Modeling and Optimization of a Hybrid Solar PV-Powered Air Conditioning System with Ice Storage

by

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ABSTRACT

In this thesis the performance of a Hybrid AC System (HACS) is modeled and optimized. The HACS utilizes solar photovoltaic (PV) panels to help reduce the demand from the utility during peak hours. The system also includes an ice Thermal Energy Storage (TES) tank to accumulate cooling energy during off-peak hours.

The AC runs continuously on grid power during off-peak hours to generate cooling for the house and to store thermal energy in the TES. During peak hours, the AC runs on the power supplied from the PV, and cools the house along with the energy stored in the TES.

A higher initial cost is expected due to the additional components of the HACS (PV and TES), but a lower operational cost due to higher energy efficiency, energy storage and renewable energy utilization. A house cooled by the HACS will require a smaller size AC unit (about 48% less in the rated capacity), compared to a conventional AC system. To compare the cost effectiveness of the HACS with a regular AC system, time-of-use (TOU) utility rates are considered, as well as the cost of the system components and the annual maintenance.

The model shows that the HACS pays back its initial cost of $28k in about 6 years with an 8% APR, and saves about $45k in total cost when compared to a regular AC system that cools the same house for the same period of 6 years.

DEDICATION

I dedicate my thesis to my parents Elias and Rugina Jubran and to my sister Shirin Hartman for their continuous support and encouragement for hard work and excellence during my graduate studies, particularly in the last phase of my research and thesis.

I also dedicate this thesis to my nephews Samuel and Eli and to my nieces Haide, Lozan and Eden to encourage and inspire them for excellence, commitment and dedication in their future educational careers.

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LIST OF SYMBOLS

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1. COP - Coefficient of Performance	1
2. W – Work [kJ]	1
3. Q – Cooling/Heat [kJ]	1
4. T – Temperature [°C]	1
5. CL - Cooling Load [kW]	2
6. TES - Thermal Energy Storage	2
7. PV – Photo Voltaic	2
8. AC – Air Conditioning/Conditioner	2
9. HACS – Hybrid Air Conditioning System	2
10. A – Area [m^2]	4
11. β – Incline [°]	4
12. γ – Aimuth [°]	4
13. q''_{sun} – Solar Irradiance	4
14. η – Efficiency	4
15. NSRDB – National Solar Radiation Data Base	5
16. TS - Thermal Storage	9
17. kW – Kilowatt	10
18. THR – Ton Hour Refrigeration	49
19. NPV – Net Present Value	51

CHAPTER 1

INTRODUCTION

1.1 Overview

In hot and dry weather such as Phoenix summers, Air Conditioning (AC) and cooling becomes a large percentage of the power load [8] on the electric utility grid. The efficiency and the energy consumption of AC systems depend on two main external factors that vary throughout each hour of the day:

1. The outside air (ambient) temperature which affects the condensing temperature for cooling and the evaporating temperature for heating, that determine the Coefficient of Performance (COP) of the AC cycle [1]:

   $$COP = Q_{out} / W_{in} \tag{1.1.1}$$

   where the COP (Max) for an ideal Carnot cooling and heating cycles is expressed as [1]:

   $$COP_{cool} = T_C / (T_H - T_C) \tag{1.1.2}$$

   $$COP_{heat} = T_H / (T_H - T_C) \tag{1.1.3}$$

   where T_C is the cold-side temperature (in Kelvin) or the evaporation temperature which is set by the user (for cooling) and T_H is the hot-side temperature (in Kelvin) or the condensing temperature which depends on the outside air temperature (for cooling). For heating these would be reversed -- the evaporating temperature depends on the outside temperature.

2. The cooling load (CL) and heating load depend on many factors, such as outside air temperature, solar radiation intensity, insulation and internal loads.

The Hybrid AC system (HACS) will use thermal energy storage (TES) to reduce part of the cooling required from the AC during peak hours (12 – 6 pm) based on the utility time-of-use (TOU) plan, when the COP is lower due to high ambient temperatures, thus the thermal energy will be stored during off-peak hours.

Along with the TES, solar photovoltaic (PV) panels will supply power to run the AC to generate the other part of the cooling required to keep the house at the design temperature range. Thus, the cooling load during peak hours will be supplied from both the TES and the PV panels.

During off-peak hours, the AC will use grid power to cool the house and to store thermal energy in the TES alternatively. Therefore, over a daily cycle, lower total energy consumption is expected compared to a conventional system and the HACS will require a smaller size AC (since the peak CL is supplied by the AC and the TES) but a higher initial cost due to the additional cost of the PV panels and the TES. The main goal is to optimize the HACS in such a way that brings a reasonable payback period when compared to a conventional AC system that supplies a similar CL in the summer, and heating load in the winter.

1.2 Motivation

With the global increase in the average temperatures [6] and the increasing demand for AC [7], the electric utilities have to withstand the growing demand for power during peak hours – power that is usually produced by peaking-power plants that run gas turbines (Brayton cycles) [1] that are usually less efficient (thermodynamically) and use more expensive fuels (such as natural gas).

In addition to expanding and building new power plants that are very expensive and take a lot of time to build, cheaper and faster alternatives for meeting such increasing demand such as lowering the demand at the user (home) side (known as demand side management, DSM) are preferred and subsidized by federal, state and utility incentives.

Storing thermal energy during off-peak hours and utilizing it during peak hours along with renewable solar energy play a crucial role in lowering such demand by the user. In this research we will investigate how this can be achieved and applied in the residential sector, and examine the economics of such a system.

Other than decreasing the user demand for electric power during peak hours, more benefits of the HACS include a potential decrease in carbon emissions and can contribute to the overall efficiency at the utility side by shifting some of the load during peak hours to off-peak hours and thus helping the utility to supply a more stable (less aggressive) load curve on a 24 hr basis (known as load leveling).

1.3 Literature Review

A few studies have been done on thermal energy storage for AC applications (references [9], [10] and [11]) which all show the advantages of storing energy during off-peak hours and utilizing it during peak hours, including resulting energy savings. However, no study could be found that investigates a system such as the HACS, in which solar photovoltaic panels are used in conjunction with thermal energy storage, to supply the same amount of cooling to the house (as a conventional AC system) while reducing the required cooling capacity from the AC and running off-grid during peak hours. This illustrates the innovative concept of the HACS and encourages further and deeper work in order to prove that such a system could impact energy savings in the AC field in a recognized manner.

The studies (references [9], [10] and [11]) also indicate a strong relationship between the energy savings and the difference between the energy cost during peak and off-peak hours (time-of-use plans). Other studies [12] are regarding electrical energy storage in batteries and also indicate a certain reduction in the total monthly energy bill. The advantage of thermal energy storage over electrical energy storage is that it utilizes the system’s higher efficiency (thermodynamic) during off-peak hours as a result of the lower temperatures (the higher COP) and the energy is stored during off-peak hours in the same form (thermal) it is used during peak hours.

1.4 Objectives

The main objective of this thesis is to model and optimize the performance of an AC system that avoids grid power during peak hours by utilizing solar photovoltaic power and thermal energy storage. Other major objectives are:

I. Examine the economic profitability, with the current market and utility pricings, of utilizing solar photovoltaic panels to supply the electric power to run the system during peak hours.
II. Analyze the improvement in the thermodynamic efficiency by operating the system continuously during off-peak hours when the cooling load and the temperatures are lower.
III. Investigate the benefits of storing thermal energy during off-peak hours and calculate the savings in energy when the thermal energy is used during peak hours.
IV. Explore the overall performance and the economic advantages of an AC system that utilizes renewable solar energy and thermal energy storage.

In addition to the above this research will help reveal the challenges and complexity in implementing such a system that depends on a diversity of energy resources (such as: grid power, solar energy and energy storage), and understand the effects of the main factors (such as: system cost, time of use plans, available solar power, cooling load and ambient temperatures) on the feasibility of the system for the residential sector.

1.5 Schematics of the HACS

The schematic in Fig. 1.4.1 is color coded, where the arrows in the grey color indicate the flow of energy (electrical or thermal) during night time and off-peak hours and the arrows in the yellow color indicate the flow of energy (electrical or thermal) during day time and peak hours.

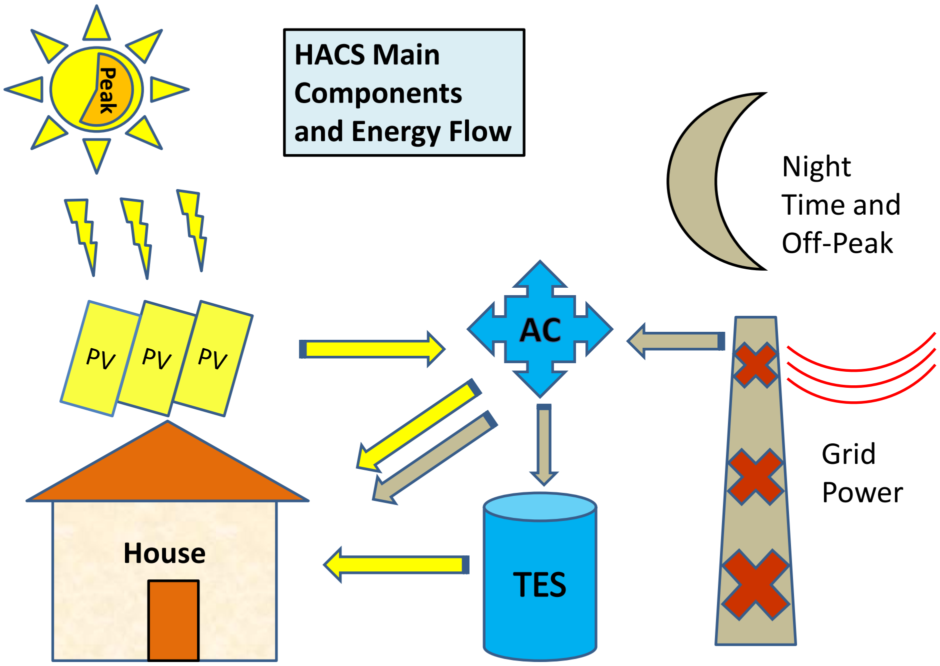


Figure 1.4.1: Color-Coded Schematic of the HACS

Figure 1.4.1 is not drawn to scale, and is just a simple illustration of the main components of the systems that will be optimized (TES, AC and PV). Energy (yellow and grey arrows) flowing into (inwards) the AC is electrical, and energy (yellow and grey arrows) flowing out of (outwards) the AC is thermal. (the AC “converts” electrical energy to thermal (cool) energy – as a heat pump).

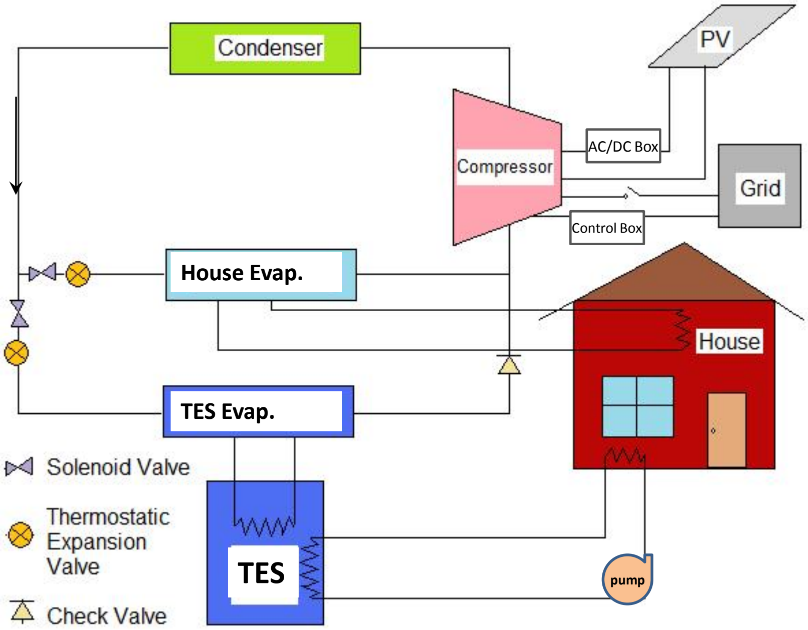


Figure 1.4.2: Component-Circuit Schematic of the HACS

The HACS operates two evaporators (as opposed to a conventional AC system that usually has only one evaporator), one evaporator to cool the house and another evaporator to cool the TES. For simplicity, the current HACS system is designed to operate one evaporator at a time, either the evaporator that cools the house or the evaporator that cools the TES, but not both together at the same time. However, this constraint does not affect the efficiency and the energy consumption of the system. (The actual physical model of the HACS is being built and assembled in the lab located on the roof of the ECF building at the Tempe campus of ASU).

CHAPTER 2

HACS COMPONENTS AND OPERATION MODES

2.1 The Solar PV Panels

The PV panels will supply electric power to run the AC during peak hours, where the energy cost is higher in all of the Time of Use (TOU) plans that the utility (APS) offers [5] (TOU plan rates are shown in figure 3.1.7). The power output of the PV panels depends on the following parameters:

Area – A_{PV} [m^2], Efficiency – η_{PV}, q''_{sun} - Solar Radiation, Tilt angle – β and the Azimuth angle – γ.

And the power output from the PV panels is calculated as follows:

$$PV_{out} = \eta_{PV} \times A_{PV} \times q''_{sun}\ (\beta,\gamma) \qquad (2.1.1)$$

where q''_{sun} is the total solar radiation on the PV panels and is a function of β and γ and is based on the values taken from the National Solar Radiation Data Base (NSRDB) [2] on a horizontal surface for Phoenix. It varies each hour of the day, and the values used to calculate the PV output are based on the average radiation for the entire month of July for each hour of the day.

To calculate the radiation on a tilted plate, we used the 'isentropic sky' method detailed in chapter 2 in 'Solar Engineering of Thermal Processes' [3], where the total radiation on a tilted surface is calculated as follows:

$$q''_{sun} = I_{Beam} \times R_b + I_{Diffuse} \times (1 + COS\beta) / 2 + I_{Global} \times \rho \times (1 - COS\beta) / 2$$

(2.1.2)

where q''_{sun} is the total incident radiation on the panel, I_{Beam} the beam or direct radiation, $I_{Diffuse}$ the diffuse radiation and I_{Global} the global radiation on the panel. These 3 parameters are taken from NSRDB, and ρ is the ground reflectance and is assumed to be 30% as a typical value.

R_b is the correction for a tilted surface and it includes the effects of the azimuth angle (γ) and other factors such as the hour of the day (ω), the day of the year (δ) and the latitude (φ):

$$R_b = COS\theta \,/\, COS\theta_z \tag{2.1.3}$$

where:

$$\begin{aligned} COS\theta = {} & SIN\delta \times SIN\varphi \times COS\beta - SIN\delta \times COS\varphi \times SIN\beta \times COS\gamma + COS\delta \times \\ & COS\varphi \times COS\beta \times COS\omega + COS\delta \times SIN\varphi \times SIN\beta \times COS\gamma \times \\ & COS\omega + COS\delta \times SIN\beta \times SIN\gamma \times SIN\omega \end{aligned} \tag{2.1.4}$$

and

$$COS\theta_z = SIN\delta \times SIN\varphi + COS\delta \times COS\varphi \times COS\omega \tag{2.1.5}$$

where $\varphi = 33.45°$ is the latitude for Phoenix.

Since the main goal is to run the AC on PV power to avoid grid power during peak hours, the tilt (β) and azimuth (γ) angles were optimized in such a way that maximizes the radiation on the PV panels during peak hours. The results are presented in chapter 3.1.

The size (area) and efficiency of the panels will determine the cost which in return will determine the area and efficiency after optimizing the rest of the parameters involved in optimizing the entire system.

2.2 The Thermal Energy Storage (TES)

The TES shown in figure 2.2.1 will store thermal energy during off-peak hours at T=-3°C, and consists of Cryogel Ice Balls [13] that are 103 mm diameter spheres constructed of high-density polyethylene and filled with water to form ice for cool energy storage. The Cryogel Ice Balls are placed in the TES and are charged (frozen) and discharged (melted) by means of circulating a glycol-based heat transfer fluid around the balls. During the charge mode (during off-peak hours), the glycol is circulated through the Ice Balls in the TES where the AC evaporator is submerged and the glycol is cooled to temperatures low enough (-6.7°C) to make ice.

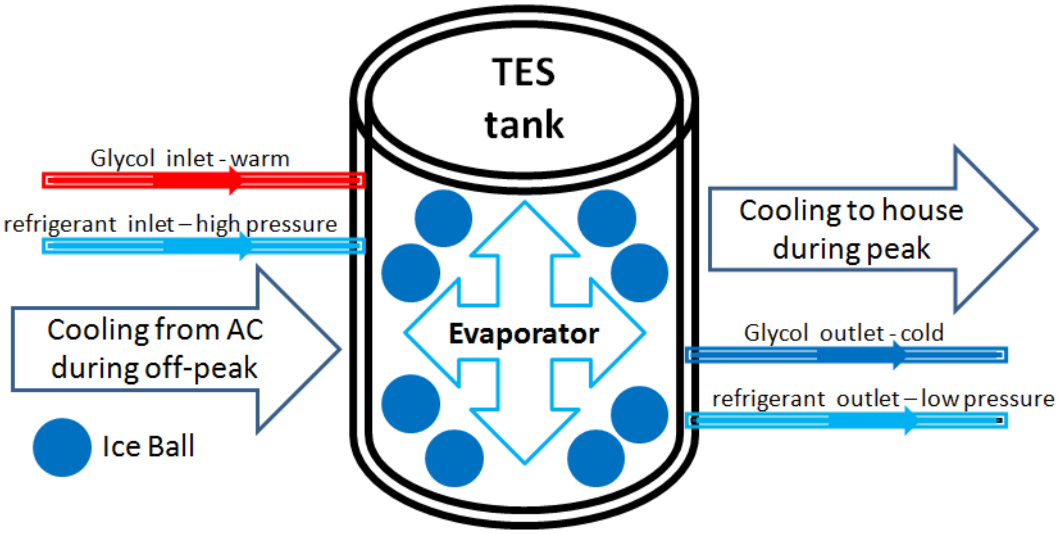


Figure 2.2.1: Schematic of the TES

The evaporating temperature of -6.7°C was selected from the tables (spec) of the manufacturer of the actual AC system that is being built and assembled on the roof of building ECF. This will enable more accurate comparison between the performance (COP, power consumption and mass flow) of the theoretical model optimized in this thesis to the performance of the actual system on the roof of ECF.

