of the year. In order to find the declination angle, elevation angle and azimuth of the sun equations 7 through 11 are utilized [22], [23], [24].

$$\delta = sin^{-1}\left(\sin(23.45°)\sin\left(\frac{360}{365}(d - 81)\right)\right) \quad (7)$$

$$\alpha = sin^{-1}[\sin(\delta)\sin(\varphi) + \cos(\delta)\cos(\varphi)\cos(HRA)] \quad (8)$$

$$azi = \ cos^{-1}\left(\frac{\sin(\delta)\cos(\varphi) - \cos(\delta)\sin(\varphi)\cos(HRA)}{\cos(\alpha)}\right) \quad (9)$$

$$\theta = azi, for\ LST < 12\ or\ HRA < 0 \quad (10)$$

$$\theta = 360° - azi, for\ LST > 12\ or\ HRA > 0 \tag{11}$$

Where:

φ = Latitude of the Location

δ = Declination Angle (in degrees)

α = Sun Elevation (in degrees)

θ = Sun Azimuth (in degrees)

Last, using the direct normal irradiance (DNI) and the diffuse horizontal irradiance (DHI) from the TMY data, the global irradiance was calculated for each individual PV array at ASU, as seen in equations 12 through 14 [25], [26]. Each array had to be calculated separately due to differences in the tilt and azimuth angles of the array panels.

$$B = DNI * [\cos(\alpha)\sin(\beta)\cos(\psi - \theta) + \sin(\alpha)\cos(\beta)] \tag{12}$$

$$D = DHI\left(\frac{180 - \beta}{180}\right) \tag{13}$$

$$G = B + D \tag{14}$$

Where:

B = Direct Irradiance Normal to the Module (in W/m^2)

D = Diffuse Irradiance (in W/m^2)

G = Total Irradiance (in W/m^2)

β = Module Tilt (in degrees)

ψ = Module Azimuth (in degrees)

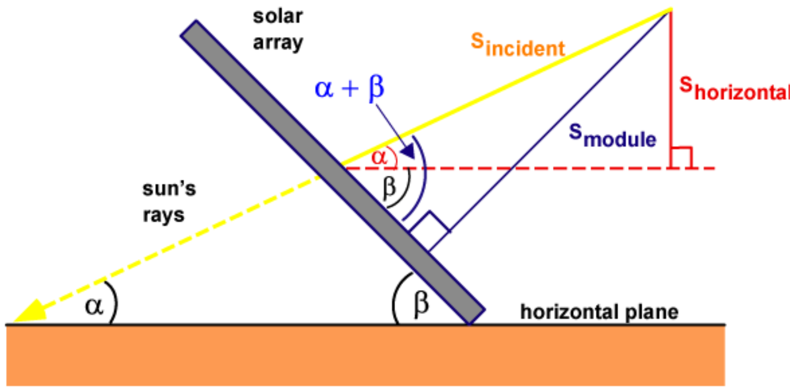

Figure 4: Solar Radiation on a Tilted Surface [25]

There are other, more accurate models of the movement of the sun, which are used in astronomy and astrophysics, but these are not necessary for this application. These general approximations provide a sufficient model for this utilization.

To calculate the power produced by each array the calculated global irradiance was used, along with the specifications of the module and array set-up [26]. A PV array is made of PV panels, which is made of PV cells. The temperature effects were taken into consideration, which can be seen in equation 15 [27]. To calculate the array output, it is first required to calculate the temperature of the cells in the array.

$$T_{Cell} = T_{Air} + \frac{NOCT - 20}{0.8} * S \tag{15}$$

Where:

T_{Cell} = Temperature of the Cell

T_{Air} = Ambient Air Temperature

NOCT = Nominal Operating Cell Temperature

S = Insolation (in kW/m[2])

The cell temperature is calculated for each cell in each period, and then used, along with the temperature derating factor to determine each individual panel's output. To find the total output of each array, in equations 16 and 17, the panel output is multiplied by the number of panels [27].

$$P_{Out} = P_{Rated}\left[1 - D_{Temp}(T_{Cell} - STC)\right] * G_{Irr}/1000 \tag{16}$$

$$P_{Array} = P_{Out} * n_{Panel} \tag{17}$$

Where:

P_{Out} = Power Output of Cell

P_{Rated} = Rated Power of Cell

D_{Temp} = Temperature Derating Factor (in %/°C)

STC = Standard Test Conditions (25° C)

G_{Irr} = Total Irradiance (in W)

P_{Array} = Power Output of Array

n_{Panel} = Number of Panels in an Array

There is considerable debate from researchers as to the highest possible PV penetration, while maintaining stability, reliability, and other ancillary services of the grid. [28], [29] and [30] are just a few of the numerous findings available. Since PV can only generate energy during the day when the sun is shining, for high penetration rates, storage will be required. Batteries are the most well-known form of storage, but TES is common, already in place, and cost effective.

CHAPTER 4: MODELING/STUDY SCOPE AND LIMITATIONS

While this research paper is based on ASU's Tempe campus system, there are several factors which are not taken into account. The electricity generated by all PV cells is direct current (DC). In most cases, in order to make this usable by consumers it has to be converted into alternating current (AC) by an inverter. The inverters, and the losses due to the inverter efficiencies are not considered in this paper. It is assumed that power generated in DC is converted into AC power with 100% efficiency. Due to the large number of inverters involved, and the fact that inverters have widely varying efficiency ratings under different operating conditions, it was out of the scope of this research to determine their operational efficiencies. Total Harmonic Distortion (THD) and other power quality issues associated with the pulse width modulation (PWM) used in the inverters are also not considered in this paper.

The ASU micro-grid also includes a small array of thin film cells. This array is not included in this study due to a lack of available data. The "Parking Canopy South of Police Bldg" system has some information available at [31].

Three of the arrays at ASU use single access tracking. The software for these systems is proprietary. A generalized tracking algorithm has been used to compensate for this lack of information.

The study also does not consider any issues with grid reliability, or system stability. The model considers the overall power in and power out of the system, but not the specific topology or connections of any one part of the electric grid to any other.

This research is done as a deterministic model. Weather patterns and cloud cover are not taken into account for this study. Due to minimal cloud cover in the Tempe area, where 85% of days are considered sunny, shading impacts will have a relatively low influence [32].

The TES state of charge is not taken into account for this model. Although there is almost certainly some variation, it is assumed that for a one-year period the amount of energy stored in TES is removed before the end of the year. This means losses are not accounted for, and the state of charge is assumed to be identical at the beginning of the year and the end of the year to balance the input and output energy.

Load leveling is generally accepted as a way of decreasing peak loads, and also making a system more economically efficient. This is not always true, and there are cases where load leveling can cause an increase in costs. For this paper it is assumed that load leveling is desirable, and the main focus is not related to cost, but on increasing PV penetration and decreasing CO_2 and other GHG emissions.

CHAPTER 5: EXISTING SYSTEM DESIGN AND OPERATION

There are currently 77 total solar systems on ASU's Tempe campus. These have been condensed in the data tables down to 66 systems, in order to decrease the number of computations the model is required to perform. Several of the arrays were installed simultaneously with identical specifications, which allowed the consolidation to be completed seamlessly. This condensation limited the data inputs into the model. Combined with the other ASU campuses, these PV solar resources have a combined capacity of 22.5 MW_P equivalent, and generated 40,412,653 kWh in fiscal year 2015 [31].

These solar arrays are primarily rooftop arrays, located on both academic and residential buildings, along with a majority of parking structures. They each individually have a capacity factor between 20 and 25%. All of the arrays were commissioned between January of 2009 and August of 2014. Nearly all of the information needed for the array components and set-up is available at [31]. Some of this data was incomplete, and additional research was required by reviewing the plaques on location for several of the arrays. You can see an example of one of these plaques in Figure 5. It was also required to use Google Earth to measure the azimuth angle, and count the number of panels in several of the arrays.