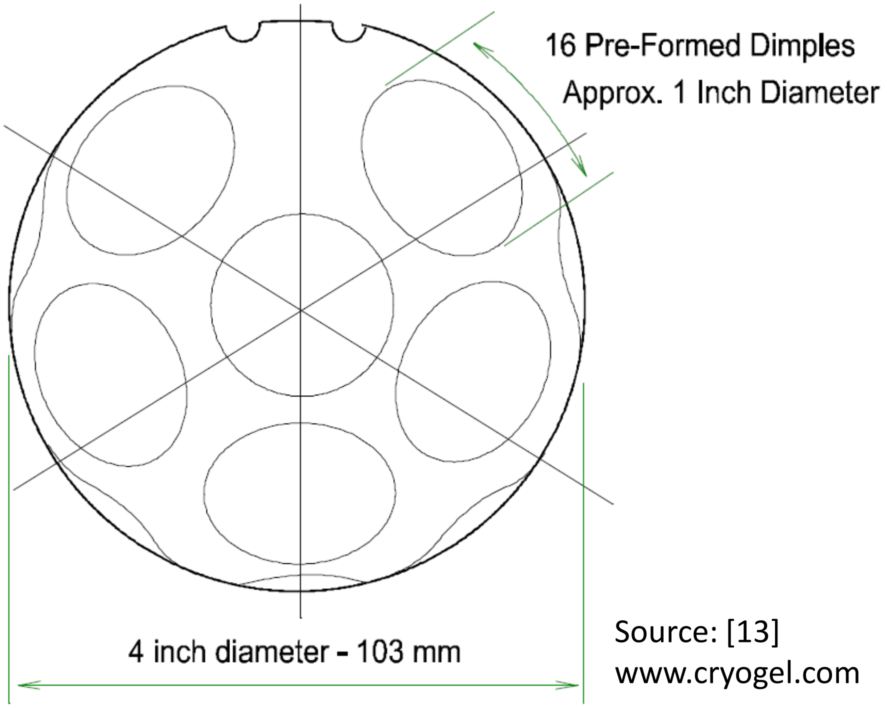
The temperature of the TES is assumed to reach -3°C when it (the ice balls) is fully frozen (charged) in order to utilize the latent heat of the ice balls, and will increase up to T=10°C when the ice balls in the TES are fully melted, this (T=10°C) will be the minimal temperature difference between the TES and the house and will always allow enough cool energy to flow from the TES to the house which is assumed to be kept at T=20°C.

The equation for charging and discharging of the TES is:

$$m \times \{ (C_{p,liquid} \times \Delta T_{liquid}) + (C_{p,solid} \times \Delta T_{solid}) + L_{latent} \} = \Delta Q - Losses \tag{2.2.1}$$

where Q is the cool energy in kJ, C_p the specific heat for solid (2 kJ/Kg/K) and liquid (4.2 kJ/Kg/K) states, L the latent heat for water (334 kJ/kg) and m the mass of the TES in kg (ice balls -- assumed to have the same properties as for water), the losses will represent thermal insulation losses and heat transfer / exchange inefficiencies and are represented in the equations in appendix B, however, the heat losses from the TES are negligible since the TES is assumed to be placed in the cooled space inside the house, moreover, the TES is designed to accumulate 10% extra of cool energy to account for such and other potential thermal losses.

Cryogel Ice Balls are designed such that the expansion of freezing water inside each ball is accommodated by the outward motion of pre-formed dimples in the surface of each ball. During the melting of the ice, each ball returns to its approximate original shape. The TES will be assumed as water since most of it is water balls, and thus has the thermodynamic properties of water.



Source: [13]
www.cryogel.com

Figure 2.2.2: Cryogel Ice Ball

Ice Balls are constructed with a proprietary high performance polyethylene polymer [13]. As water inside the Ice Ball freezes to form ice, the dimples flex out to allow for expansion. Without the dimples, the life of the balls would be diminished due to stretching and stressing of the plastic walls.

2.3 The AC Unit

The AC unit will run continuously and alternate between 2 set points, one when cooling the house directly through the air-side evaporator at T_{evap}=10°C and the 2nd when cooling the TES at T_{evap}=-6.7°C. Running the AC continuously is more efficient due to the elimination of the cycling off-and-on losses of the compressor, and will also extend the life time of the compressor by reducing the stress on the bearings caused during each restart of the compressor/motor assembly (hermetic for the smaller unit in the lab, and semi-hermetic for a 4 TR unit). It will also reduce the wear of the motor’s stator/rotor wind (coil) and maintain higher efficiency for longer years. The AC will maintain the house at a comfortable temperature range/zone (20°C), and when the house reaches that point, the AC (controller) will divert the refrigerant to the TES evaporator.

The size of the AC and TES will be matched such that the TES will be completely frozen and reach its lowest temperature (-3°C) just before peak hours start. The AC will run on PV power during grid peak hours, and will cool the house along with the TES to match the required Cooling Load (CL) at peak hours. Therefore a smaller size AC will be required, since the peak CL will be supplied also from the TES (since the off-peak CL is much smaller than the peak CL as shown in figure 2.4.1). The following figure 2.3.1 illustrates the operation modes of the AC.

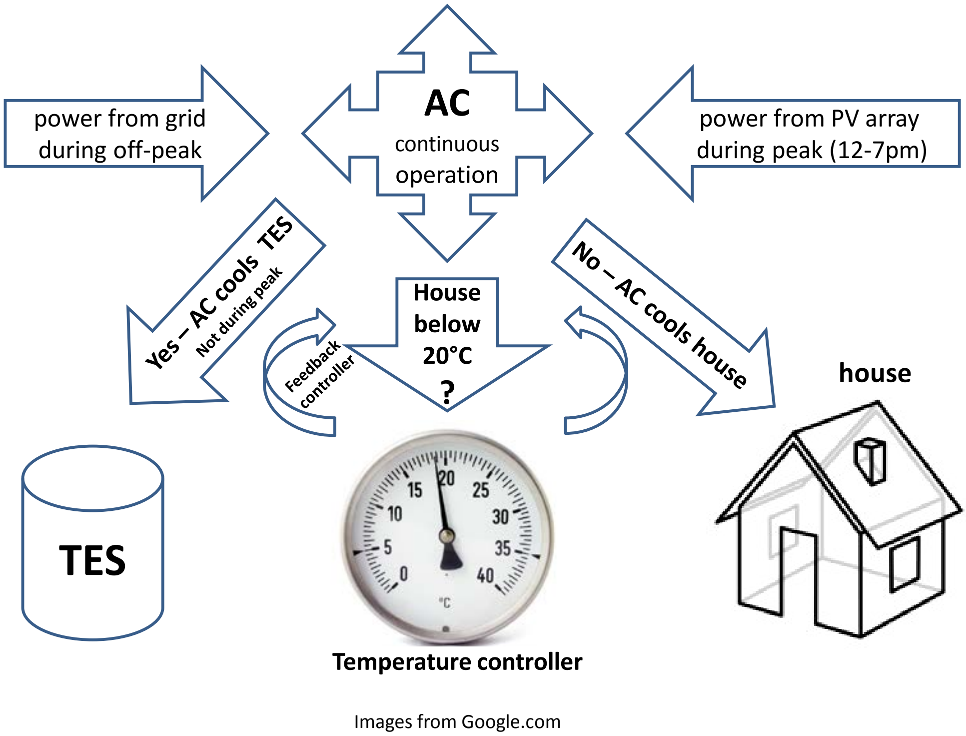


Figure 2.3.1: AC operation modes

The equations used to model the AC unit are as follows:

AC to TES: $Q_{AC\text{-}TES}=W_{IN,AC} \times COP_{AC\text{-}TES}$ (2.3.1)

AC to house: $Q_{AC\text{-}HOUSE}=W_{IN,AC} \times COP_{AC\text{-}HOUSE}$ (2.3.2)

$COP = \text{Function}\ (T_{\text{Condensing}}, T_{\text{Evaporating}})$ (2.3.3)

where *Q* is the cooling energy from the AC to either the house or the TES and *W* the power consumption of the AC.

2.4 The House and the Cooling Load

The size of the house is one of the main factors that determine the required hourly Cooling Load (CL). An average size house in Phoenix is about 1,600 [ft^2] with a regular AC (not HACS) unit sized for 4TR (~14$kW_{cooling}$ as max CL) [14]. It is assumed that the house's internal temperature is constant (the comfort zone temperature at T=20°C) all the time (24 hrs a day) and this parameter (T=20°C) is another main factor that determines the required CL.

The CL varies each hour of the day and depends on the outside ambient air temperature, the internal heat loads and the solar radiation absorbed by the house. For this project, we will use an hourly CL used in other research projects done for Phoenix by Yeshpal Gupta for an average monthly in July. The Max CL occurs in the late afternoon / early evening hours as shown in figure 2.4.1.

The heating load during the winter months is necessary for calculating the annual operational cost of the system, and is also obtained from Yeshpal Gupta for January in Phoenix.

This CL can be normalized based on the size of the house assuming a direct (linear) relationship between the CL and the size of the house and this method is also explained in ASHRAE [15]. The CL includes external and internal loads such as solar radiation, people and appliances inside the house. The CL is optimized where the maximum required CL matches the rated cooling capacity of the AC. i.e. if a house requires a

4TR AC system, it means that the maximum CL that is required from the AC is 4TR (~14kW$_c$) and that is the maximum heat gain of the house (external and internal) that the AC have to remove (cool) in order to keep the house at the same temperature.

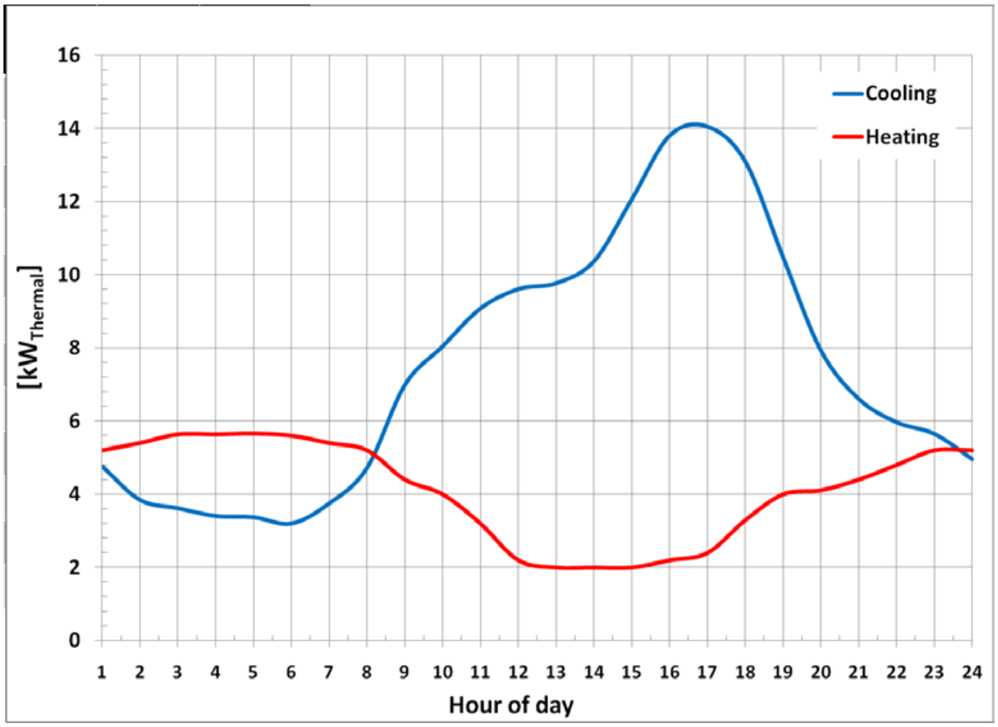


Figure 2.4.1: The Hourly Cooling and Heating Loads

This hourly cooling and heating loads matche a house in Phoenix, where it's rated as 4TR or 14kW$_{cooling}$ (1TR = 3.51 kW) at peak time during July. The CL and heating load for the rest of the months are shown in the following chapters and are based (as percentages) on the above figure which represents the extreme months (July for cooling and January for heating).

CHAPTER 3

HACS MODELING AND OPTIMIZATION

3.1 The Solar Power Generation

To maximize the solar PV power during peak hours (12-6pm), the power output is calculated for different combinations of the incline (β) and azimuth (γ) angles, where the target is to maximize the power in the middle of the peak hours (of the TOU) at 3pm. The final results for the best combination of the angles are shown in the tables and figures in the following pages, and the results and details for the other angles are included in appendix C.

For the hours before 5am and after 7pm, the radiation is zero or negligible. For each hour, the incline angle (β) changes from zero (horizontal) to 45 degrees, where the green (on the left) is horizontal and the dark green (on the right) is 45 degrees facing south.

Increasing the tilt (incline) angle (β) increases the incident radiation on the panels during peak hours and increasing the azimuth (γ) angle, shifts the peak of the radiation received on the PV panels from about noon time to later (3pm) in the afternoon / early evening hours as shown in the tables and figures. However, doing so reduces the total daily radiation received on the panels, and it’s limited to a certain level, where increasing γ does not further shift the received radiation peak to later hours without significantly decreasing the total daily radiation. The following tables and results show the final results for the optimum tilt and azimuth angles. The highlighted cell indicates the maximum radiation at 3pm at β=35°

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	Radiation [Wh/m^2] for Azimuth (γ) = 70°														
0	111	234	568	762	860	919	929	958	961	929	859	742	533	296	125
5	89	187	455	661	791	875	906	951	970	954	898	770	594	373	183
10	58	123	298	557	717	826	878	939	974	973	931	813	644	420	206
15	27	58	141	449	639	772	845	922	972	986	959	851	689	464	227
20	18	37	90	338	558	713	808	899	964	993	981	883	730	505	247
25	9	19	46	227	473	651	766	872	951	994	997	910	766	543	266
30	7	14	33	114	387	586	720	839	932	990	1,006	932	798	577	283
35	5	10	23	88	298	517	670	802	908	979	1,010	947	824	608	297
40	0	0	0	68	209	447	617	761	879	963	1,007	956	844	634	310
45	0	0	0	0	119	374	561	716	844	941	998	959	859	656	321

Table 3.1.1: Radiation for Azimuth 70 degrees

And is bolded / distinguished in the following chart at γ=70°

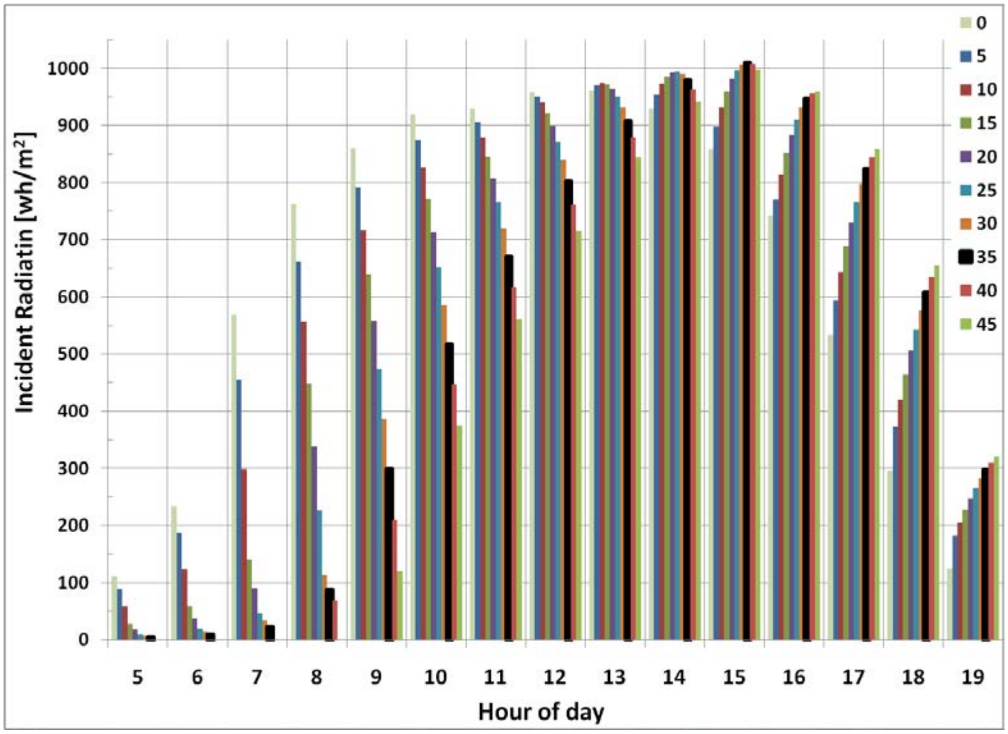
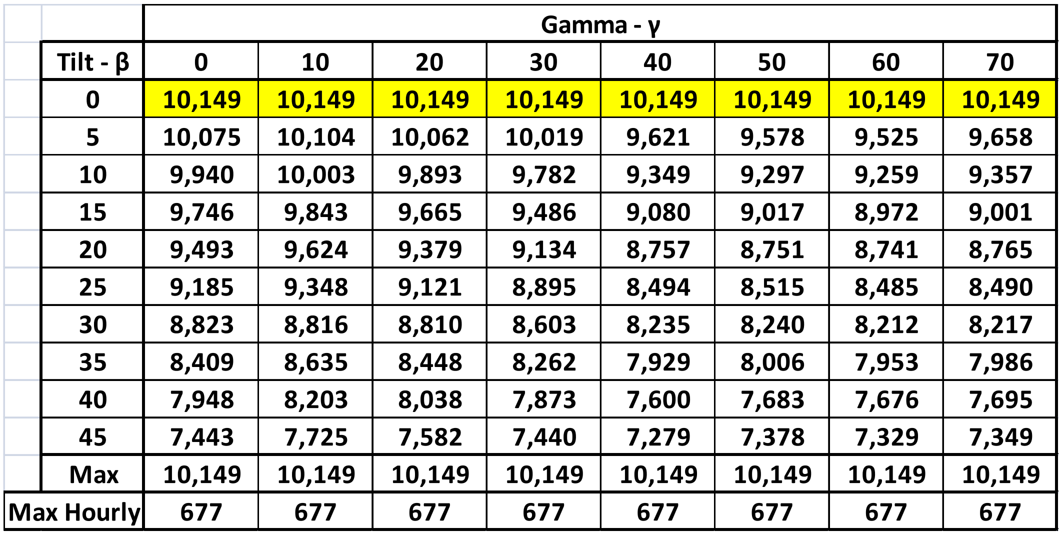


Figure 3.1.1: Radiation for Azimuth 70 degrees

As we can see in the last figure and table above (3.1.1), the incident radiation at 3pm (middle of the peak hours) is maximized for the incline angle of 35 degrees and the azimuth angle of 70 degrees (highlighted in the table and bolded in the figure).

The following table and figure (3.1.2) show the total daily radiation received on the panel for the various tilt and azimuth angles. We still want to maximize the total daily radiation, but the radiation during peak hours is most important for our goals (time of use plan).



		Gamma - γ							
	Tilt - β	0	10	20	30	40	50	60	70
	0	10,149	10,149	10,149	10,149	10,149	10,149	10,149	10,149
	5	10,075	10,104	10,062	10,019	9,621	9,578	9,525	9,658
	10	9,940	10,003	9,893	9,782	9,349	9,297	9,259	9,357
	15	9,746	9,843	9,665	9,486	9,080	9,017	8,972	9,001
	20	9,493	9,624	9,379	9,134	8,757	8,751	8,741	8,765
	25	9,185	9,348	9,121	8,895	8,494	8,515	8,485	8,490
	30	8,823	8,816	8,810	8,603	8,235	8,240	8,212	8,217
	35	8,409	8,635	8,448	8,262	7,929	8,006	7,953	7,986
	40	7,948	8,203	8,038	7,873	7,600	7,683	7,676	7,695
	45	7,443	7,725	7,582	7,440	7,279	7,378	7,329	7,349
	Max	10,149	10,149	10,149	10,149	10,149	10,149	10,149	10,149
Max Hourly		677	677	677	677	677	677	677	677

Table 3.1.2: Total Day Radiation for Each Incline and Azimuth

The radiation received on a horizontal (β=0°) plate does not change when changing the Azimuth (γ) since it only rotates the PV panel but it stays horizontal.

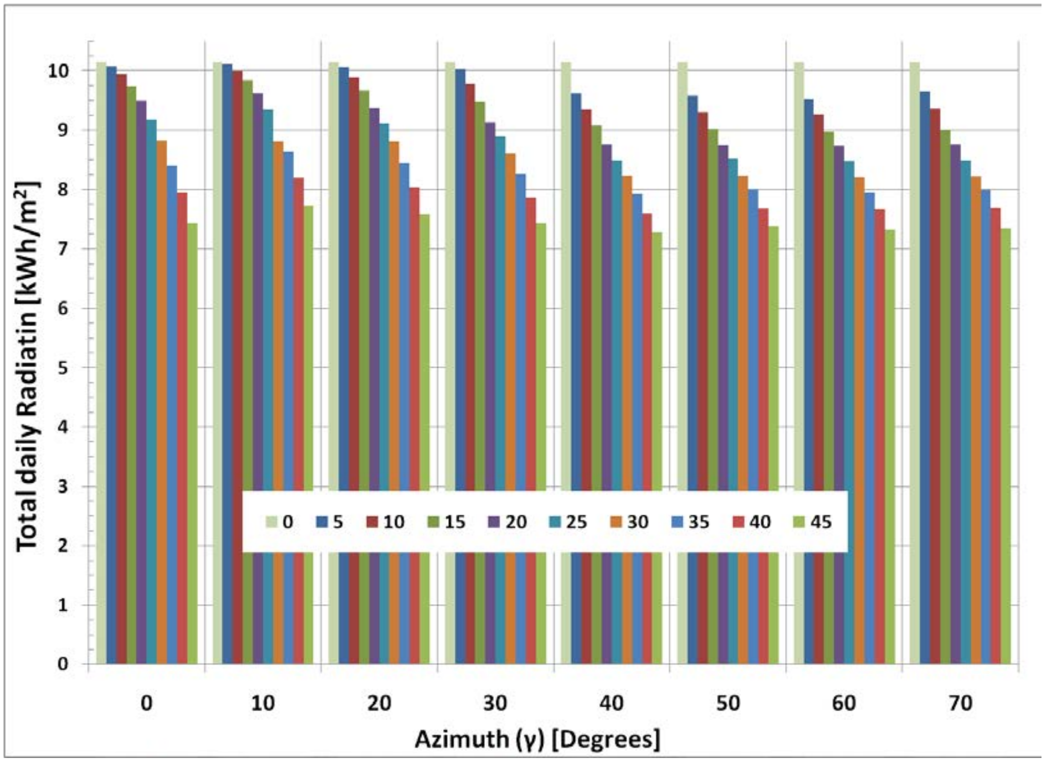


Figure 3.1.2: Total Day Radiation for Each Incline and Azimuth

The total daily radiation (Insolation) is maximized for horizontal (β=0°) panel. In the next table and figure, we see the incident average hourly radiation during the super peak hours (3-5pm). The radiation is increased with the increase of β and γ, but to a certain level where after β=40° it does not increase anymore, and it continues to increase with the increase of γ to a certain limit. However, we recall that the total daily radiation has decreased. The maximum values are highlighted in yellow.

	Gamma - γ							
Tilt - β	0	10	20	30	40	50	60	70
0	742	742	721	742	742	742	742	742
5	741	750	724	768	743	746	751	754
10	734	754	736	790	766	779	789	796
15	723	752	743	806	789	807	822	833
20	708	746	744	818	806	831	851	865
25	689	736	744	824	819	849	873	891
30	665	721	738	826	826	862	891	912
35	638	702	728	822	829	870	903	927
40	607	678	713	813	826	872	909	940
45	572	651	693	799	818	868	907	931
Max	742	754	744	826	829	872	909	940

Table 3.1.3: Average Hourly Radiation during Super Peak Hours

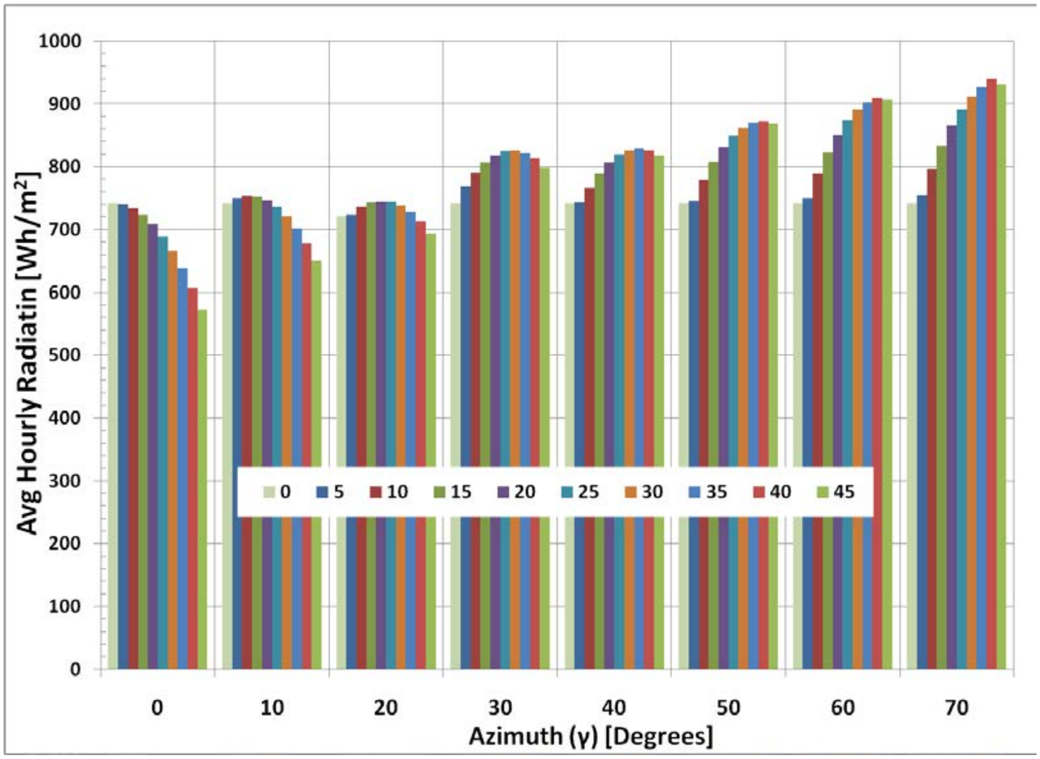


Figure 3.1.3: Average Hourly Radiation during Super Peak Hours

	Azimuth - γ							
Tilt - β	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**
0	780	780	759	780	754	754	754	754
5	781	788	770	800	781	783	785	787
10	778	791	778	815	797	804	810	813
15	770	789	782	825	810	821	829	835
20	757	783	782	830	819	833	844	851
25	740	772	777	829	822	840	853	862
30	718	756	767	824	821	841	857	868
35	693	736	752	814	814	838	856	868
40	663	711	733	800	803	830	850	863
45	630	683	710	780	787	816	839	853
Max	781	791	782	830	822	841	857	868

Table 3.1.4: Average Hourly Radiation during Peak Hours (12-6pm)

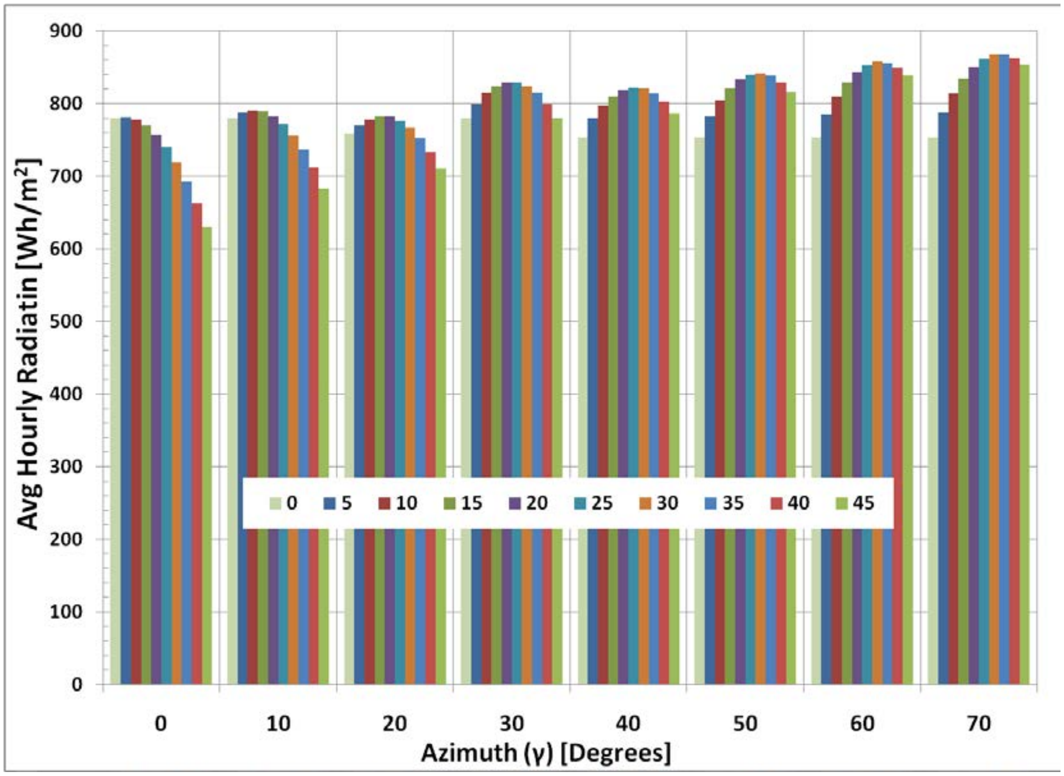


Figure 3.1.4: Average Hourly Radiation during Peak Hours (12-6pm)

The radiation is maximized for β=35°. In the next table and figure we see the average hourly radiation during peak hours (12-6pm), but not including the super peak hours (between 3-5pm).

	Gamma - γ							
Tilt - β	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**
0	809	809	792	809	786	786	786	786
5	812	816	804	823	809	811	812	812
10	810	819	810	833	820	823	826	823
15	804	817	812	838	826	831	835	836
20	794	810	808	838	828	834	839	840
25	778	798	801	833	824	833	838	840
30	758	782	788	823	816	826	832	835
35	734	761	771	809	803	814	821	824
40	706	736	749	790	786	798	806	809
45	673	707	723	766	763	777	786	789
Max	812	819	812	838	828	834	839	840

Table 3.1.5: Average Hourly Radiation during Peak Hours, Excluding Super Peak Hours

The maximum occurs for β=20° and γ=70°, which shows that radiation for the early hours of the peak (12-2pm) is maximized when the incline β is smaller (than for later hours (super peak) that occurs for β=40°).

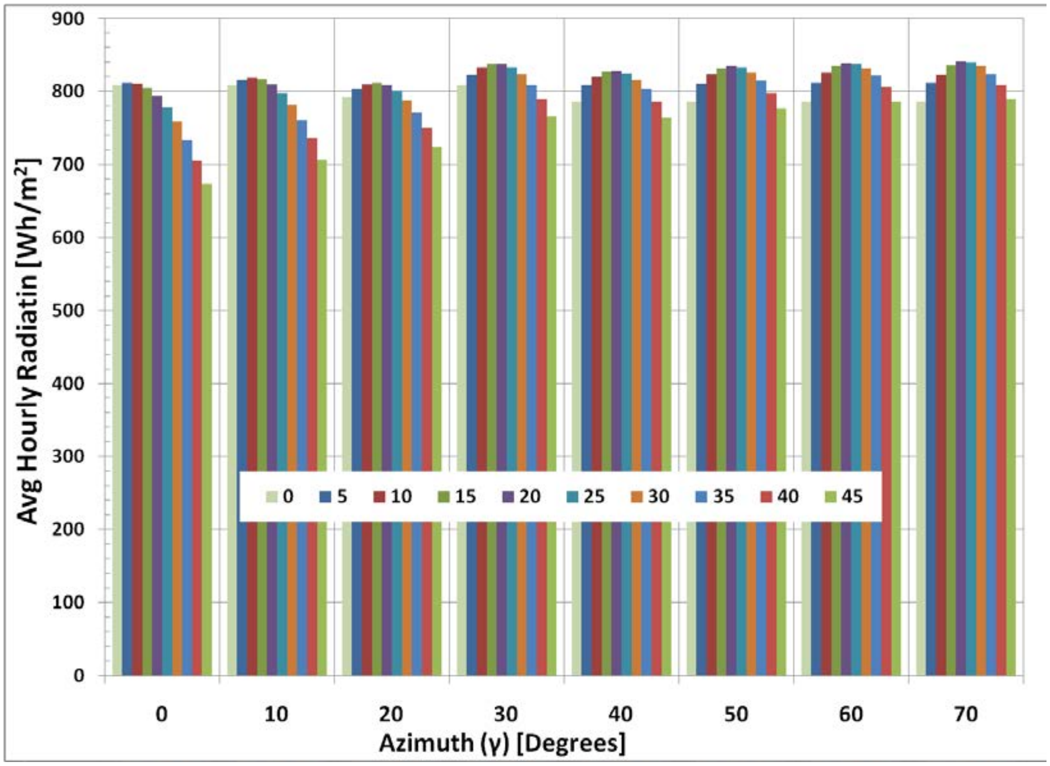


Figure 3.1.5: Average Hourly Radiation during Peak Hours, without Super Peak hours

In the following table 3.1.6, in the left column, we see the combination of β and γ where a maximum value of the radiation occurs for the parameter on the top row of table 3.1.6, in the previous 4 tables**.** In other words, it represents only the maximum values of radiation in the previous 4 tables (super peak, peak, peak without super peak and off-peak) highlighted in yellow with the corresponding β and γ angles. i.e. for β=0° and γ=0°, the maximum radiation during the super peak hours (2nd column on the left) is 742kWh, but the maximum of all the maximums for the radiation during super peak occurs at β=40° and γ=70° at 840kWh, and the total daily (3rd column from left) and average hourly (4th column from left) are the maximum value for the corresponding β and γ, respectively.

$(\beta, \gamma)_{max}$	super peak [kWh]	Tot day [kWh]	Avg Tot Hr Day [kWh]	peak [kWh/h]	peak w/o super [kWh]	Avg day w/o peaks [kWh]
0,0	742	**10,149**	**677**	780	809	**586**
5,0	741	10,075	672	781	812	576
10,10	754	10,003	667	791	819	558
15,20	743	9,665	640	782	812	523
20,20	763	9,379	620	782	808	488
20,30	818	9,134	609	830	838	416
20,40	806	8,757	589	819	828	378
20,50	831	8,751	583	833	834	365
20,60	851	8,741	583	844	839	354
20,70	865	8,765	584	851	**840**	351
25,20	744	9,121	608	777	801	461
25,40	819	8,494	566	822	824	342
30,30	826	8,603	554	824	823	354
30,50	862	8,240	549	841	826	294
30,60	891	8,212	547	857	832	276
35,40	829	7,929	537	814	803	279
35,70	927	7,986	532	**868**	824	239
40,50	872	7,683	519	830	798	235
40,60	909	7,676	509	850	806	216
40,70	**940**	7,695	503	863	809	206
Max	**940**	**10,149**	**677**	**868**	**840**	**586**

Table 3.1.6: Maximums for β and γ Combinations

The maximum (of all the maximums) of the average hourly radiation during peak hours occurs for β=35° and γ=70°.