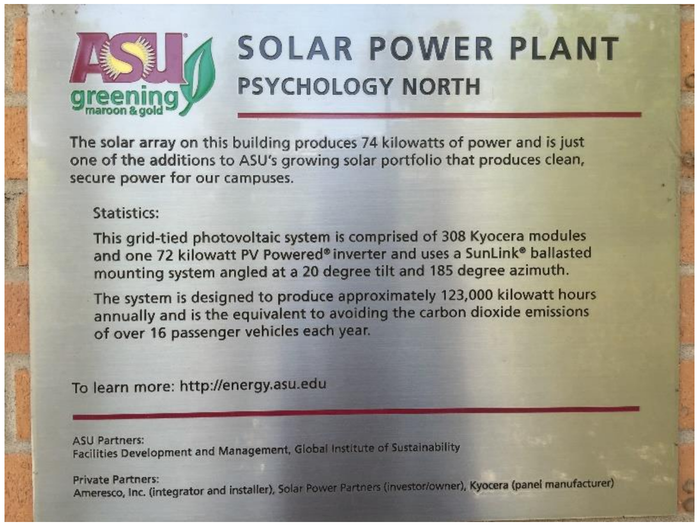

Figure 5: An example of the solar plaques located on ASU Tempe Campus

ASU's Central Plant is located in the center of the Tempe campus. This is where ten of the 200-ton air-conditioning chillers are located, along with all of their associated pumps and cooling towers. You can see one of the chillers in Figure 6. The Combined Heating and Power (CHP) building on the East side of campus also houses five chillers. The TES tanks are in an underground facility, also on campus near the Central Plant. These tanks are only fed by the Central Plant chillers. These consist of six, one million gallon stratified water tanks. The piping between the central plant, the TES tanks, and the air-handlers in each individual building are located in a network of underground tunnels and crawl spaces. The chilled water can be pumped from the chillers to the TES tanks, or directly to the individual buildings' air handlers. Each building has its own air handlers, which convert the cold water into the cold air that comes out of the air-conditioning ducts.

Figure 6: A Chiller from ASU's Central Plant

ASU is connected to the grid by Arizona Public Service (APS). They are connected on various parts of campus by four dedicated substations, along with several buildings that are directly tied into the APS grid. Figure 7 shows a model of the ASU system, including both electrical supply and electrical loads.

Notice in Figure 7, the TES is both a supplier and a load. This is due to the charging and discharging nature of the TES. It acts as a load when it is charging, and as a supplier when it is discharging. This enables the load shifting ability that was discussed in chapter 1.

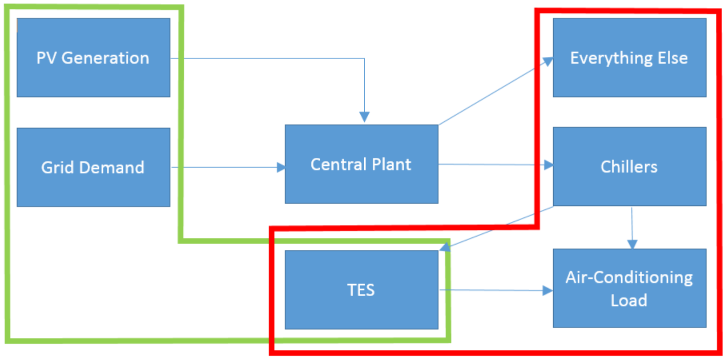

Figure 7: Simplified Model of ASU's Electric and AIr-Conditioning System. Items in Green are Suppliers and Items in Red are Loads.

Figure 8 below shows the ASU hourly grid consumption. The total energy consumed from the grid was 175.9 GWh, which is approximately 86% of the annual energy consumed. All electrical usage for the grid is monitored at the Central Plant. They also monitor and archive data for the chillers, and TES systems, along with PV generation, among many other data points. This data is collectively known as the campus metabolism, and this is the source of load data used for this research study.

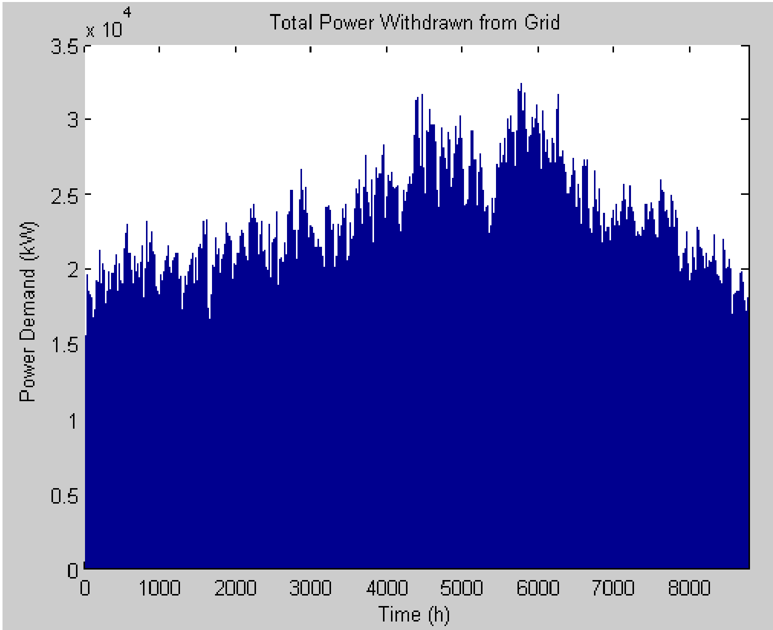

Figure 8: Total Hourly Power Withdrawn from the Grid

CHAPTER 6: MODEL DETAILS

The Model is programmed in MATLAB using the equations referenced in chapter 3. The TMY and array data is stored in several Microsoft Excel spreadsheets and imported into the model. All of the specific code can be found in Appendix A. All of the historical data being used is from 2013.

As discussed in Chapter 3, the TMY data being used was collected at Sky Harbor Airport in Phoenix, AZ. The TMY has a large amount of data, but only a limited number of data is required. The data points which were used were the DNI, DHI, ambient temperature along with the day and hour of the year.

Each array's irradiance and power must be calculated separately, as the panel tilt angle and the azimuth angle are unique for each array. The TMY data also changes every hour. Since there are 66 arrays, and 8760 hours in a year, this means that these calculations are completed 578,160 times each time the model runs. The model has the ability to process these calculations, and combine the power generated by all of the arrays for each hour of the year. This gives a total annual system-wide PV energy generated. This is then used in conjunction with the historical data for the ASU grid and the HVAC system to determine the load profile.

Below, in Figure 9 and Figure 10 is an example of the irradiance that is generated using the Chapter 3 equations and the TMY data. When these two are combined, the total irradiance from Figure 11 is the result. This data is then used to calculate the power produced by an individual solar array for one hour.

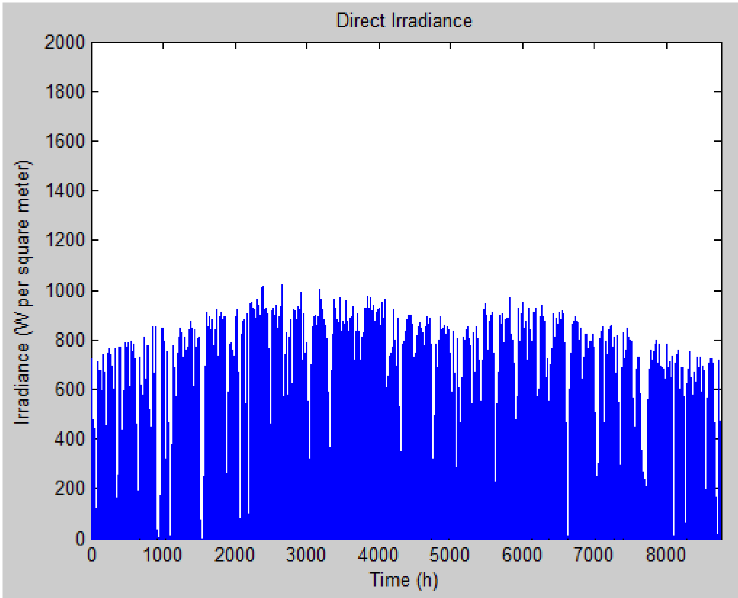

Figure 9: Direct Solar Irradiation Calculated from TMY Data on a Panel with 10° Panel Tilt and 180° Azimuth Angle