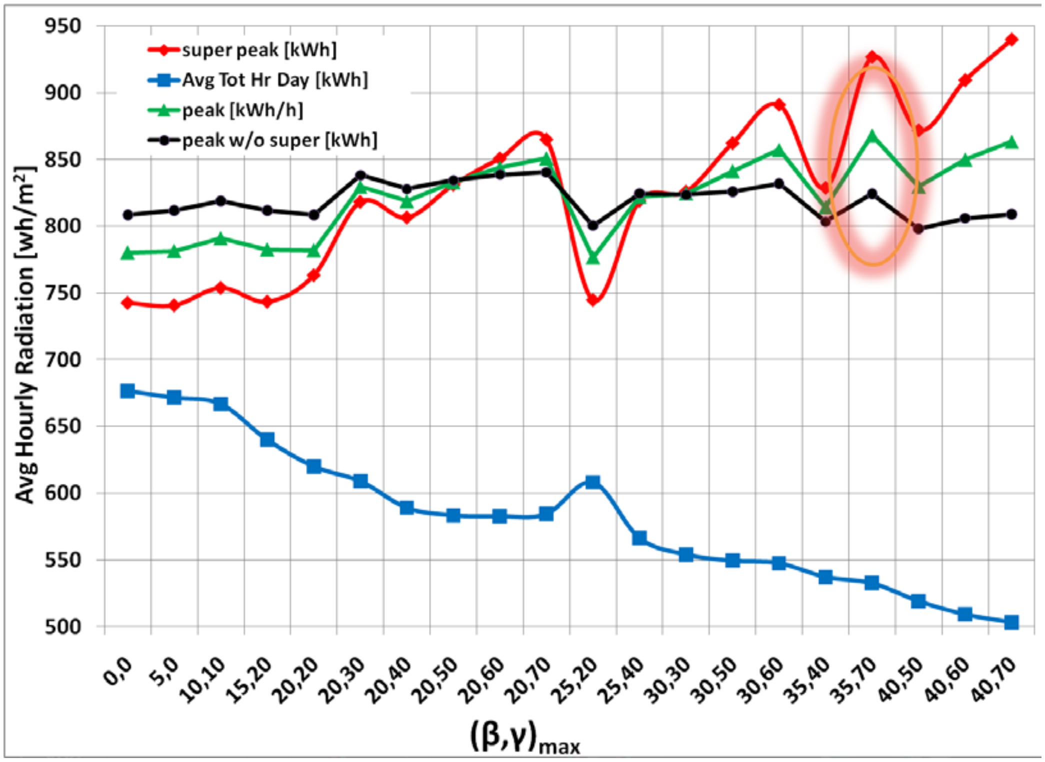
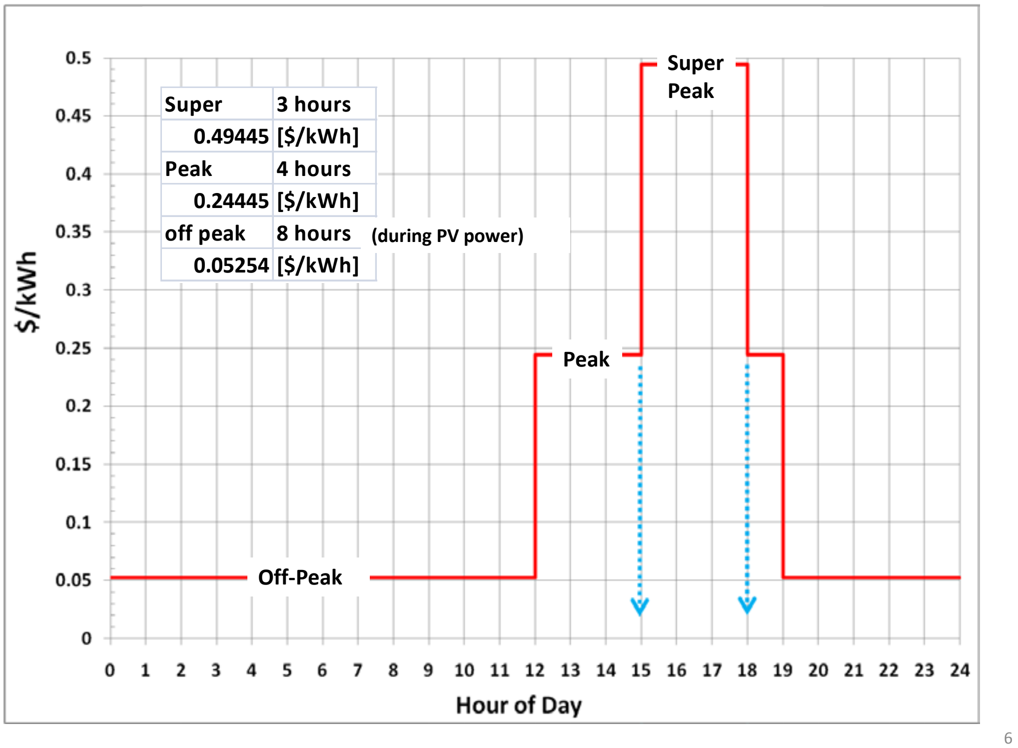


Figure 3.1.6: Maximums for β and γ Combinations.

In the above figure, we see a graphic representation of the previous table. As observed, the total daily radiation (blue line) per hour decreases when increasing β and γ. However, the radiation during peak hours increases.



Super	3 hours
0.49445	[$/kWh]
Peak	4 hours
0.24445	[$/kWh]
off peak	8 hours (during PV power)
0.05254	[$/kWh]

Figure 3.1.7: Time Advantage Super Peak TOU plan from APS [5]

Super peak hours are between 3-5pm, peak hours between 12-6pm and off-peak hours between 7pm to 12pm next day. Note: 8 hours of off-peak hours during sunlight (5am-7pm), night hours are also considered off-peak but are not considered when optimizing β and γ since the solar radiation is zero.

The following table quantifies the maximum radiation (energy) in dollars according to the “time advantage super peak” TOU plan from APS [5] in figure 3.1.7 above. The rates and the duration are shown on the right side of the table. The last column on the right side shows the total value of the daily radiation (including peak and off-peak hours) in $$. We can also see that when β=35° and γ=70°, we get the highest daily value in dollars for radiation.

$(\beta,\gamma)_{max}$	Super [$/day]	peak w/o super [$/day]	Avg day w/o peaks [$/day]	Tot [$$/day]		
0,0	8.259	5.929	1.847	16.035	PV Area	
5,0	8.238	5.954	1.815	16.007	50	[m^2]
10,10	8.384	6.004	1.761	16.148	PV Efficie.	
15,20	8.269	5.953	1.650	15.871	15%	
20,20	8.488	5.929	1.539	15.957	Super	3 hours
20,30	9.100	6.147	1.311	16.558	0.49445	[$/kWh]
20,40	8.970	6.071	1.193	16.234	Peak	4 hours
20,50	9.243	6.119	1.151	16.513	0.24445	[$/kWh]
20,60	9.462	6.150	1.117	16.729	off peak	8 hours
20,70	9.622	6.163	1.107	16.891	0.05254	[$/kWh]
25,20	8.282	5.871	1.452	15.606		
25,40	9.110	6.046	1.079	16.235		
30,30	9.186	6.039	1.116	16.341		
30,50	9.590	6.057	0.926	16.573		
30,60	9.911	6.102	0.871	16.884		
35,40	9.218	5.891	0.879	15.987		
35,70	10.310	6.045	0.752	17.107		
40,50	9.697	5.852	0.739	16.289		
40,60	10.116	5.910	0.680	16.707		
40,70	10.455	5.934	0.651	17.040		
Max	10.455	6.163	1.847	17.107		

Table 3.1.7: Value in Dollars for the Generated Solar Energy.

The PV area is taken as 50[m^2] and the efficiency as 15% for comparison purposes only, and it does not affect the choice of β and γ.

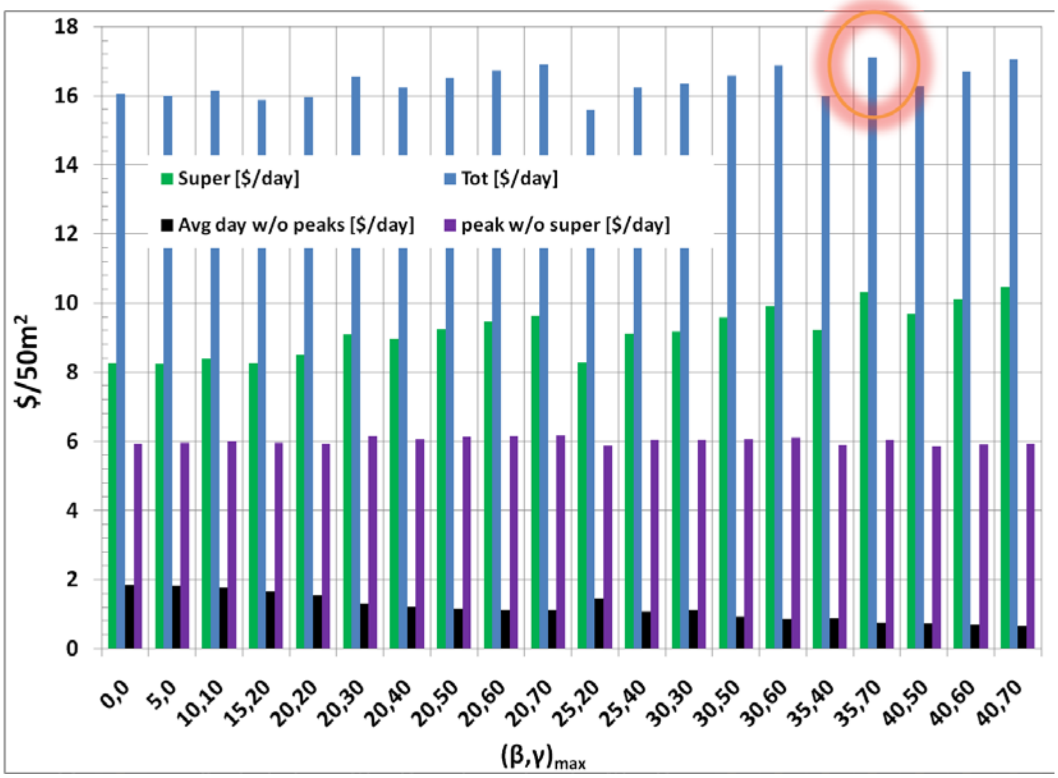


Figure 3.1.8: Money Value of Total Day Radiation

We see that for γ=70° and β=35°, we get the maximum daily. Thus, the optimum combination is β=35° and γ=70°. Note that for other TOU plans, the optimum γ and β angles might be different than γ=70° and β=35°, therefore, this is a limitation in this type of analysis and can be resolved by adjusting the rates of the TOU in table 3.1.7.

3.2 The AC Performance

To calculate the hourly COP of the HACS with the varying outside air and refrigerant condensing temperatures, we used the performance tables provided by the manufacturer of the actual system (built in the lab on the roof of building ECF) and compared it to the Carnot efficiency of the ideal cycle, found the relative Carnot efficiency (The COP of the real cycle relative to the efficiency of the ideal Carnot cycle operating at the same temperatures) and calculated the COP of the system.

The following are the tables given from the manufacturer for the compressor used to build the actual system, assuming a similar behavior for the larger (4TR) system. The 2 operating modes of the AC (house and TES) are marked in the orange elliptical / rectangular shapes.

Q_c[w] @ T_{con}=54.4°C=129.92F										
RPM	Tevap[°C]									
	-12	-9.4	-6.7	-3.9	-1.1	1.7	4.4	7.2	10	12.8
1,800	471	512	567	634	713	805	910	1,028	1,159	1,302
2,300	641	699	773	862	967	1,088	1,224	1,376	1,544	1,727
2,800	805	861	940	1,041	1,164	1,309	1,477	1,668	1,881	2,116
3,500	1,047	1,139	1,257	1,401	1,571	1,767	1,990	2,238	2,513	2,813
3,700	1,110	1,241	1,396	1,575	1,780	2,009	2,263	2,542	2,845	3,174
4,500	1,459	1,584	1,745	1,941	2,174	2,443	2,747	3,088	3,464	3,877
5,300	1,693	1,856	2,061	2,306	2,592	2,919	3,287	3,696	4,145	4,636
6,500	2,448	2,593	2,789	3,035	3,332	3,680	4,078	4,527	5,027	5,578

Table 3.2.1: The Cooling Capacity of the Actual System.

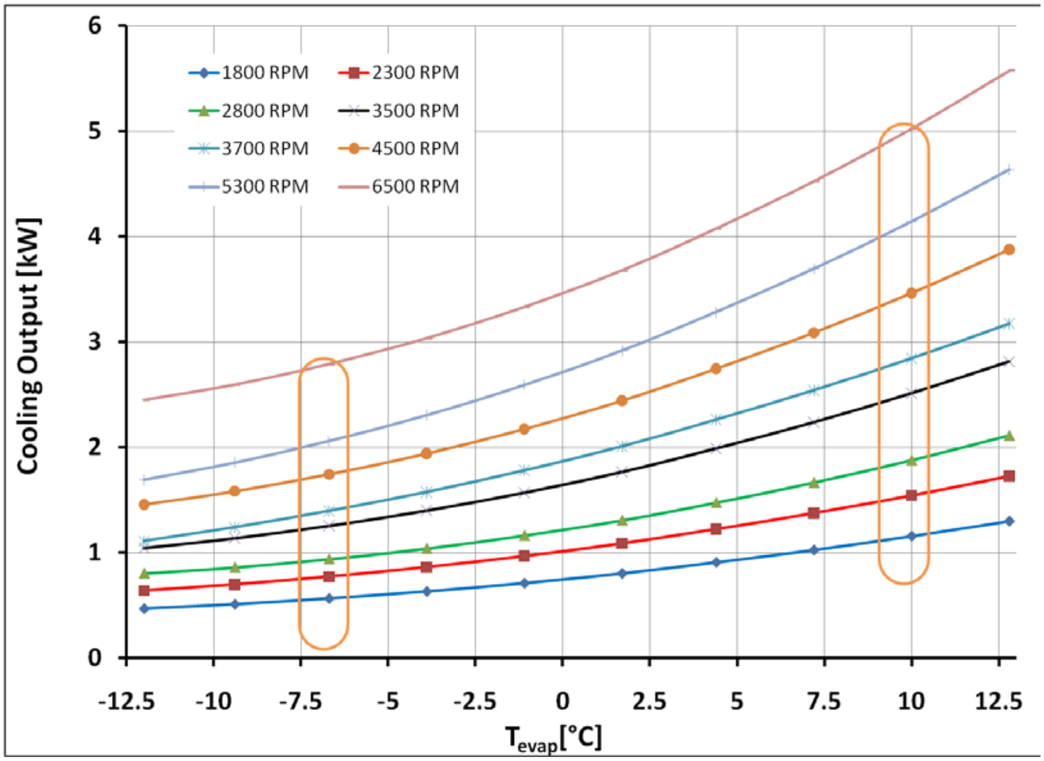


Figure 3.2.1: The Cooling Capacity of the Actual System

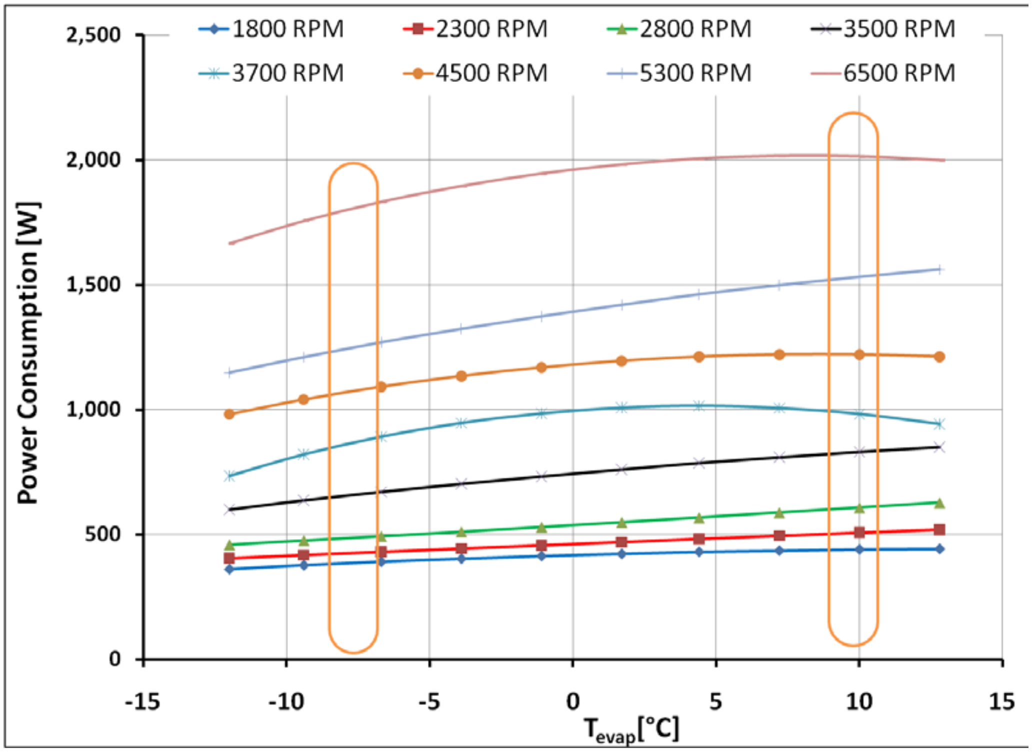


Figure 3.2.2: The Power Consumption of the Actual System.

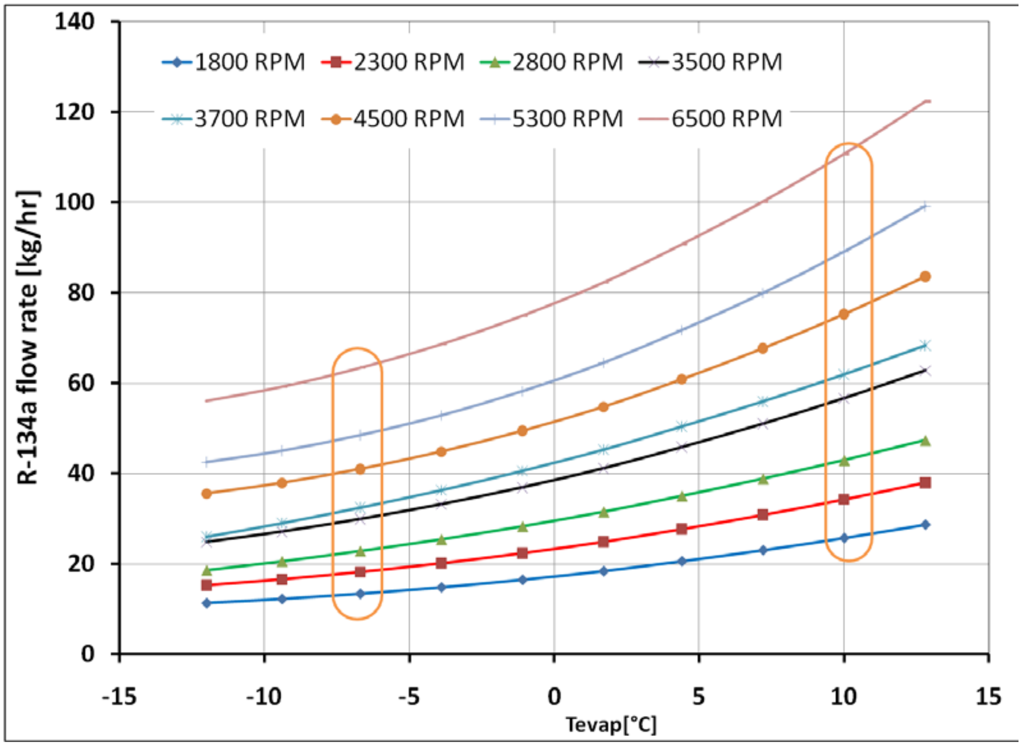


Figure 3.2.3: The Mass Flow of the Actual System.

The maximum COP is for the frequency of 2,800RPM, and is used to calculate the relative Carnot efficiency as explained in the following pages.

COP @ T_{con}=54.4°C=129.92F										
RPM	**T_{evap}[°C]**									
	-12	-9.4	-6.7	-3.9	-1.1	1.7	4.4	7.2	10	12.8
1800	1.31	1.36	1.45	1.58	1.73	1.91	2.12	2.36	2.63	2.94
2300	1.59	1.68	1.8	1.95	2.12	2.32	2.54	2.78	3.05	3.33
2800	1.76	1.81	1.91	2.04	2.2	2.39	2.61	2.84	3.1	3.37
3500	1.75	1.79	1.88	1.99	2.14	2.32	2.53	2.76	3.02	3.31
3700	1.51	1.51	1.57	1.67	1.81	1.99	2.23	2.53	2.9	3.37
4500	1.49	1.52	1.6	1.71	1.86	2.05	2.27	2.53	2.84	3.2
5300	1.48	1.53	1.62	1.74	1.89	2.06	2.25	2.47	2.71	2.97
6500	1.47	1.48	1.52	1.6	1.71	1.86	2.03	2.25	2.5	2.79
Max	**1.76**	**1.81**	**1.91**	**2.04**	**2.2**	**2.39**	**2.61**	**2.84**	**3.1**	**3.37**
Min	**1.31**	**1.36**	**1.45**	**1.58**	**1.71**	**1.86**	**2.03**	**2.25**	**2.5**	**2.79**

Table 3.2.2: The COP of the Actual System.

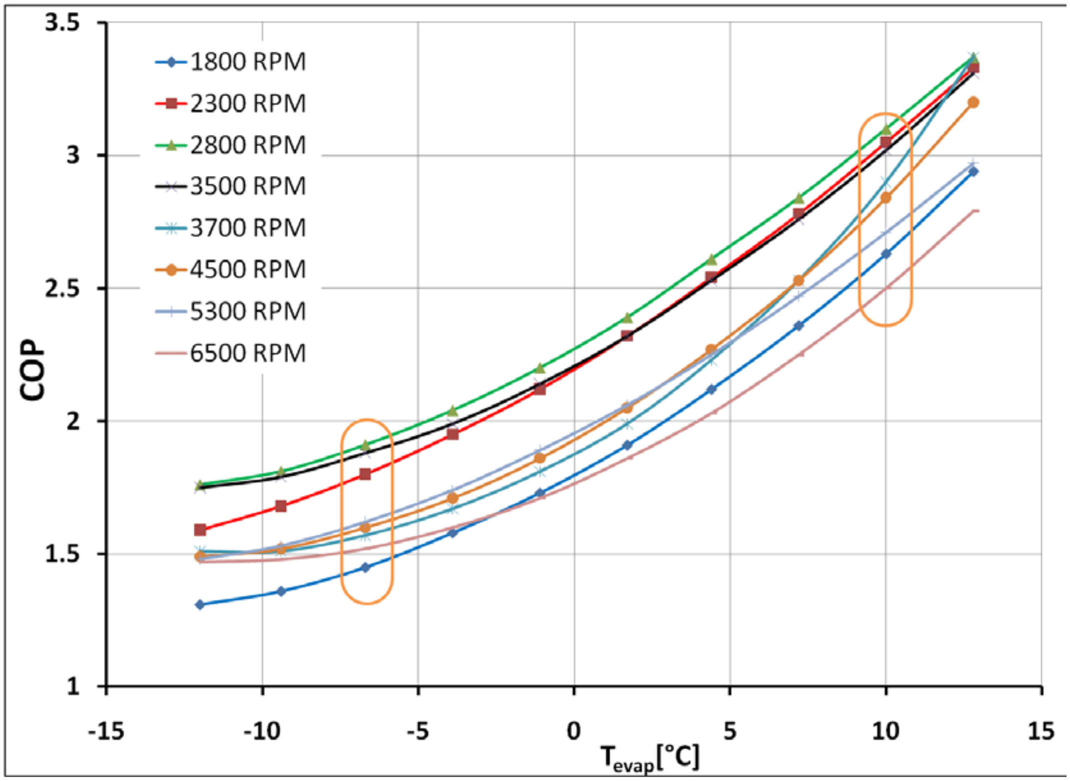


Figure 3.2.4: The COP of the Actual System.

The dry bulb temperature was taken from the NSRDB [2] as the average hourly for July and the condensing temperature for both modes (house and TES) is 12.4°C above the ambient (dry bulb) temperature (54.4°C-42.03°C=12.4°C) at 4pm where the outside temperature is highest at 4pm we get the lowest COP of 3.11 for the house mode and 2.09 for the TES.

The values for 4pm in table 3.2.3 were used to determine the relative Carnot efficiency (%) of the actual cycle by comparing the calculated COP in table 3.2.3 to the manufacturer COP in table 3.2.2 where the condensing (54.4°C = (42.03°C + 12.4°C)) and evaporating (10°C and -6.7°C) temperatures match and found out that at 4pm (highest dry bulb temperature, lowest COP) that the average relative Carnot efficiency (for the TES and for the house) is 46.2%.

Illustration: at 4pm (16th hour of the day) the outside air (dry bulb) temperature is 42.03°C, the condensing temperature is 54.4°C (42.03°C + 12.4°C) which matches the manufacturers' condensing temperature (54.4°C=129.92°F) at which the COP from table 3.2.2 at evaporating temperature of 10°C is 3.1, the Carnot efficiency (COP) for this cycle based on equation 1.1.2 in page 1 is (in Kelvin temperature scale): COP = (10 + 273) / ((54.4 + 273) – (10 + 273)) = 6.37, thus the relative Carnot efficiency of the cycle at evaporating temperature of 10°C is 3.1 / 6.37 = 48.6%. In the same manner we calculate the relative Carnot efficiency at evaporating temperature of -6.7°C and it is 43.8%. Therefore the COP values in table 3.2.3 were calculated using the average ((48.6% + 43.8%) / 2 = 46.2%, AKA the relative Carnot efficiency) Carnot efficiency for each evaporating temperature.

In figure 3.2.5 we see how the COP changes with the outside temperatures which change during each hour of the day. Note that there are 2 vertical axes, one axis on the left for the COP and another axis on the right for temperatures.

July Hr of day	**AC-CL COP @ T_{Eva}=10[°C]**	**AC-TS COP @ T_{Eva}=-6.7[°C]**	**Dry Bulb Temp. [°C]**
1	3.87	2.44	33.82
2	3.97	2.48	32.95
3	4.07	2.52	32.14
4	4.20	2.57	31.09
5	4.31	2.62	30.34
6	4.36	2.63	30.00
7	4.28	2.60	30.57
8	4.07	2.52	32.13
9	3.85	2.43	33.98
10	3.65	2.34	35.78
11	3.49	2.27	37.47
12	3.36	2.21	38.93
13	3.25	2.16	40.18
14	3.18	2.13	41.13
15	3.13	2.10	41.75
16	3.11	2.09	42.03
17	3.12	2.10	41.95
18	3.16	2.12	41.42
19	3.26	2.17	40.06
20	3.36	2.21	38.96
21	3.47	2.26	37.68
22	3.63	2.33	36.02
23	3.73	2.38	35.05
24	3.80	2.41	34.38
AVG	**3.65**	**2.34**	**36.24**
MAX	**4.36**	**2.63**	**42.03**
MIN	**3.11**	**2.09**	**30.00**

Table 3.2.3: The Hourly Variation of the COP and the Ambient Temperatures.

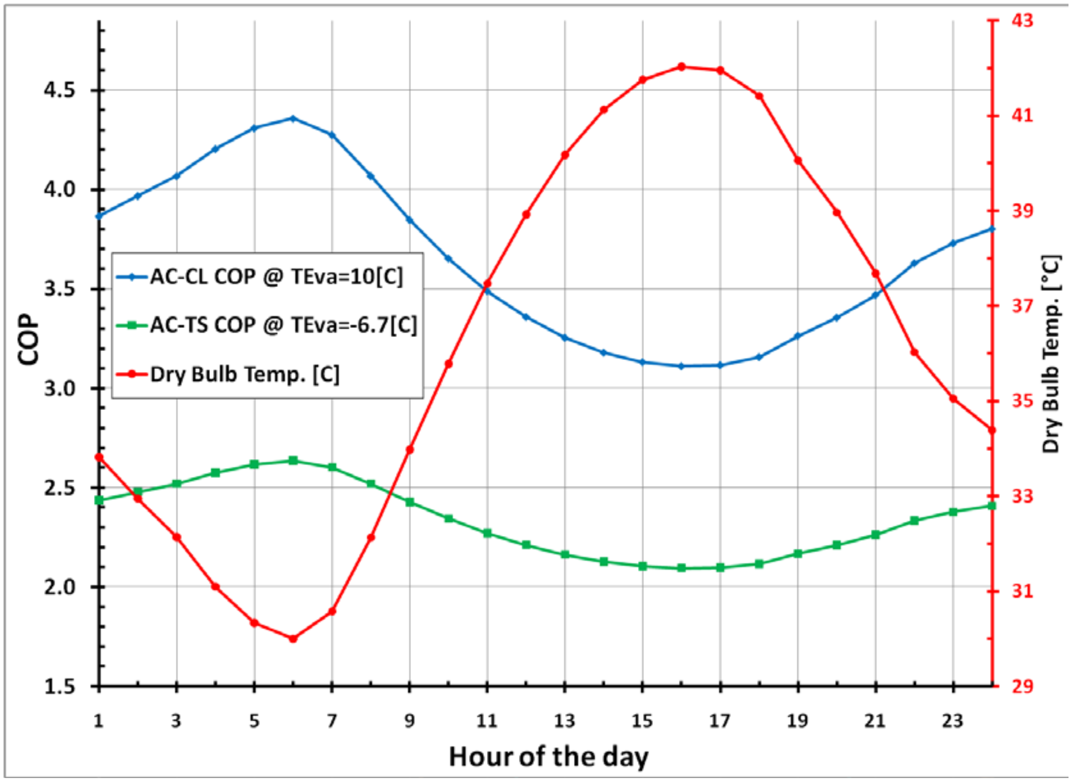
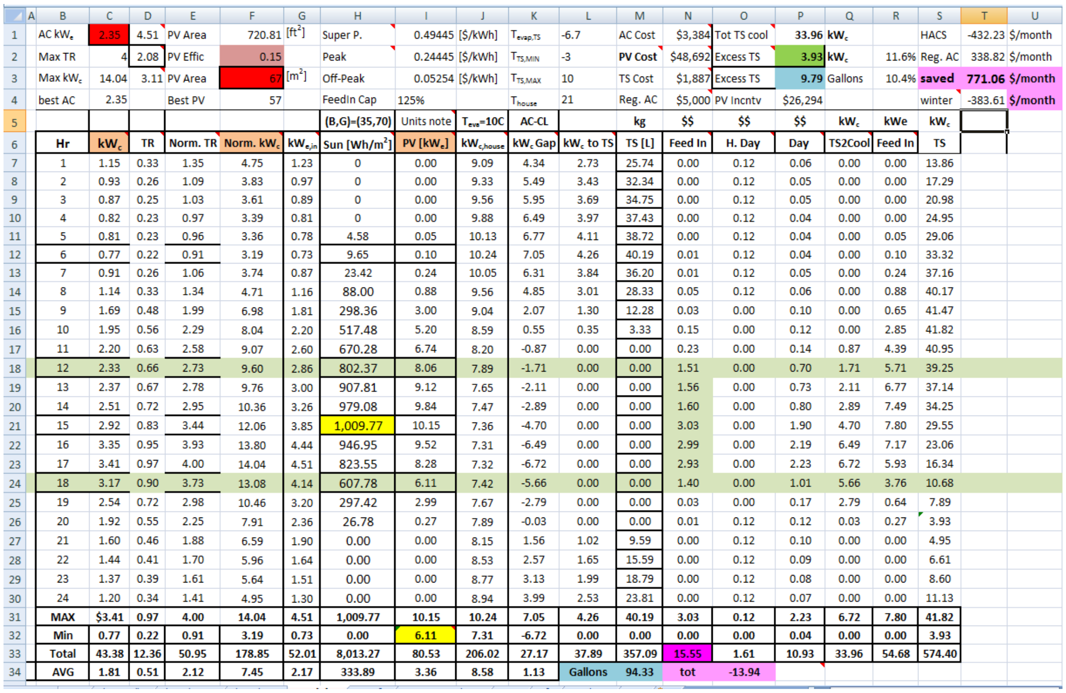


Figure 3.2.5: The Hourly Variation of the COP and the Temperature.

As seen in the above figure and table, the COP is highest when the outside temperature is lowest and vice versa. The changes in the COP of the AC when it's cooling the house (the blue line) are larger than the changes of the COP when the AC is cooling the TES (the green line) due to the larger difference between the condensing temperatures and the evaporating temperatures.

3.3 The Optimization Model

The following figure 3.3.1 is a snapshot of one of the excel program sheet that represent part of the computer model. The model links all the required results from the previous sections via the equations for each component and calculates the capital and the monthly operational costs of the HACS and the conventional AC system in order to calculate the economic effectiveness of each system.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1		AC kW$_e$	2.35	4.51	PV Area	720.81	[ft^2]	Super P.	0.49445	[\$/kWh]	T$_{evap,TS}$	-6.7	AC Cost	\$3,384	Tot TS cool	**33.96**	**kW$_c$**		HACS	-432.23	\$/month
2		Max TR	4	2.08	PV Effic	0.15		Peak	0.24445	[\$/kWh]	T$_{TS,MIN}$	-3	**PV Cost**	\$48,692	Excess TS	**3.93**	**kW$_c$**	11.6%	Reg. AC	338.82	\$/month
3		Max kW$_c$	14.04	3.11	PV Area	67	[m^2]	Off-Peak	0.05254	[\$/kWh]	T$_{TS,MAX}$	10	TS Cost	\$1,887	Excess TS	**9.79**	Gallons	10.4%	**saved**	**771.06**	**\$/month**
4		best AC	2.35		Best PV	57		FeedIn Cap	125%		T$_{house}$	21	Reg. AC	\$5,000	PV Incntv	\$26,294			winter	-383.61	**\$/month**
5								**(B,G)=(35,70)**	Units note	**T$_{eva}$=10C**	**AC-CL**		**kg**	**\$\$**	**\$\$**	**\$\$**	**kW$_c$**	**kWe**	**kW$_c$**		
6		**Hr**	**kW$_c$**	**TR**	**Norm. TR**	**Norm. kW$_c$**	**kW$_{e,in}$**	**Sun [Wh/m^2]**	**PV [kW$_e$]**	**kW$_{c,house}$**	**kW$_c$ Gap**	**kW$_c$ to TS**	**TS [L]**	**Feed In**	**H. Day**	**Day**	**TS2Cool**	**Feed In**	**TS**		
7		1	1.15	0.33	1.35	4.75	1.23	0	0.00	9.09	4.34	2.73	25.74	0.00	0.12	0.06	0.00	0.00	13.86		
8		2	0.93	0.26	1.09	3.83	0.97	0	0.00	9.33	5.49	3.43	32.34	0.00	0.12	0.05	0.00	0.00	17.29		
9		3	0.87	0.25	1.03	3.61	0.89	0	0.00	9.56	5.95	3.69	34.75	0.00	0.12	0.05	0.00	0.00	20.98		
10		4	0.82	0.23	0.97	3.39	0.81	0	0.00	9.88	6.49	3.97	37.43	0.00	0.12	0.04	0.00	0.00	24.95		
11		5	0.81	0.23	0.96	3.36	0.78	4.58	0.05	10.13	6.77	4.11	38.72	0.00	0.12	0.04	0.00	0.05	29.06		
12		6	0.77	0.22	0.91	3.19	0.73	9.65	0.10	10.24	7.05	4.26	40.19	0.01	0.12	0.04	0.00	0.10	33.32		
13		7	0.91	0.26	1.06	3.74	0.87	23.42	0.24	10.05	6.31	3.84	36.20	0.01	0.12	0.05	0.00	0.24	37.16		
14		8	1.14	0.33	1.34	4.71	1.16	88.00	0.88	9.56	4.85	3.01	28.33	0.05	0.12	0.06	0.00	0.88	40.17		
15		9	1.69	0.48	1.99	6.98	1.81	298.36	3.00	9.04	2.07	1.30	12.28	0.03	0.00	0.10	0.00	0.65	41.47		
16		10	1.95	0.56	2.29	8.04	2.20	517.48	5.20	8.59	0.55	0.35	3.33	0.15	0.00	0.12	0.00	2.85	41.82		
17		11	2.20	0.63	2.58	9.07	2.60	670.28	6.74	8.20	-0.87	0.00	0.00	0.23	0.00	0.14	0.87	4.39	40.95		
18		12	2.33	0.66	2.73	9.60	2.86	802.37	8.06	7.89	-1.71	0.00	0.00	1.51	0.00	0.70	1.71	5.71	39.25		
19		13	2.37	0.67	2.78	9.76	3.00	907.81	9.12	7.65	-2.11	0.00	0.00	1.56	0.00	0.73	2.11	6.77	37.14		
20		14	2.51	0.72	2.95	10.36	3.26	979.08	9.84	7.47	-2.89	0.00	0.00	1.60	0.00	0.80	2.89	7.49	34.25		
21		15	2.92	0.83	3.44	12.06	3.85	1,009.77	10.15	7.36	-4.70	0.00	0.00	3.03	0.00	1.90	4.70	7.80	29.55		
22		16	3.35	0.95	3.93	13.80	4.44	946.95	9.52	7.31	-6.49	0.00	0.00	2.99	0.00	2.19	6.49	7.17	23.06		
23		17	3.41	0.97	4.00	14.04	4.51	823.55	8.28	7.32	-6.72	0.00	0.00	2.93	0.00	2.23	6.72	5.93	16.34		
24		18	3.17	0.90	3.73	13.08	4.14	607.78	6.11	7.42	-5.66	0.00	0.00	1.40	0.00	1.01	5.66	3.76	10.68		
25		19	2.54	0.72	2.98	10.46	3.20	297.42	2.99	7.67	-2.79	0.00	0.00	0.03	0.00	0.17	2.79	0.64	7.89		
26		20	1.92	0.55	2.25	7.91	2.36	26.78	0.27	7.89	-0.03	0.00	0.00	0.01	0.12	0.12	0.03	0.27	3.93		
27		21	1.60	0.46	1.88	6.59	1.90	0.00	0.00	8.15	1.56	1.02	9.59	0.00	0.12	0.10	0.00	0.00	4.95		
28		22	1.44	0.41	1.70	5.96	1.64	0.00	0.00	8.53	2.57	1.65	15.59	0.00	0.12	0.09	0.00	0.00	6.61		
29		23	1.37	0.39	1.61	5.64	1.51	0.00	0.00	8.77	3.13	1.99	18.79	0.00	0.12	0.08	0.00	0.00	8.60		
30		24	1.20	0.34	1.41	4.95	1.30	0.00	0.00	8.94	3.99	2.53	23.81	0.00	0.12	0.07	0.00	0.00	11.13		
31		**MAX**	**\$3.41**	**0.97**	**4.00**	**14.04**	**4.51**	**1,009.77**	**10.15**	**10.24**	**7.05**	**4.26**	**40.19**	**3.03**	**0.12**	**2.23**	**6.72**	**7.80**	**41.82**		
32		**Min**	**0.77**	**0.22**	**0.91**	**3.19**	**0.73**	**0.00**	**6.11**	**7.31**	**-6.72**	**0.00**	**0.00**	**0.00**	**0.00**	**0.04**	**0.00**	**0.00**	**3.93**		
33		**Total**	**43.38**	**12.36**	**50.95**	**178.85**	**52.01**	**8,013.27**	**80.53**	**206.02**	**27.17**	**37.89**	**357.09**	**15.55**	**1.61**	**10.93**	**33.96**	**54.68**	**574.40**		
34		**AVG**	**1.81**	**0.51**	**2.12**	**7.45**	**2.17**	**333.89**	**3.36**	**8.58**	**1.13**	**Gallons**	**94.33**	**tot**	**-13.94**						