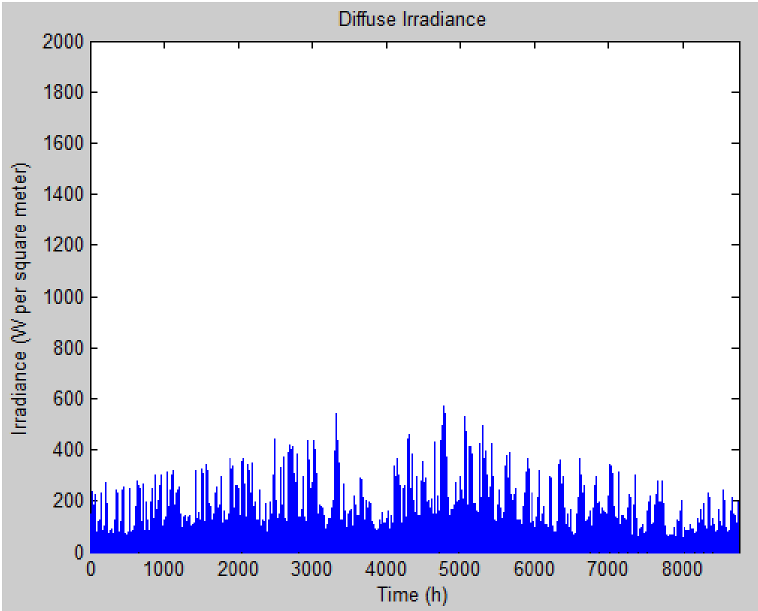

Figure 10: Diffuse Solar Irradiation Calculated from TMY Data on a panel with 10° Panel Tilt and 180° Azimuth Angle

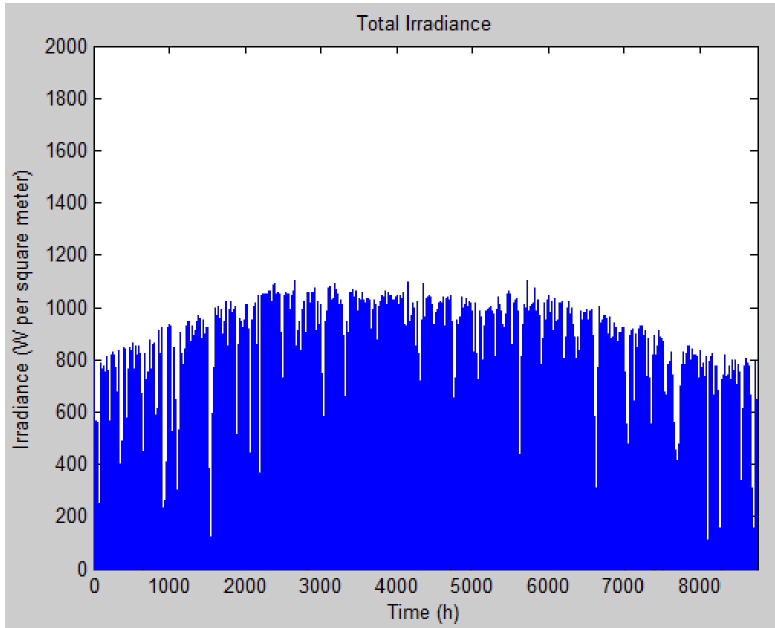

Figure 11: Total Irradiation Calculated from TMY Data on a Panel with 10° Panel Tilt and 180° Azimuth Angle

Figure 12 shows the chiller data, which shows any time the chillers were running. The total energy consumed by the chillers was 66.183 GWh, which is approximately 32% of the annual energy consumed by Tempe's ASU campus. This data is a good approximation of daily use, but alone it cannot distinguish between when the chillers are running the air-conditioning directly, and when they are charging the TES.

Figure 13 shows both the charging and discharging of the TES. When the system is charging, it is positive, and negative when discharging. When you combine the information from Figure 12 and Figure 13 it is possible to determine how much air-conditioning is being utilized in the system during each hour. This air-conditioning utilization can be seen below in Chapter 7.

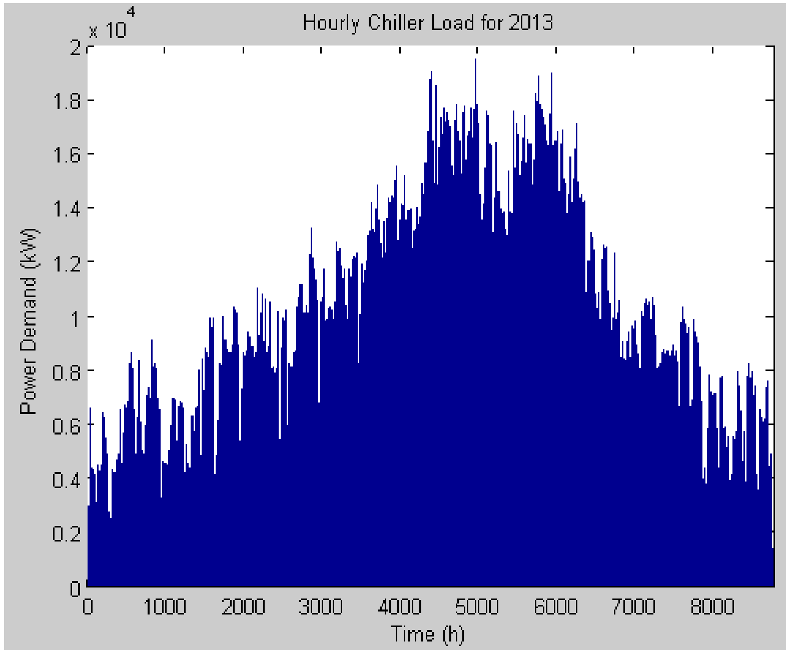

Figure 12: 2013 Hourly Chiller Data

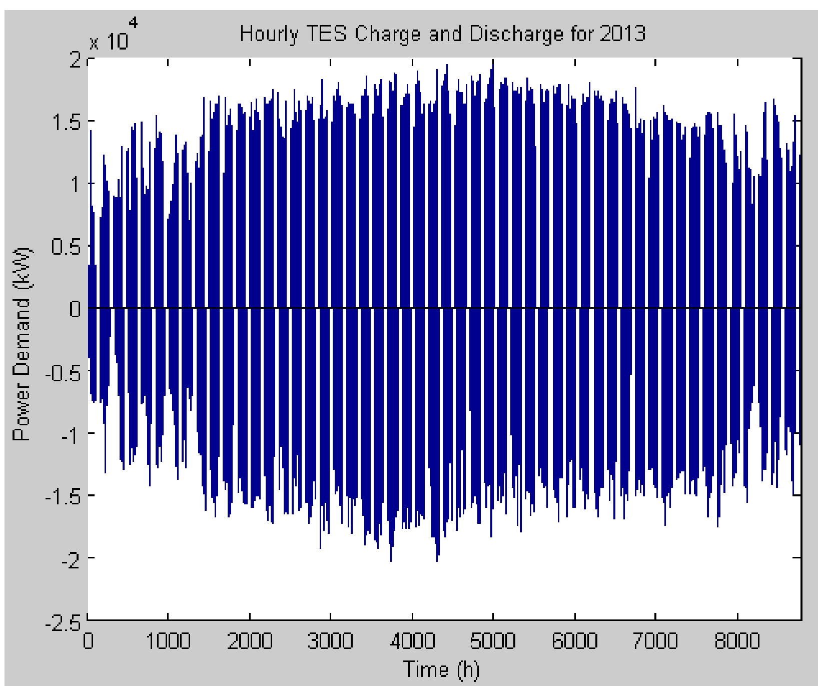

Figure 13: 2013 Hourly Thermal Energy Storage Charging and Discharging

CHAPTER 7: RESULTS

The objective of the new management method is to match the load profile to the generation profile of the PV resources. By increasing the amount of power generated by solar PV, it will decrease the reliance on grid power, and also help to level the load profile. The ultimate goal is to determine how the maximum PV generation the ASU system can handle without the need to send energy to the grid and impact APS's baseload.

First, as discussed in chapter 3, when the irradiance is calculated for each of the arrays, it is then used to calculate the power produced by each array. The arrays are each constructed with different brands and power ratings of cells. This means that they have different power outputs, temperature coefficients, and NOCTs.

Using the chapter 3 equations, the power output of each array is calculated for each hour of the year, including the temperature derating effects. The data is then compiled into a total hourly generation array. This array is shown in Figure 14 below. This total of 28.564 GWh per year is approximately 71% of the solar PV generated by ASU's campuses and approximately 14% of energy consumed on ASU's Tempe campus.

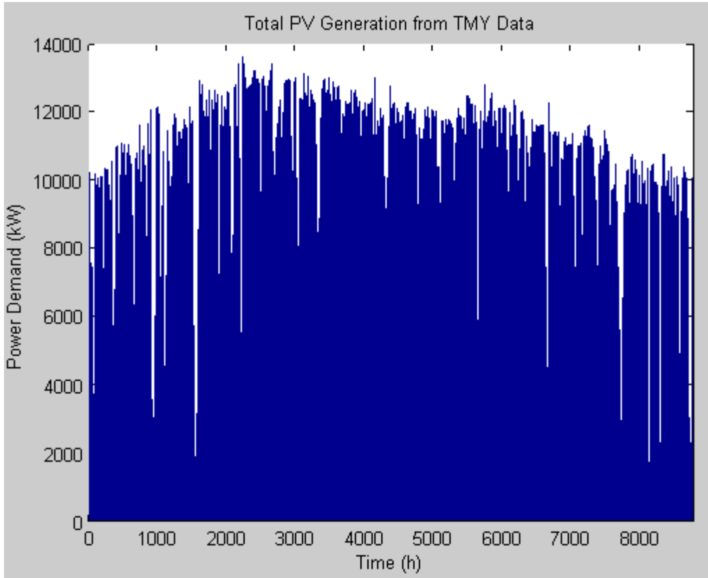

Figure 14: Total PV Generated using TMY Data

If you combine the generation from Figure 14 with the historical data found in Figure 8, it gives you the total amount of power consumed per hour in the current TES management method. This total power consumed can be seen below in Figure 15.

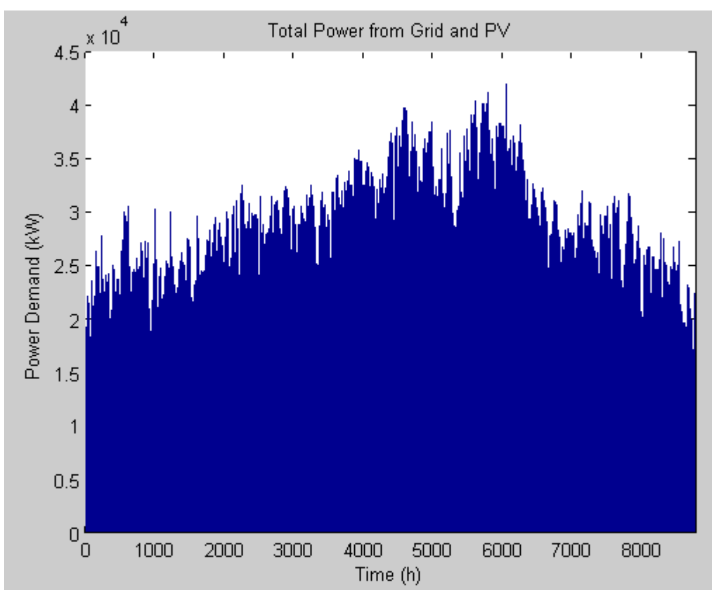

Figure 15: Total Power Consumed Using Current TES Management Method

As discussed in chapter 6, if you combine the chiller data from Figure 12 and the TES data from Figure 13, you can extrapolate the air-conditioning load profile. Knowing the load profile of the air-conditioning will ensure that there is ample cooling available in the future state at any time throughout the year. The total air-conditioning load can be seen in Figure 16. The total air-conditioning load is 66.183 GWh/yr, which is approximately 32% of annual energy consumption. This is the portion of the total load which can be shifted using the TES.

Figure 16 reveals an issue with the data set which is being used. When subtracting the charging of the TES from the chiller output, there shouldn't be any negative numbers. When the TES is charging, it should always be less than the chiller output, as the TES can't absorb more than the chiller is producing. When the TES is discharging, the values are negative, so when it's subtracted from the chiller output, it is added to the air-conditioning load. The negative values occur while the TES is charging. This is an issue with the data. After reviewing the issue with the Central Plant, it is unknown why the data issue is occurring. As Figure 16 shows, the issue with the data is not a one-time problem, it is a systematic problem that is occurring on a regular basis. TES and chiller data were reviewed for 2012 through 2015, and the issue is occurring in all datasets. Despite this issue, the analysis will be completed, assuming that the data is valid.

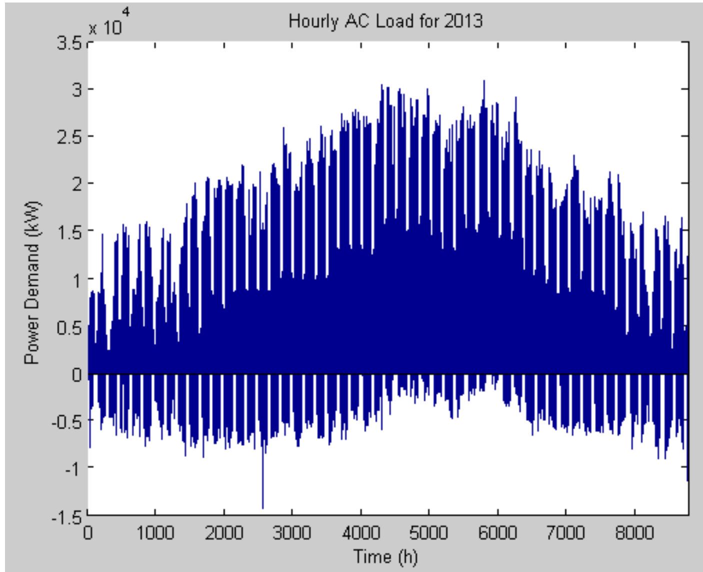

Figure 16: Total AC Load for 2013

By combining the TES data with the grid data and the PV data, the total load can be extrapolated. Figure 15 shows the total load, but due to the TES influence, the total amount is correct, however the profile is shifted from daytime demand to the appearance of significant nightly load demand. Using the combination of data described above, Figure 17 shows the total load, with the overall demand profile. This, along with the air-conditioning load creates a base to fit the future state solar and TES data.

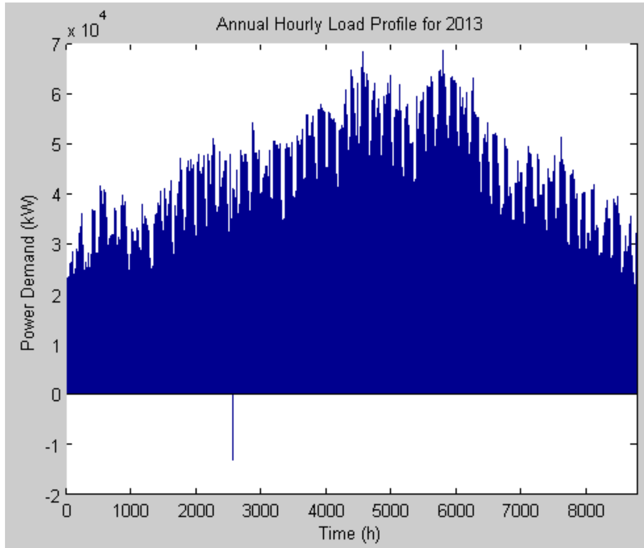

Figure 17: Extrapolated Annual Load Profile

This data also enables the creation of a daily and hourly profile of when the air-conditioning is used. Comparing this with the daily PV generation profile, it is possible to determine how much cold water needs to be stored to meet cooling needs, and the PV power required to produce sufficient cold water for those cooling requirements. Figure 18 shows this daily average, for all days over the year. It starts on Sunday at 1:00 a.m., and goes to Saturday at 12:00 a.m.