Figure 3.3.1: The Optimization Model

<u>Explanations on the table's components:</u>

Cells B1/C1 represent the rated capacity of the AC for the HACS in kW$_e$ (kW electric) and it's also the HACS maximum power consumption.

Cell D2 represents the rated capacity of the HACS AC in TR.

Cells B2/C2 represent the cooling load in TR which depends on the size of the house.

Cell D1 represents the maximum power consumption of the conventional AC system in kW_e.

Cells B3/C3 represent the maximum required cooling load in kW_c (kW cooling/thermal), which corresponds to the cooling load in TR (1TR= 3.51 kW_c).

Cell D3 represents the minimum COP to calculate the maximum kW_e draw for maximum CL that occurs at 4pm.

Cells E1/F1/G1 – E3/F3/G3 represent the PV area with the units and the efficiency.

Cells H1/I1/J1 – H3/I3/J3 represent the utility (APS) charge for energy based on the ‘time advantage super peak’ time of use (TOU) plan during the different hours of the day.

Cells K1/L1 represent the evaporator’s temperatures in Celsius degrees for the TES.

Cells K2/L2 represent the minimum temperature of the TES, when it’s fully frozen (charged).

Cells K3/L3 represent the maximum temperature of the TES when it’s fully melted (discharged).

Cells M1/N1 – M4/N4 represent the cost of each major component of both systems (1st three components are for the HACS).

Cells O1/P1/Q1 represent the total amount of cooling in a 24 hours period that is required from the TES in kW_c.

Cells O2/P2/Q2/R2 represent the excess amount of cooling in kW_c that has not been used and it is desired to remain around 10% of the total required cooling, as a reliability factor (also to account for potential thermal losses).

Cells O3/P3/Q3/R3 represent the excess volume of the TES in gallons that corresponds to the amount of excess kW_c with the following conversion formula $m = Q / C_p \times \Delta T$ (= V, since 1kg / 1L of water =1) assuming the properties of water for the TES where C_p changes with the phase and slightly with the temperature (for solid 4.2 kJ/kg/K, liquid 2 kJ/kg/K), and it includes the latent heat (334 kJ/kg).

Cells O4/P4 represent the total incentive amount for the PV (utility, state and federal).

Cells S1/T1/U1 – S3/T3/U3 represent the monthly operational cost of the HACS (savings) and the regular AC system, and the difference between them (total HACS monthly savings).

Cells S4/T4/U4 represent the monthly value of the energy generated from the PV in the months when the AC is not used for cooling (November till April).

Column B: Cells B7 – B30 represent the hours of the day.

Cells C7 – C30 represent the cooling load in kW_c as obtained from Yeshpal Gupta for Phoenix in July.

Cells D7 – D30 represent the cooling load in TR as obtained from Yeshpal Gupta for Phoenix in July. (1TR= 3.51 kW_c).

Cells E7 – E30 represent the above cooling load normalized to a 4TR rated cooling load.

Cells F7 – F30 represent the normalized cooling load in kW_c units.

Cells G7 – G30 represent the power consumption of the conventional AC system to cool the house for each hour of the day (changes are based on the different hourly cooling load and COP which depends on the outside air temperature, typically, the AC power consumption is constant and the AC will cycle off and on, but instead of calculating the real number of minutes in which the AC was on, we used $W_{in,hourly} = Q_{in,hourly} / COP_{hourly}$, where $Q_{in,hourly}$ = the hourly cooling load (CL)) in energy units.

Cells H7 – H30 represent the solar irradiance on a plate with β=35° and γ=70 in $Wh/m^{2.}$

Cells I7 – I30 represent the power generated in kW_e from the solar irradiance on a PV array with the area and efficiency in cells F3 and F2 respectively.

Cells J7 – J30 represent the cooling generated in kW_c by the AC of the HACS when it's cooling the house (operating at T_{evap} = 10°C).

Cells K7 – K30 represent the gap (for negative values) and excess (for positive values) between the cooling generated by the AC of the HACS to the required cooling load for the house on an hourly basis.

Cells L7 – L30 represent the cooling stored in the TES (TS), and it is above zero only when the AC cooling output is larger than the CL. (kW_c to TES = excess kW_c / COP_{house} x COP_{TES}) calculated in energy terms rather than in minutes of each hour, similar to the explanation for Cells G7 – G30.

Cells M7 – M30 represent the volume of the TES required to store the cooling energy, similar to the explanation for Cells O3/P3/Q3/R3.

Cells N7 – N30 represent the value of the power produced by the PV that is not used by the AC and used in the house (with a cap proportional to the size of the house, where the rest of the power that house does not utilize (above the cap) is sent back to the utility grid on a lower rate).

Cells O7 – O30 represent the hourly cost of cooling for the HACS, where it's zero during peak hours (12-6pm) to avoid peak grid power, in the case the PV generates enough power to run the AC, otherwise, the AC will shut off and the house will be cooled by the TES only.

Cells P7 – P30 represent the hourly cost of cooling for the conventional AC system, according to the same TOU rates and the power in column G.

Cells Q7 – Q30 represent the cooling required from the TES and is conditional with the values in column K7-K30.

Cells R7 – R30 represent excess PV power in kW_e that is not used by the AC, and determines the values in cells N7-N30.

Cells S7 – S30 represent the amount of cooling available in the TES during each hour of the day.

Cells H4/I4 represent the cap on the excess PV power that can be used in the house before it's sent back to the grid. 100% means that up to 4.51 kW_e (= the power consumption of the conventional AC) can be used in the house, including the HACS power consumption, and the additional power is sent back to the grid at the utility "feed-in" tariff ($0.05/kWh).

The cells in the red background are the input cells and the cells in the green background are the output cells: The 2 cells on the upper left with the red background are the inputs for the PV size in m^2 and the AC size in kW_e (kW electric) and the outputs are: on the top right which is the size of the TES in green background, where the goal is to keep around 10% extra of TES as a reliability factor, and the pink cells indicate the monthly operating cost and savings of each system.

The HACS AC will not draw power from the grid during peak hours thus the AC power consumption during peak hours is dependent on the power supplied from the PV and the excess power from the PV feeds back to the house. The excess cooling energy generated by the AC during off-peak hours is stored in the TES, but at a different (smaller) amount since the AC will be operating on a lower COP when the refrigerant is flowing through the TES' evaporator. $kW_c \text{ to } TES = (AC_{cool} – CL) / COP_{house} \times COP_{TES}$ (See similar explanation for cells L7 – L30 above)

The following chart (figure 3.3.2) shows the kW_e hourly distribution of the PV output, AC input, PV feed-in to the house and the cooling load (CL) in kW_c converted to kW_e (by dividing the required CL by the COP of the AC, kW_c / COP = kW_e, which is also the power consumption of the conventional AC).

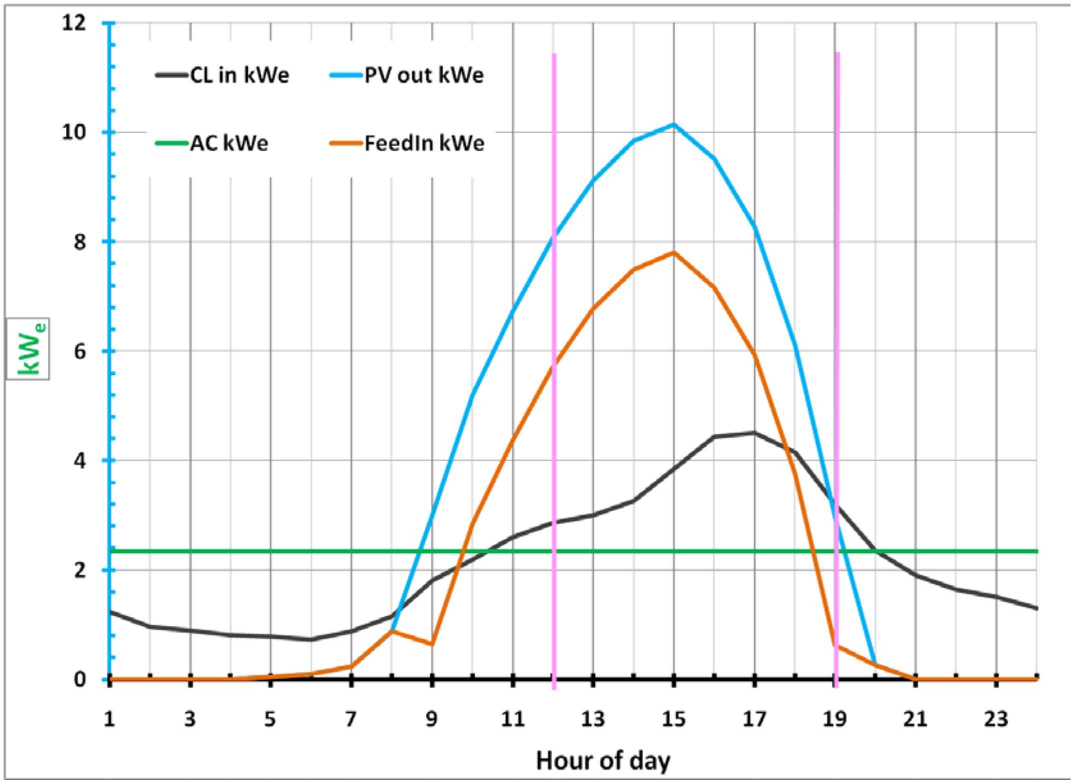


Figure 3.3.2: The Hourly Variation of the kW_e of the HACS.

In the above chart, the “FeedIn kWe” (orange color) is the total excess power produced by the PV (after the deduction of the AC consumption) in kWe, but not all of it is used by the house! Part of it is sent back to the utility grid (depends on the Cap) on a different (lower) rate than the hourly TOU plan rate (at which it is used in the house), thus the monthly savings (cells S1/T1/U1) are not “linear” to the represented kWe

FeedIn in the above chart. The pink vertical lines represent the start (at 12:00pm) and the end (at 7:00pm) of the peak hours, respectively.

The following chart shows in thermal units (kW_c) the CL, the AC cooling output, the cooling required from the TES (TS2Cool: the part of the CL that the AC is not covering) and the cooling stored (not cumulative) each hour in the TES (kW_c to TS).

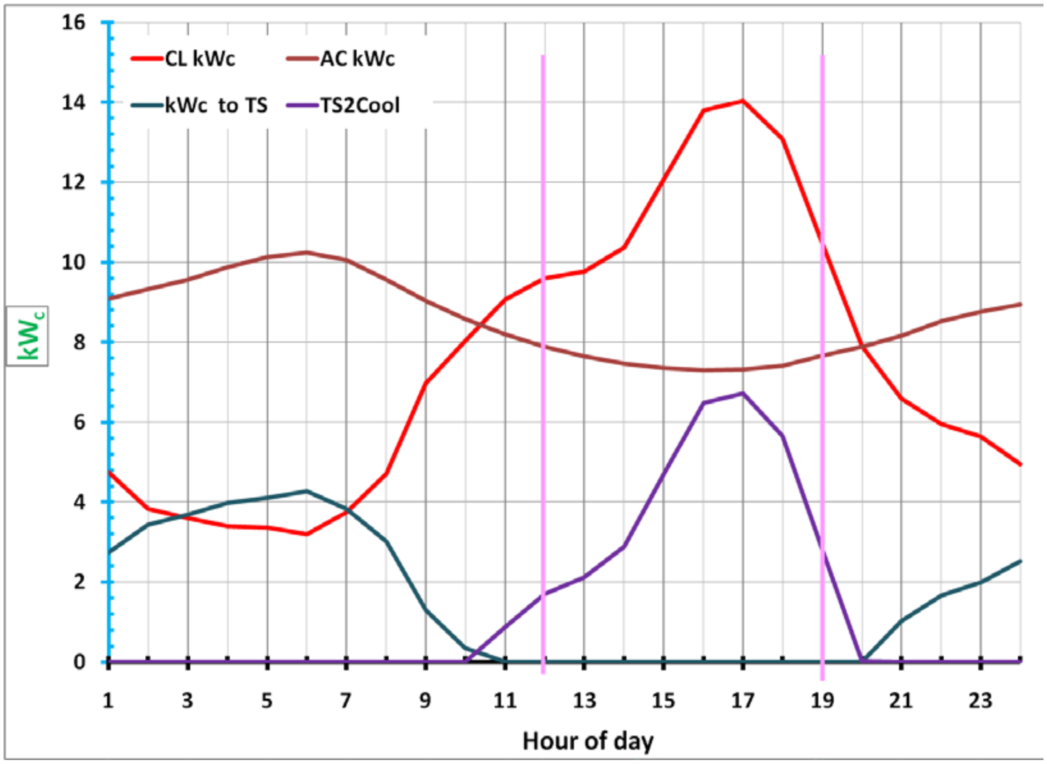


Figure 3.3.3: The Hourly Variation of the kW_c of the HACS.

Note in the above chart that the TES (TS) is either charging or discharging, but not both at the same time (when the aqua color curve (kWc to TS) is positive (mostly during off-peak hours), the purple color curve (TS to Cool) is zero, and vice versa), and the reason for that is when the house needs cooling during off peak hours, it’s always more efficient (higher COP) to supply that cooling from the AC directly (recall that the AC cools either the house or the TES, but not both together).

In the following chart (figure 3.3.4) there are 2 vertical axes, one axis on the left for the kW_e and another axis on the right for the kW_c, and it's a combination of the above two graphs, and shows the mode of the HACS at each hour of the day for all the major components together.

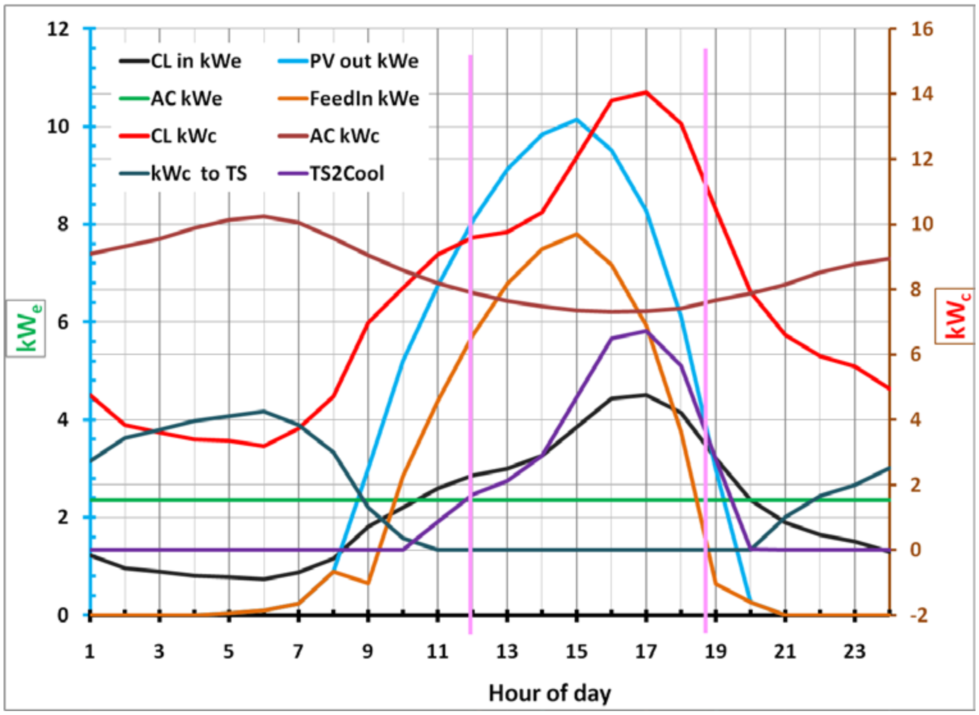


Figure 3.3.4: The Hourly Variation of the kWe and the kWc of the HACS.