The results in Figure 18 were unexpected. The average is approximately the same for each day of the week. It was initially anticipated that the weekdays would have higher peak loads than the weekends, due to the fact that students would be on campus and in class during the week, but not on the weekends. This unexpected outcome actually makes it easier to fit the PV generation profile to the air-conditioning load profile.

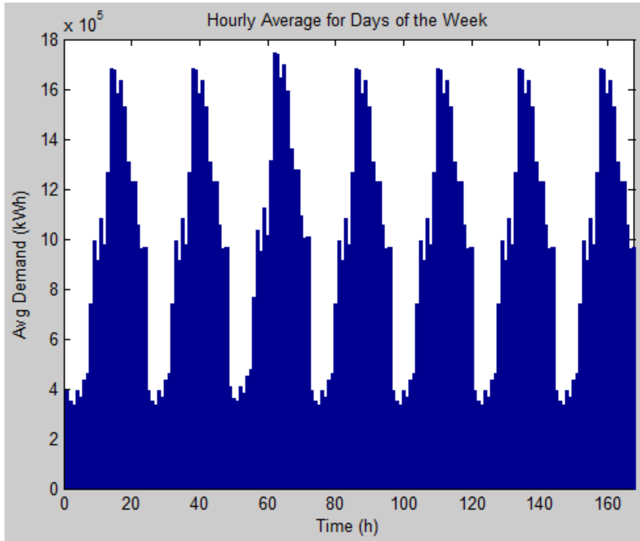

Figure 18: Average AC Load Over for a Week

The amount of energy consumed by the air-conditioning is approximately 2.32 times higher than the PV generation. If the PV generation output is increased by a factor of 2.32 and compare it to the air-conditioning load, the result can be seen in Figure 19. The PV generation at this factor is significantly more than the chiller load, but based on the totals over the year, it should be possible to shift this load to the proper periods using TES. It is important to remember that the air-conditioning is not the total load. When the PV generation is compared to the total load, a much different conclusion is possible.

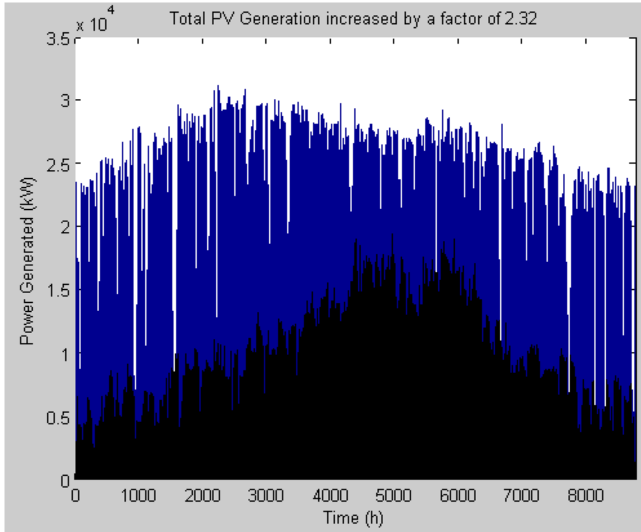

Figure 19: Chiller load compared to PV Generation Multiplied by a Factor of 2.32. PV Generation is Blue and Chiller Output is Black.

When the total load is compared to the PV generation, the load very few hours are showing over-generation. This is shown in Figure 20 and Figure 21. This can easily be shifted using the TES. What this shows is that with very low TES utilization, the PV generation capacity at ASU can be increased by at least a factor of 2.32.

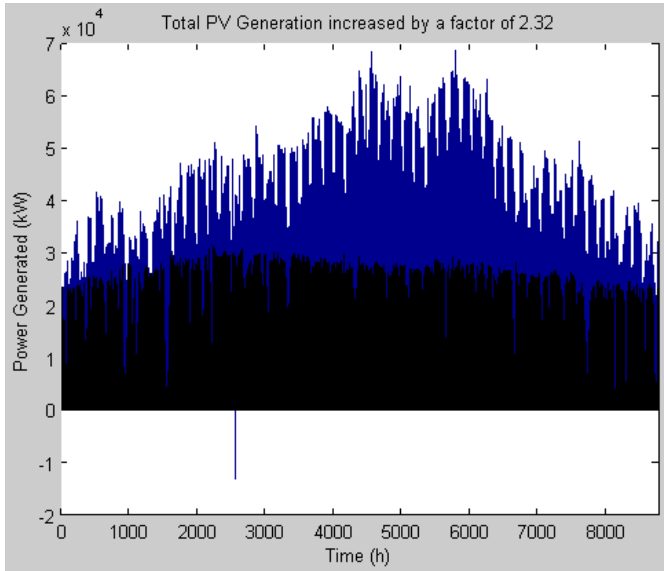

Figure 20: PV Generation increased by a factor of 2.32 Compared to Total Load. Total Load is Blue and PV Generation is Black.

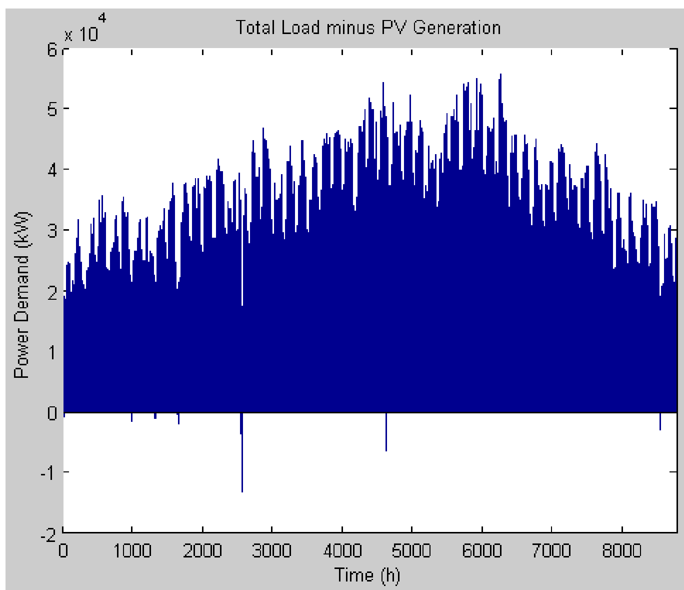

Figure 21: Total Load Minus PV Generation (Increased by a Factor of 2.32)

While increasing the PV generation by a factor of 2.32 would be a significant increase, it is clearly not the maximum. At a factor of 2.32, the amount of energy collected from PV would be 32.4% of energy consumption. This is only 2.6% below ASU's goal of 35% generation from on-campus renewables [12]. An iterative approach is used to find the maximum factor by which PV generation can be increased. Over the period of 2012 to 2015, the maximum amount of energy stored in TES over one hour is 19,511.59 kWh and the maximum amount discharged is -20,293.24 kWh. These numbers are used as operational limits for the TES.

Figure 7 above shows a simplified view of the ASU system. To calculate the total load, the air-conditioning (AC) load, and the "everything else" load from above, the following equations were used. The TES is positive when it is charging, and negative when it is discharging, which makes these equations valid for both situations. The TES is subtracted from the power inputs because when it is charging, it appears to be a load, but is not actually being consumed at that time, and when it is discharging, it is fulfilling a load, but is not consuming power.

$$Grid + PV - TES = Total\ Load \tag{18}$$

$$Chillers - TES = AC\ load \tag{19}$$

$$Total\ Load - AC\ Load = Everything\ Else \tag{20}$$

These loads do not change, with changes to the PV generation. By increasing the PV by a scaling factor, it can be determined how much additional PV generation is acceptable. Referencing Figure 7 again shows that while these loads state the same, the other variables can all change. On the supply side, both the grid power and the TES are changing. The total grid power should be decreased by the amount of the total PV generation increase. This does not hold true for each individual period due to the TES's flexibility, storage capability, and load shifting ability.

On the demand side, as with the supply side, although the total load, AC load and everything else load remain the same, the TES and chillers are varying. This means that on both the supply side and on the demand side, there are more unknowns than it is possible to solve for. To account for this, the hourly output data for both the supply and demand side was exported to a Microsoft Excel spreadsheet.

Within the Excel spreadsheet, a new dataset was created for each hour, which can be seen in equation 21. By using an absolute reference to the scaling factor, the dataset could be easily manipulated. If equation 21 is positive, then the total load is more than the PV. If the total load is negative, then the PV is greater than the total load. This value represents a combination of the supply from the grid, and also the TES in the future state. If the value from equation 21 is negative, the TES would be charging, as this would be excess power, that would otherwise be sent to the grid. When the value is positive, this means that the system will need to either draw power from the grid, or discharge the TES. Since negative values below the maximum TES charging rate (19,511.59 kWh) would be wasted, this was the value which was used to iterate the scaling factor.

Using the Excel function "MIN" the scaling factor was increased as high as possible without going above the TES charging rate. The scaling factor which was achieved was 3.460. This means the PV on ASU Tempe campus can be increased to produce 98.831 GWh per year. This is over 48% of the annual energy consumed at ASU Tempe campus, and significantly above the carbon neutrality goal of 35% of energy generated from on-campus renewables [12]. The graph of the hourly excess load above PV generation can be seen in Figure 22.

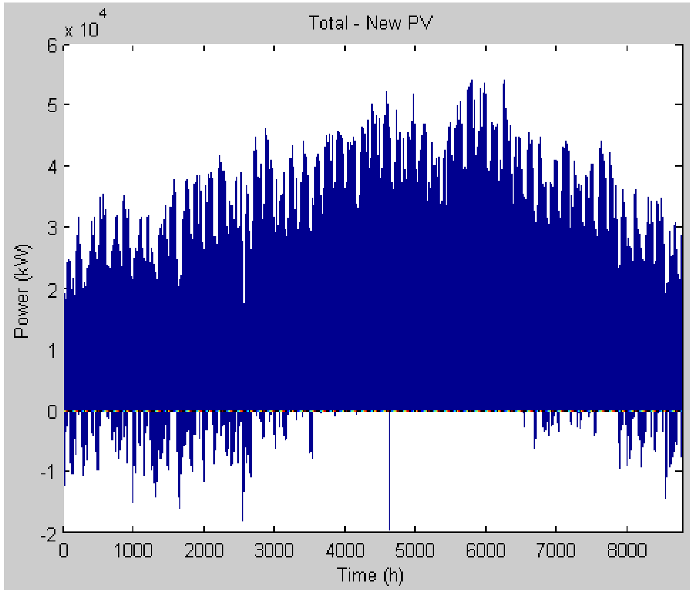

Figure 22: Excess Load above PV generation

As can be determined from Figure 22, during peak summer days the excess load doesn't always drop below zero every day. This means that during peak summer days, the TES will still have to be charged at night. During non-peak days, the TES can still be charged, at least partially, during the day to meet nighttime cooling loads.

CHAPTER 8: CONCLUSION

The existing TES system will allow a large increase in PV capacity, without sending electricity back to the grid. This new management method allows an increase of PV by a factor of 3.460, which would account for 48% of ASU's energy consumption. The new management method is a seasonal affect. There is an oversupply in the winter, which allows the chillers to run and the TES to charge during the day. In the summer, there is an undersupply, which means using the existing method of charging TES at night, and discharging during the day.

The methods used in this paper are suitable for completing this analysis, but the data problems bring questions of validity into the final conclusions. If the data issues can be resolved, the model will give valid results. Due to the nature of TES, the new results should be close to the results found in this work. Despite the TES and chiller data coming into question, the total energy supplied by the grid and by PV wouldn't change. This means that the total value should be correct, but the profile for the load is incorrect. If the data is corrected, and the correct profile is attained, then the iteration process would need to be re-done in order to verify the findings in this paper.

Also, since the last PV array was installed in August of 2014, it would be more accurate to use the 2015 data. The complete 2015 dataset was unavailable at the time this paper was written. Also, the data that is available for fiscal year 2015, only includes 11 months of data for several of the installations which were installed in 2014.

Due to the way the model is programmed, and the availability of TMY data, it is very easy to change the scale and the location of the analysis. Since the data is all kept in Microsoft Excel spreadsheets, it is relatively simple to change the data sets. Considerations must be made to ensure that the new data has the same format and units as the existing data, but should also be relatively simple to implement. The model counts the number of arrays being imported from the spreadsheet, so changes in size in number of arrays should be seamless.

There needs to be a transition period from the current state operation, to the future state proposed here. The installation of new PV arrays cannot take place instantaneously, which would mean a period where the chillers are able to charge the TES during the day, but continued nighttime charging would also be required to maintain cost savings. The duration and extent of this transition period needs to be studied in further detail, but will be heavily contingent on how quickly the new PV systems can be installed.

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APPENDIX A

GENERATIONMODEL.M

```
%%% Alex Routhier QESST summer research project
%%% Thermal storage model for ASU's campus
%%% Main File
%%% Created 6/29/2015
%%% Last updated 3/31/2016


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Read input values from TMY file  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

TMY_data = 'Phoenix TMY.xlsx';
sheet_TMY = 1;
[num] = xlsread(TMY_data,sheet_TMY);
TMY = num;

% Set days and times in TMY data
% Day is in column 1 (1 to 365)
% Hour is in column 2 (1 to 24 for each day)
for i = 0:364;
   for j = 0:23
      TMY((3+i*24+j),1) = i+1;
      TMY((3+i*24+j),2) = j+1;
   end
end

Day = zeros(8760,1);
Hour = zeros(8760,1);

for j = 3:8762
   Day(j-2,1) = TMY(j,1);
   Hour(j-2,1) = TMY(j,2);
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Extract TMY data out of imported matrix and into arrays %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

[Latitude, HRA, delta, DNI, DHI, AmTemp] = Phoenix_Irradiance(TMY);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Use TMY data to calculate the power generated each hour %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

[ Phourly ] = ASUGeneration( Day, Hour, Latitude, HRA, delta, DNI, DHI, AmTemp);
```

```
xlswrite('Test.xlsx',Phourly);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Import chiller, TES and grid data %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

Chiller_TES_data = '2013_Chiller_TES_Conversion_Corrected.xlsx';
sheet_Chiller_TES = 1;
[num] = xlsread(Chiller_TES_data,sheet_Chiller_TES);
Chiller_TES = num;

Grid_power_data = '2013_Power_Usage.xlsx';
sheet_Grid = 1;
[num] = xlsread(Grid_power_data,sheet_Grid);
Grid_power = num;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Extract chiller, TES and grid data %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

[ chiller, TES_discharge, grid ] = Phoenix_Power( Chiller_TES, Grid_power );

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Combine data %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

system_total = zeros(8760,1);
total = 0;

for k = 1:8760
   system_total(k,1) = grid(k,1); %+ TES_discharge(k,1); - chiller(k,1);
   total = total + grid(k,1); %Phourly(k,1) + grid(k,1);
end

total

%for k = 1:8760
%    system_total(k,1) = system_total(k,1) + chiller(k,1) - TES_discharge(k,1);
%end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Graph the results %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
```

```
figure
x = linspace(1,8760,8760);
bar(x,system_total)
xlim([0,8760])
%ylim([0,14e6])
title('Hourly TES Charge and Discharge for 2013')
xlabel('Time (h)')
ylabel('Power Demand (kW)')

%Load_total = 0;

%for n = 1:8760
%    Load_total = Load_total + Phourly(n,1) + grid(n,1);
%end

%Load_total
```