The optimum system's configuration (size) of the HACS will be determined based on the economic parameters that will be shown in the next chapter.

The next chart (figure 3.3.5) shows a configuration where the HACS has no PV, but TES only for storage, Where a 877.5 Liters TES with a max 3.75 kW_e (3.32 TR) AC are able to cool a house that is normally cooled by a 4 TR (4.51 max kW_e), where the entire peak cooling load is supplied by the TES (since the AC is off to avoid peak grid power).

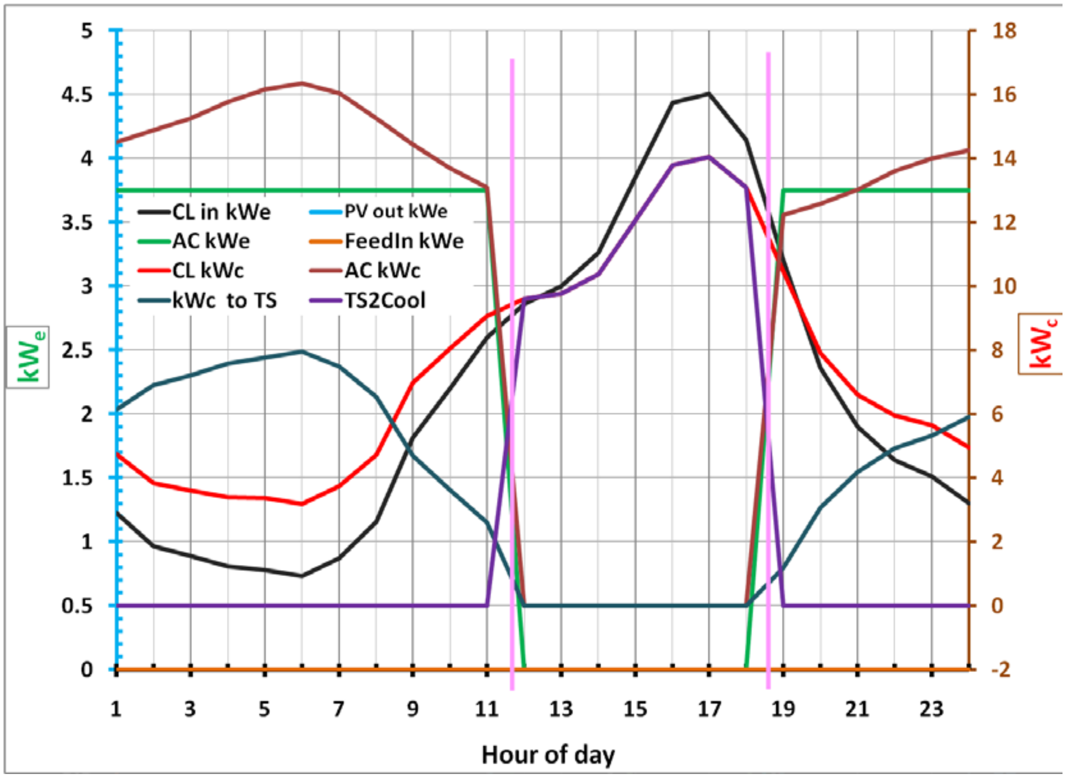


Figure 3.3.5: The Hourly Variation of the kW_e and the kW_c of the HACS without PV

The configuration where the HACS has no TES, but enough PV to supply power for the AC during peak hours and peak CL will require the same size AC of a regular AC system (4TR), but the AC will not be 100% utilized since it will cycle off and on during off-peak hours.

An important observation from the “no PV” case is that the size of the TES is directly dependent on the CL and the size of the AC only, but not on the size of the PV, whereas the size of the PV and the AC must match the CL. Therefore, the TES and the PV are relative to the size of the AC which is determined the by the CL (depends on the size of the house) but are not directly related to each other. In other words, increasing the size (area) of the house will increase the maximum cooling load during peak hours and that will require two things: increasing the size of the AC (in kW_e or TR) and increasing the size of the TES (it can be simplified as, in thermal / cooling units (kW_c or TR): AC + TES = CL). But the size of the PV is still independent and is determined by the cap and economic calculations only (as long as it has enough area to supply enough power to run the AC during peak hours).

CHAPTER 4

ECONOMIC ANALYSIS

4.1 Comparison Parameters

To evaluate the economic profitability (effectiveness) of the HACS, we will calculate the Net Present Value (NPV) of the system in a few variations and see how the NPV changes along the years, and this function (NPV) will also show us the best configuration (size) of PV.

The NPV is calculated according to the following formula:

$$NPV_n = -CC + (tot\ ann) \times [(1-(1+i)^{-n}) / i] \quad ; \qquad n \geq 0\ ,\ i \geq 0 \qquad (4.1.1)$$

where *n* indicates the number of years, CC the Capital Cost, i the interest rate (APR%) and ‘tot ann’ the total annual operational cost of the system including annual maintenance cost (A. MC) and is equivalent (the ‘tot ann’) to PV (Present Value) of cash flows.

The NPV is calculated in a few different methods where the **first** (tot ann1) one includes the cost of heating in the winter (the cost of cooling is included in all methods), the **second** (tot ann2) method is without the cost of heating in the winter, and this method is used since some of the houses use a furnace (natural gas) to heat the house in the winter rather than using the AC, the **third** (tot ann3) where the annual operating cost is taken as the total savings of the HACS (the difference between the operational cost of the regular AC system and the savings (cost) of the HACS). For example, if the operating cost of the regular AC system in July is $400 and the operating cost (savings) of the HACS is -$300 ($300 savings due to the payback from the PV) then the total operating cost (savings) is $400 – (-$300) = $700. This method was used because a typical house would have an AC system (Conventional or HACS) anyways, since it’s a necessity in this type of weather (and it is equivalent for the option of retrofitting or replacing an existing regular AC with a HACS). The **fourth** (tot ann4) method is the same as the third just without the cost of heating in the winter. In the following tables we see the details of each method and a comparison of the profitability of the system in each of the four methods with the regular AC system. A Simple Payback (SPB) according to the four methods above is also shown.

The total annual (tot ann) includes 100% of the system’s cooling cost for July for the CL from Yeshpal, and for heating, 100% for January for the heating load from Yeshpal as well, and for the rest of the months as shown in the following table 4.1.1 (Percentage estimates suggested by Dr. Steven Trimble).

Month	Cooling Load	Heating Load
1	0%	100%
2	0%	90%
3	0%	70%
4	65%	0%
5	85%	0%
6	95%	0%
7	100%	0%
8	95%	0%
9	85%	0%
10	65%	0%
11	0%	70%
12	0%	90%

Table 4.1.1: Cooling and Heating Loads Percentages

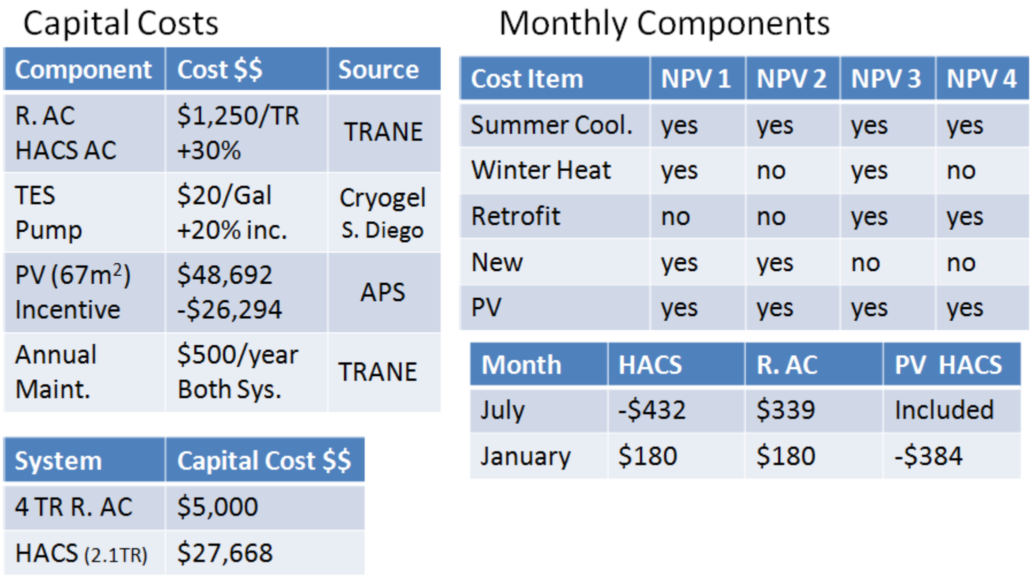
The “FeedIn” cap represents the amount of solar power generation that can be used in the house during peak hours including the power consumption of the AC. The cap represents the percentage above the regular AC consumption of the PV power before it’s sent back to the grid on a lower rate than the TOU plan rate.

4.2 Profitability of the System

The total annual (tot ann) represents the cost of energy used for cooling and heating (when used), annual maintenance cost as positive outflow and the excess energy produced by the PV during the summer and the winter as inflow (negative). Therefore, the total annual is usually negative since the HACS pays back more than it consumes. Thus, there is a payback period.

<u>The NPV components:</u>

CC (Capital Cost) includes the initial cost of the AC ($1,250 / TR), for the AC of the HACS (H. AC) we added 30% extra in initial cost to account for the additional evaporator for the TES and other piping work and controls. TES ($20 / gallon including 20% extra for service equipment such as pumps, pipes and liquids) and PV (after incentive (utility, state and federal) based on APS calculator).



Capital Costs

Component	Cost $$	Source
R. AC HACS AC	$1,250/TR +30%	TRANE
TES Pump	$20/Gal +20% inc.	Cryogel S. Diego
PV (67m^2) Incentive	$48,692 -$26,294	APS
Annual Maint.	$500/year Both Sys.	TRANE

System	Capital Cost $$
4 TR R. AC	$5,000
HACS (2.1TR)	$27,668

Monthly Components

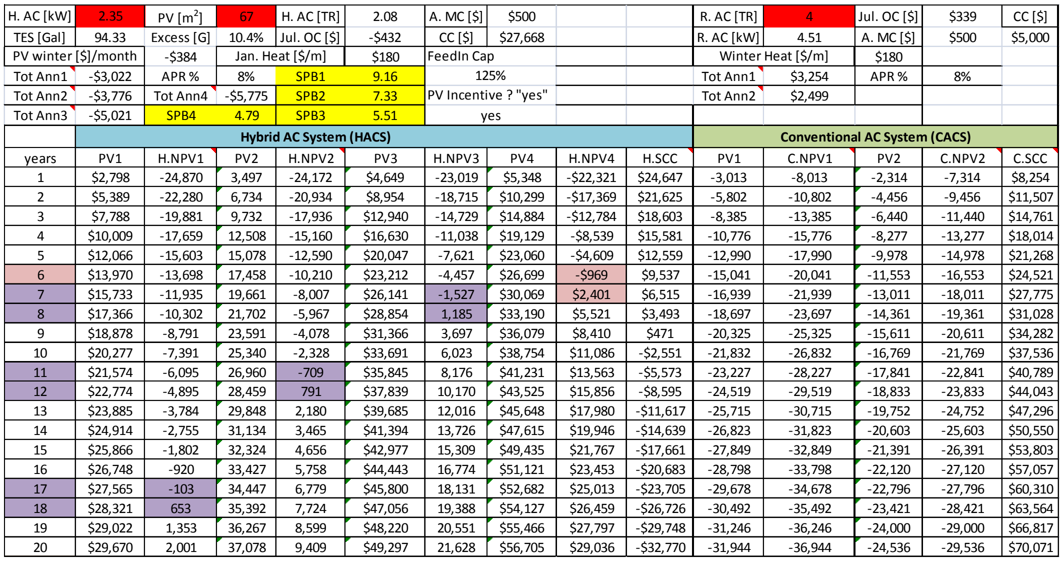
Cost Item	NPV 1	NPV 2	NPV 3	NPV 4
Summer Cool.	yes	yes	yes	yes
Winter Heat	yes	no	yes	no
Retrofit	no	no	yes	yes
New	yes	yes	no	no
PV	yes	yes	yes	yes

Month	HACS	R. AC	PV HACS
July	-$432	$339	Included
January	$180	$180	-$384

Table 4.2.1: Capital Cost and Monthly Operational Costs Summary

The following table (4.2.2) shows the HACS’ and the regular / conventional AC systems’ (CACS) cost where A. MC is the Annual Maintenance Cost. We assume that the most reasonable cap is 125% (1.25 x 4.51 = 5.64 kW_e can be used in the house including the HACS AC power consumption which is 2.35 kW_e), as stated before the cap is relative to the conventional (regular) AC (C. AC or R. AC) system maximum power consumption (4TR cooling load requires 4.51 kW_e at 3.11 COP). This cap refers to power that can be used in the house for additional appliances such as refrigerators, freezers, TV and more.

For the 125% cap we get that 67m^2 (after inputting several values for PV area) of PV area gives the best system’s configuration (highest NPV values). H stands for HACS and C for Conventional. H. NPV1 represents the HACS NPV based on the first method.



H. AC [kW]	2.35	PV [m^2]	67	H. AC [TR]	2.08	A. MC [$]	$500			R. AC [TR]	4	Jul. OC [$]	$339	CC [$]
TES [Gal]	94.33	Excess [G]	10.4%	Jul. OC [$]	-$432	CC [$]	$27,668			R. AC [kW]	4.51	A. MC [$]	$500	$5,000
PV winter [$]/month		-$384	Jan. Heat [$/m]		$180	FeedIn Cap				Winter Heat [$/m]		$180		
Tot Ann1	-$3,022	APR %	8%	SPB1	9.16	125%				Tot Ann1	$3,254	APR %	8%	
Tot Ann2	-$3,776	Tot Ann4	-$5,775	SPB2	7.33	PV Incentive ? "yes"				Tot Ann2	$2,499			
Tot Ann3	-$5,021	SPB4	4.79	SPB3	5.51	yes								
	Hybrid AC System (HACS)									Conventional AC System (CACS)				
years	PV1	H.NPV1	PV2	H.NPV2	PV3	H.NPV3	PV4	H.NPV4	H.SCC	PV1	C.NPV1	PV2	C.NPV2	C.SCC
1	$2,798	-24,870	3,497	-24,172	$4,649	-23,019	$5,348	-$22,321	$24,647	-3,013	-8,013	-2,314	-7,314	$8,254
2	$5,389	-22,280	6,734	-20,934	$8,954	-18,715	$10,299	-$17,369	$21,625	-5,802	-10,802	-4,456	-9,456	$11,507
3	$7,788	-19,881	9,732	-17,936	$12,940	-14,729	$14,884	-$12,784	$18,603	-8,385	-13,385	-6,440	-11,440	$14,761
4	$10,009	-17,659	12,508	-15,160	$16,630	-11,038	$19,129	-$8,539	$15,581	-10,776	-15,776	-8,277	-13,277	$18,014
5	$12,066	-15,603	15,078	-12,590	$20,047	-7,621	$23,060	-$4,609	$12,559	-12,990	-17,990	-9,978	-14,978	$21,268
6	$13,970	-13,698	17,458	-10,210	$23,212	-4,457	$26,699	-$969	$9,537	-15,041	-20,041	-11,553	-16,553	$24,521
7	$15,733	-11,935	19,661	-8,007	$26,141	-1,527	$30,069	$2,401	$6,515	-16,939	-21,939	-13,011	-18,011	$27,775
8	$17,366	-10,302	21,702	-5,967	$28,854	1,185	$33,190	$5,521	$3,493	-18,697	-23,697	-14,361	-19,361	$31,028
9	$18,878	-8,791	23,591	-4,078	$31,366	3,697	$36,079	$8,410	$471	-20,325	-25,325	-15,611	-20,611	$34,282
10	$20,277	-7,391	25,340	-2,328	$33,691	6,023	$38,754	$11,086	-$2,551	-21,832	-26,832	-16,769	-21,769	$37,536
11	$21,574	-6,095	26,960	-709	$35,845	8,176	$41,231	$13,563	-$5,573	-23,227	-28,227	-17,841	-22,841	$40,789
12	$22,774	-4,895	28,459	791	$37,839	10,170	$43,525	$15,856	-$8,595	-24,519	-29,519	-18,833	-23,833	$44,043
13	$23,885	-3,784	29,848	2,180	$39,685	12,016	$45,648	$17,980	-$11,617	-25,715	-30,715	-19,752	-24,752	$47,296
14	$24,914	-2,755	31,134	3,465	$41,394	13,726	$47,615	$19,946	-$14,639	-26,823	-31,823	-20,603	-25,603	$50,550
15	$25,866	-1,802	32,324	4,656	$42,977	15,309	$49,435	$21,767	-$17,661	-27,849	-32,849	-21,391	-26,391	$53,803
16	$26,748	-920	33,427	5,758	$44,443	16,774	$51,121	$23,453	-$20,683	-28,798	-33,798	-22,120	-27,120	$57,057
17	$27,565	-103	34,447	6,779	$45,800	18,131	$52,682	$25,013	-$23,705	-29,678	-34,678	-22,796	-27,796	$60,310
18	$28,321	653	35,392	7,724	$47,056	19,388	$54,127	$26,459	-$26,726	-30,492	-35,492	-23,421	-28,421	$63,564
19	$29,022	1,353	36,267	8,599	$48,220	20,551	$55,466	$27,797	-$29,748	-31,246	-36,246	-24,000	-29,000	$66,817
20	$29,670	2,001	37,078	9,409	$49,297	21,628	$56,705	$29,036	-$32,770	-31,944	-36,944	-24,536	-29,536	$70,071

Table 4.2.2: Optimum HACS and CACS NPV and Simple Cost of Cooling

The following figure 4.2.1 illustrates the cost results and shows the payback time for the HACS and the cost savings when compared to the conventional AC system for the best configuration in the above chart. It also shows the H. SCC (HACS Simple Cooling Cost) and C. SCC (Conventional (AC) Simple Cooling Cost) which is identical to the case of the first method (Tot Ann1 and NPV1) when there is no interest (0% APR).