PHOENIX_IRRADIANCE.M

```
function [ Latitude, HRA, delta, DNI, DHI, AmTemp ] = Phoenix_Irradiance( TMY )
%%% Alex Routhier QESST summer research project
%%% Thermal storage model for ASU's campus
%%% Irradiance file, called by GenerationModel.m
%%% Created 7/6/2015
%%% Last updated 7/8/2015

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%
%%% Extract data from TMY file  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%

% create an array for days, hours, GHI, DNI, DHI and ambient temp from TMY
% data
day = zeros(8760,1);
hour = zeros(8760,1);
%GHI = zeros(8760,1);
DNI = zeros(8760,1);
DHI = zeros(8760,1);
AmTemp = zeros(8760,1);

% day is column 1
% hour is column 2
% GHI is column 5
% DNI is column 8
% DHI is column 11
% Dry bulb (ambient) temp is column 32
for i = 1:8760
   day(i,1) = TMY((i+2),1);
   hour(i,1) = TMY((i+2),2);
%    GHI(i,1) = TMY((i+2),5);
   DNI(i,1) = TMY((i+2),8);
   DHI(i,1) = TMY((i+2),11);
   AmTemp(i,1) = TMY((i+2),32);
end

% the difference between local time and GMT
delta_GMT = TMY(1,4);

% extract latitude and longitude
Latitude = TMY(1,5);
Longitude = TMY(1,6);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%
%%% Calculate irradiance from the values extracted from TMY data  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%

% LSTM = local standard time meridian
```

```
LSTM = 15*delta_GMT;

% calculate HRA for each day
  % initiating these variables to avoid matlab warning about speed
BoT = zeros(8760,1);
EoT = zeros(8760,1);
TC = zeros(8760,1);
LST = zeros(8760,1);
HRA = zeros(8760,1);
delta = zeros(8760,1);

% equations are taken drom pveducation.org
% http://pveducation.org/pvcdrom/properties-of-sunlight/suns-position

for i = 1:8760
  %BoT = 360/365*(day -81)
  BoT(i,1) = 360/365*((day(i,1))-81);
  %EoT = 9.87sin(2Bot)-7.53cos(BoT)-1.5sin(Bot)
  EoT(i,1) = 9.87*sind(2*BoT(i,1))-7.53*cosd(BoT(i,1))-1.5*sind(BoT(i,1));
  %TC = 4(Longitude - LSTM)+EoT
  TC(i,1) = 4*(Longitude-LSTM)+EoT(i,1);
  %LST = LT +TC/60
  LST(i,1) = hour(i,1)+TC(i,1)/60;
  %HRA = 15*(LST-12)
  HRA(i,1) = 15*(LST(i,1)-12);
  % declanation angle = asind(sind(23.45)*sind(360/365*(d-81))) where d = day
  % of the year
  delta(i,1) = asind(sind(23.45)*sind(360/365*(TMY(i+2,1)-81)));
end

end
```

ASUGENERATION.M

```
function [ Phourly ] = ASUGeneration( Day, Hour, Latitude, HRA, delta, DNI, DHI, AmTemp )
%%% Alex Routhier
%%% EEE 598 - PV Systems, Spring 2016
%%% Mini-project 2
%%% Created 2/9/2016
%%% Last updated 3/31/2016

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Import array data from the spreadsheets %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Array_data = 'Existing_Arrays_run.xlsx';
sheet_array = 1;
[num] = xlsread(Array_data,sheet_array);
Arrays = num;
rows_arrays = length(Arrays);

SAT_data = 'Existing_SAT_Arrays.xlsx';
[num] = xlsread(SAT_data,sheet_array);
SAT_Arrays = num;
SAT_size = size(SAT_Arrays);
rows_SAT = SAT_size(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Extract the imported data into individual arrays %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Size_kWdc = zeros(rows_arrays,1);
PanelTilt = zeros(rows_arrays,1);
psi = zeros(rows_arrays,1);
Num_panels = zeros(rows_arrays,1);
Panel_size = zeros(rows_arrays,1);
NOCTemp = zeros(rows_arrays,1);
PLoss = zeros(rows_arrays,1);

for i = 1:rows_arrays
   Size_kWdc(i,1) = Arrays(i,1);
   PanelTilt(i,1) = Arrays(i,3);
   psi(i,1) = Arrays(i,4);
   Num_panels(i,1) = Arrays(i,5);
   Panel_size(i,1) = Arrays(i,6);
   NOCTemp(i,1) = Arrays(i,7);
   PLoss(i,1) = Arrays(i,8);
end

SAT_Size = zeros(rows_SAT,1);
SAT_panels = zeros(rows_SAT,1);
SAT_panel_size = zeros(rows_SAT,1);
SAT_NOCT = zeros(rows_SAT,1);
SAT_PLoss = zeros(rows_SAT,1);
```

```
for q = 1:rows_SAT
   SAT_Size(q,1) = SAT_Arrays(q,1);
   SAT_panels(q,1) = SAT_Arrays(q,3);
   SAT_panel_size(q,1) = SAT_Arrays(q,4);
   SAT_NOCT(q,1) = SAT_Arrays(q,5);
   SAT_PLoss(q,1) = SAT_Arrays(q,6);
end

Tstc = 25;
Pin = 1000;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%
%%% Calculate hourly irradiances (G = B + D) for fixed arrays %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%

Birr = zeros(8760,rows_arrays);
Dirr = zeros(8760,rows_arrays);
Girr = zeros(8760,rows_arrays);
azimuth = zeros(8760, rows_arrays);
alpha = zeros(8760, rows_arrays);

for j = 1:8760
   for k = 1:rows_arrays
      % function calls to calculate direct and indirect irradiance
      [ Birr(j,k), azimuth(j,k), alpha(j,k) ] = Birr_calc( DNI(j,1), delta(j,1), Latitude, PanelTilt(k,1),
psi(k,1), HRA(j,1) );
      [ Dirr(j,k) ] = Dirr_calc( DHI(j,1), PanelTilt(k,1) );
      Girr(j,k) = Birr(j,k) + Dirr(j,k);
   end
end

%x = linspace(1,8760,8760);
%figure
%plot(x,azimuth(:,1))

%solar_noon_azi = zeros(365,1);
%solar_noon_alpha = zeros(365,1);

%for w = 1:8760
%    if Hour(w,1) == 13
%       solar_noon_azi(Day(w,1),1) = azimuth(w,1);
%       solar_noon_alpha(Day(w,1),1) = alpha(w,1);
%    end
%end

%y = linspace(1,365,365);
%figure
%plot(y,solar_noon_azi)
%title('Solar Noon Azimuth')
```

```
%figure
%plot(y,solar_noon_alpha)
%title('Solar Noon Elevation')

%figure
%plot(x,Birr(:,2))
%title('Direct Irradiance')
%ylim([0,2000])
%xlim([0,8760])
%xlabel('Time (h)')
%ylabel('Irradiance (W per square meter)')


%figure
%plot(x,Dirr(:,2))
%title('Diffuse Irradiance')
%ylim([0,2000])
%xlim([0,8760])
%xlabel('Time (h)')
%ylabel('Irradiance (W per square meter)')

%G = Dirr(:,2) + Birr(:,2);

%figure
%plot(x,G)
%title('Total Irradiance')
%ylim([0,2000])
%xlim([0,8760])
%xlabel('Time (h)')
%ylabel('Irradiance (W per square meter)')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
%%% Calculate hourly irradiances (G = B + D) for SAT arrays %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

[ SAT_Girr ] = SAT_calc( Hour, Latitude, HRA, delta, DNI, DHI, rows_SAT );


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%
%%% Calculate power generated using cell size, temperature and irradiance %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%

Tcell = zeros(8760,rows_arrays);
SAT_Tcell = zeros(8760,rows_SAT);
Phourly = zeros(8760,1);
%dT = zeros(8760,rows_arrays);
SAT_dT = zeros(8760,rows_SAT);
Power = zeros(8760,rows_arrays);
```

```
SAT_Power = zeros(8760,rows_SAT);

for m = 1:8760
   for n = 1:rows_arrays
      Tcell(m,n) = AmTemp(m,1)+(NOCTemp(n,1)-20)/800*Girr(m,n);
      %dT(m,n) = Tcell(m,n)-Tstc;
      Power(m,n) = Panel_size(n,1)*(1-(PLoss(n,1)/100)*(Tcell(m,n)-
Tstc))/Pin*Girr(m,n)/Pin*Num_panels(n,1);
      Phourly(m,1) = Phourly(m,1) + Power(m,n);
   end
   for p = 1:rows_SAT
      SAT_Tcell(m,p) = AmTemp(m,1)+(SAT_NOCT(p,1)-20)/800*SAT_Girr(m,p);
      %SAT_dT(m,p) = SAT_Tcell(m,p)-Tstc;
      SAT_Power(m,p) = SAT_panel_size(p,1)*(1-(SAT_PLoss(p,1)/100)*(Tcell(m,p)-
Tstc))/Pin*Girr(m,n)/Pin*SAT_panels(p,1);
      Phourly(m,1) = Phourly(m,1) + SAT_Power(m,p);
   end
   if Phourly(m,1)<0
      Phourly(m,1) = 0;
   end
end

end
```

BIRR_CALC.M

```
function [ Birr, azimuth, alpha ] = Birr_calc( DNI, delta, Latitude, PanelTilt, psi, HRA )
%%% Alex Routhier QESST summer research project
%%% Thermal storage model for ASU's campus
%%% Birr calculation file, called by ASUGeneration.m
%%% Created 7/27/2015
%%% Last updated 3/21/2016

alpha = asind(sind(delta)*sind(Latitude)+cosd(delta)*cosd(Latitude)*cosd(HRA));

azi = acosd((sind(delta)*cosd(Latitude)-cosd(delta)*sind(Latitude)*cosd(HRA))/cosd(alpha));

if azi < 12 || HRA < 0
  azimuth = azi;
else
  azimuth = 360-azi;
end

%if azimuth > 60 && azimuth < 300
  if alpha > 0
    Birr = DNI*(cosd(alpha)*sind(PanelTilt)*cosd(psi-azimuth)+sind(alpha)*cosd(PanelTilt));
  else % alpha <= 0
    Birr = 0;
  end
%else
%   Birr = 0;
%end

%if Birr > 1e8 || Birr < 1e8
%   Birr = 0;
%end

%Birr = DNI*(sind(delta)*sind(Latitude)*cosd(PanelTilt)...
%   -sind(delta)*cosd(Latitude)*sind(PanelTilt)*cosd(psi)...
%   +cosd(delta)*cosd(Latitude)*cosd(PanelTilt)*cosd(HRA)...
%   +cosd(delta)*sind(Latitude)*sind(PanelTilt)*cosd(psi)*cosd(HRA)...
%   +cosd(delta)*sind(psi)*sind(HRA)*sind(PanelTilt));
%   if Birr<0
%     Birr = 0;
%   end
end
```

DIRR_CALC.M

```
function [ Dirr ] = Dirr_calc( DHI, PanelTilt )
%%% Alex Routhier QESST summer research project
%%% Thermal storage model for ASU's campus
%%% Dirr calculation file, called by ASUGeneration.m
%%% Created 7/27/2015
%%% Last updated 7/27/2015

Dirr = DHI*((180-PanelTilt)/180);
    if Dirr<0
      Dirr = 0;
    end
end
```

SAT_CALC.M

```
function [ SAT_Girr ] = SAT_calc( Hour, Latitude, HRA, delta, DNI, DHI, rows_SAT )
%%% Alex Routhier QESST summer research project
%%% Thermal storage model for ASU's campus
%%% SAT Power generation file, called by ASUGeneration.m
%%% Created 7/31/2015
%%% Last updated 1/15/2016



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Import Sunrise, sunset and solar noon data  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Time_data = 'Rise_Set_Noon.xlsx';
Time_TMY = 1;
[num] = xlsread(Time_data,Time_TMY);
time_data = num;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Calculate Panel tilt and Azimuth  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

SAT_psi = zeros(8760,1);
%before_noon = zeros(365,1);
%after_noon = zeros(365,1);
SAT_panel_tilt = zeros(8760,1);

for i = 1:8760
   if Hour(i,1) <= 12
      SAT_psi(i,1) = 90;
   elseif Hour(i,1) > 12
      SAT_psi(i,1) = 270;
   end
end

%for m = 1:365
%    before_noon(m,1) = time_data(m,16);
%    after_noon(m,1) = time_data(m,17);
%end



for n = 1:8760
   if Hour(n,1) == 6
      SAT_panel_tilt(n,1) = 38.58;
   elseif Hour(n,1) == 7
      SAT_panel_tilt(n,1) = 32.16;
   elseif Hour(n,1) == 8
      SAT_panel_tilt(n,1) = 25.74;
   elseif Hour(n,1) == 9
      SAT_panel_tilt(n,1) = 19.32;
   elseif Hour(n,1) == 10
```

```
      SAT_panel_tilt(n,1) = 12.9;
    elseif Hour(n,1) == 11
      SAT_panel_tilt(n,1) = 6.48;
    elseif Hour(n,1) == 12
      SAT_panel_tilt(n,1) = 0.05;
    elseif Hour(n,1) == 13
      SAT_panel_tilt(n,1) = 0.06;
    elseif Hour(n,1) == 14
      SAT_panel_tilt(n,1) = 6.48;
    elseif Hour(n,1) == 15
      SAT_panel_tilt(n,1) = 12.9;
    elseif Hour(n,1) == 16
      SAT_panel_tilt(n,1) = 19.32;
    elseif Hour(n,1) == 17
      SAT_panel_tilt(n,1) = 25.74;
    elseif Hour(n,1) == 18
      SAT_panel_tilt(n,1) = 32.16;
    elseif Hour(n,1) == 19
      SAT_panel_tilt(n,1) = 38.58;
    else
      SAT_panel_tilt(n,1) = 45;
    end
  end

SAT_Birr = zeros(8760,rows_SAT);
SAT_Dirr = zeros(8760,rows_SAT);
SAT_Girr = zeros(8760,rows_SAT);

for j = 1:8760
   for k = 1:rows_SAT
      % functions calls to calculate direct and indirect irradiance
      [ SAT_Birr(j,k) ] = Birr_calc( DNI(j,1), delta(j,1), Latitude, SAT_panel_tilt(k,1), SAT_psi(k,1),
HRA(j,1));
      [ SAT_Dirr(j,k) ] = Dirr_calc( DHI(j,1), SAT_panel_tilt(k,1));
      SAT_Girr(j,k) = SAT_Birr(j,k)+SAT_Dirr(j,k);
   end
end

end
```

PHOENIX_POWER.M

```
function [ chiller, TES_discharge, grid ] = Phoenix_Power( Chiller_TES, Grid_power )
%%% Alex Routhier QESST summer research project
%%% Thermal storage model for ASU's campus
%%% Power file for extracting power usage, called by GenerationModel.m
%%% Created 1/23/2016
%%% Last updated 1/23/2016

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Extract data from Chiller_TES file %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% create an array for the Chiller and TES data
chiller = zeros(8760,1);
TES_discharge = zeros(8760,1);

% values are in kWh (data for Ton hours is in the spreadsheet also)
% chiller is column 6
% TES_discharge is column 10

for i = 1:8760
   chiller(i,1) = Chiller_TES(i,15);
   TES_discharge(i,1) = Chiller_TES(i,10);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Extract data from Grid_power file %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% create an array for the grid usage data

grid = zeros(8760,1);

% values are in kWh
% total grid import is in column 10

for j = 1:8760
   grid(j,1) = Grid_power(j,10);
end


end
```