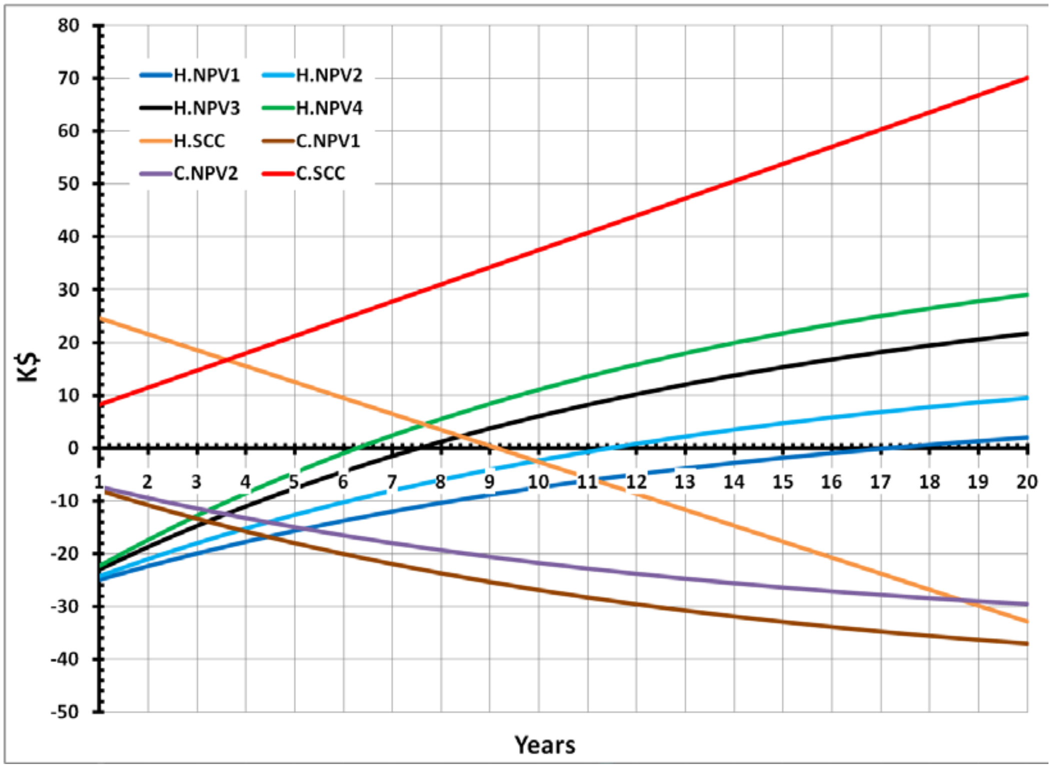


Figure 4.2.1: HACS and CACS NPV and Simple Cost of Cooling

In the following chart, we investigated the case where the cap is only 100% and we see that the payback period occurs at a longer time than 125% cap as expected, since we are feeding back to the grid more of the PV power at a lower rate (at 125% cap). We also see that the SPB (Simple Pay Back) based on the four methods (tot ann) and the SCC

(Simple Cooling Cost) which is equivalent to NPV with 0% interest (APR%).

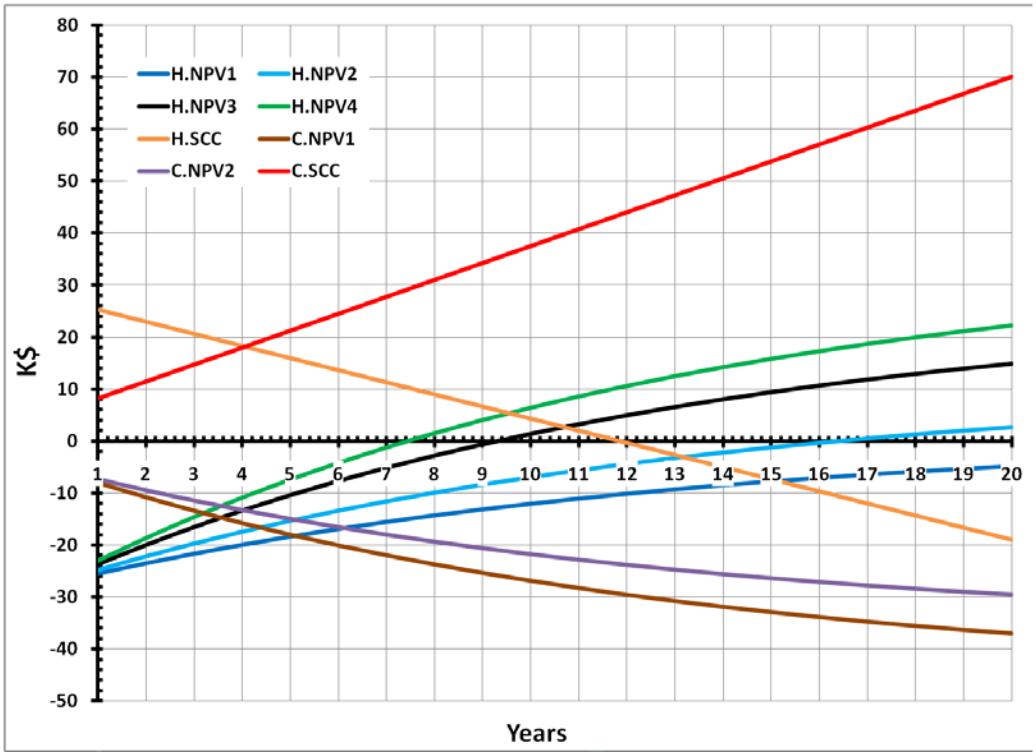


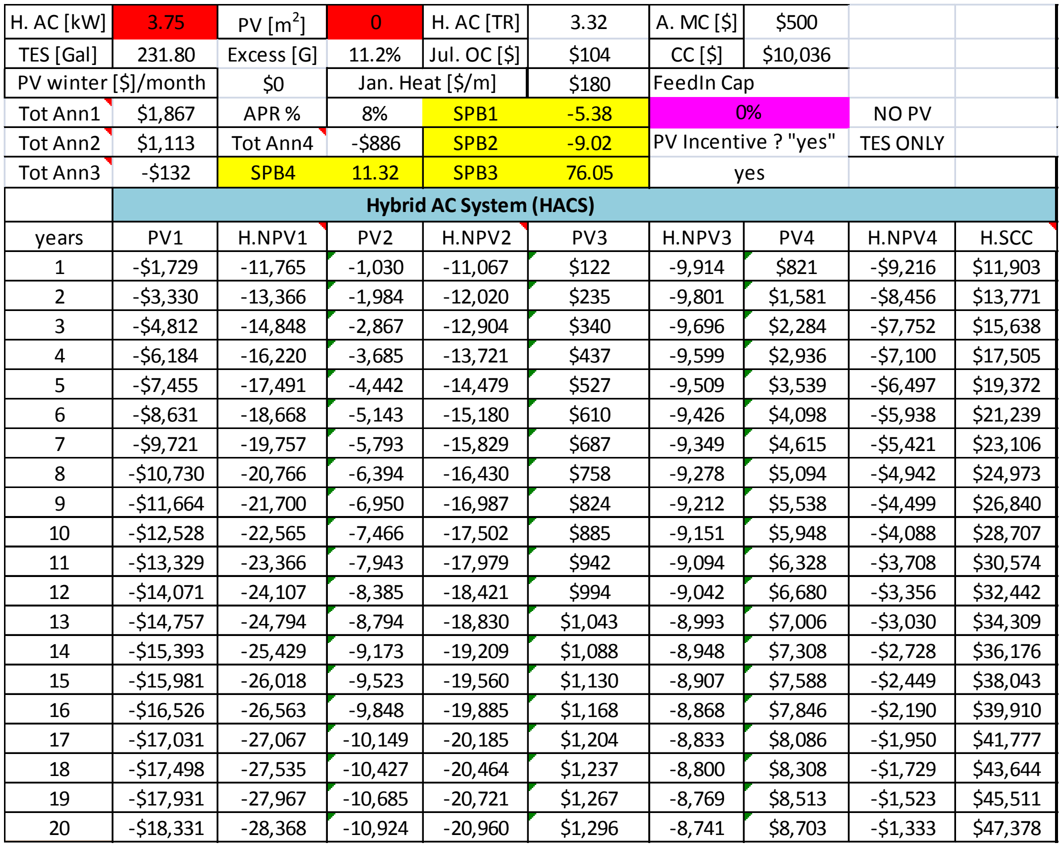
Figure 4.2.2: HACS NPV and Simple Cost of Cooling at 100% Cap

In the following chart (table 4.2.3) we see the extreme case of 150% cap where it gives the shortest payback periods (highest NPV rates).

H. AC [kW]	2.35	PV [m^2]	67	H. AC [TR]	2.08	A. MC [$]	$500		
TES [Gal]	94.33	Excess [G]	10.4%	Jul. OC [$]	-$484	CC [$]	$27,668		
PV winter [$]/month		-$432	Jan. Heat [$/m]		$180	FeedIn Cap			
Tot Ann1	-$3,543	APR %	8%	SPB1	7.81	150%			
Tot Ann2	-$4,298	Tot Ann4	-$6,297	SPB2	6.44	PV Incentive ? "yes"			
Tot Ann3	-$5,542	SPB4	4.39	SPB3	4.99	yes			
	Hybrid AC System (HACS)								
years	PV1	H.NPV1	PV2	H.NPV2	PV3	H.NPV3	PV4	H.NPV4	H.SCC
1	$3,281	-24,388	3,980	-23,689	$5,132	-22,537	$5,831	-$21,838	$24,125
2	$6,319	-21,350	7,664	-20,004	$9,884	-17,785	$11,229	-$16,439	$20,582
3	$9,132	-18,537	11,076	-16,592	$14,283	-13,385	$16,228	-$11,441	$17,038
4	$11,736	-15,932	14,235	-13,433	$18,357	-9,311	$20,856	-$6,812	$13,495
5	$14,148	-13,521	17,160	-10,508	$22,129	-5,539	$25,142	-$2,527	$9,951
6	$16,381	-11,288	19,869	-7,800	$25,622	-2,046	$29,110	$1,442	$6,408
7	$18,448	-9,220	22,376	-5,292	$28,856	1,188	$32,784	$5,116	$2,865
8	$20,363	-7,306	24,698	-2,970	$31,851	4,182	$36,186	$8,518	-$679
9	$22,135	-5,533	26,849	-820	$34,623	6,955	$39,336	$11,668	-$4,222
10	$23,777	-3,892	28,839	1,171	$37,190	9,522	$42,253	$14,585	-$7,766
11	$25,296	-2,372	30,683	3,014	$39,568	11,899	$44,954	$17,285	-$11,309
12	$26,703	-965	32,389	4,721	$41,769	14,100	$47,454	$19,786	-$14,852
13	$28,006	338	33,970	6,301	$43,806	16,138	$49,770	$22,101	-$18,396
14	$29,213	1,544	35,433	7,764	$45,693	18,025	$51,914	$24,245	-$21,939
15	$30,330	2,661	36,788	9,119	$47,441	19,772	$53,899	$26,230	-$25,483
16	$31,364	3,696	38,042	10,374	$49,058	21,390	$55,737	$28,068	-$29,026
17	$32,322	4,653	39,204	11,535	$50,556	22,888	$57,439	$29,770	-$32,570
18	$33,208	5,540	40,279	12,611	$51,943	24,275	$59,014	$31,346	-$36,113
19	$34,030	6,361	41,275	13,607	$53,228	25,559	$60,474	$32,805	-$39,656
20	$34,790	7,121	42,197	14,529	$54,417	26,748	$61,825	$34,156	-$43,200

Table 4.2.3: HACS NPV and Simple Cost of Cooling at 150% Cap

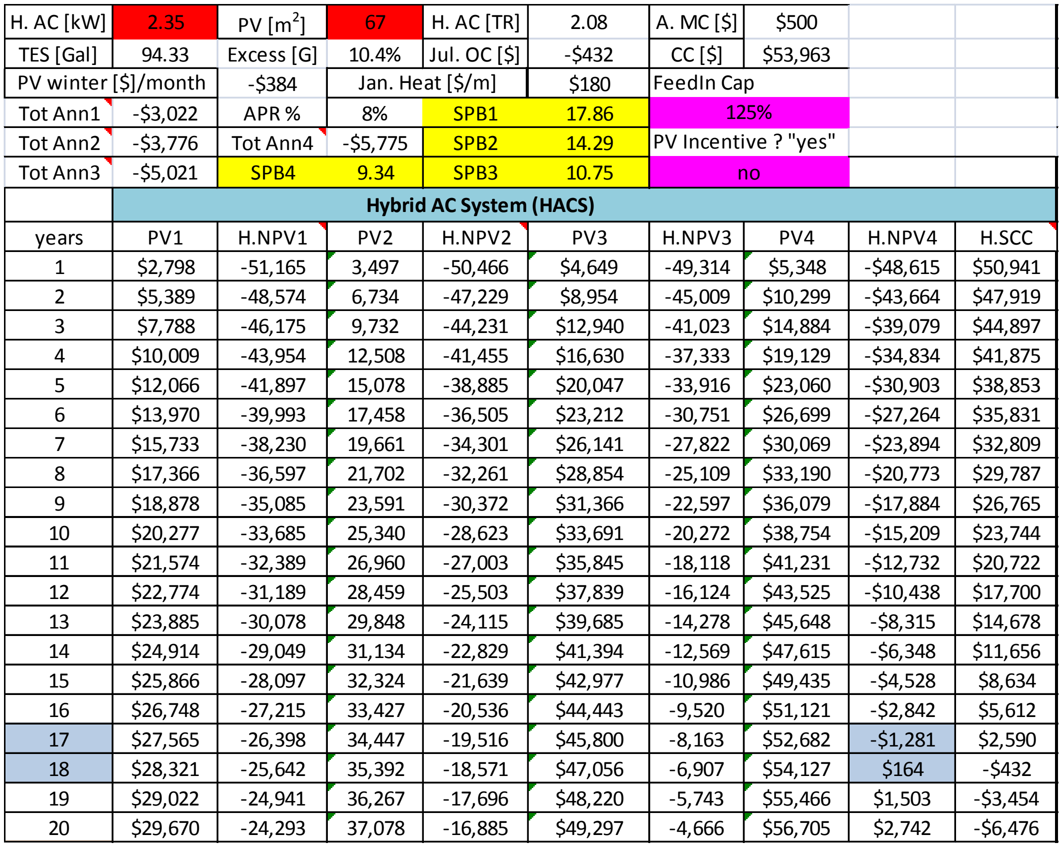
In the next chart, we explore the case where the system has no PV (with a larger TES and AC). Since the system has no PV, there is no payback period for the first two methods (H.NPV1 and H.NPV2, with and without winter heat), but for the third and the fourth method (H.NPV3 and H.NPV4 with the total annual saved between the HACS and the regular AC system) we still get a payback period, however it’s beyond 20 years. Note that this case requires a much larger TES (231.8 Gal) and a larger AC size (3.75 kWe) which increases the HACS Capital Cost (CC) to more than $10K, but still much lower than the CC of a HACS with PV.



H. AC [kW]	3.75	PV [m^2]	0	H. AC [TR]	3.32	A. MC [$]	$500		
TES [Gal]	231.80	Excess [G]	11.2%	Jul. OC [$]	$104	CC [$]	$10,036		
PV winter [$]/month		$0	Jan. Heat [$/m]		$180	FeedIn Cap			
Tot Ann1	$1,867	APR %	8%	SPB1	-5.38	0%		NO PV	
Tot Ann2	$1,113	Tot Ann4	-$886	SPB2	-9.02	PV Incentive ? "yes"		TES ONLY	
Tot Ann3	-$132	SPB4	11.32	SPB3	76.05	yes			
	Hybrid AC System (HACS)								
years	PV1	H.NPV1	PV2	H.NPV2	PV3	H.NPV3	PV4	H.NPV4	H.SCC
1	-$1,729	-11,765	-1,030	-11,067	$122	-9,914	$821	-$9,216	$11,903
2	-$3,330	-13,366	-1,984	-12,020	$235	-9,801	$1,581	-$8,456	$13,771
3	-$4,812	-14,848	-2,867	-12,904	$340	-9,696	$2,284	-$7,752	$15,638
4	-$6,184	-16,220	-3,685	-13,721	$437	-9,599	$2,936	-$7,100	$17,505
5	-$7,455	-17,491	-4,442	-14,479	$527	-9,509	$3,539	-$6,497	$19,372
6	-$8,631	-18,668	-5,143	-15,180	$610	-9,426	$4,098	-$5,938	$21,239
7	-$9,721	-19,757	-5,793	-15,829	$687	-9,349	$4,615	-$5,421	$23,106
8	-$10,730	-20,766	-6,394	-16,430	$758	-9,278	$5,094	-$4,942	$24,973
9	-$11,664	-21,700	-6,950	-16,987	$824	-9,212	$5,538	-$4,499	$26,840
10	-$12,528	-22,565	-7,466	-17,502	$885	-9,151	$5,948	-$4,088	$28,707
11	-$13,329	-23,366	-7,943	-17,979	$942	-9,094	$6,328	-$3,708	$30,574
12	-$14,071	-24,107	-8,385	-18,421	$994	-9,042	$6,680	-$3,356	$32,442
13	-$14,757	-24,794	-8,794	-18,830	$1,043	-8,993	$7,006	-$3,030	$34,309
14	-$15,393	-25,429	-9,173	-19,209	$1,088	-8,948	$7,308	-$2,728	$36,176
15	-$15,981	-26,018	-9,523	-19,560	$1,130	-8,907	$7,588	-$2,449	$38,043
16	-$16,526	-26,563	-9,848	-19,885	$1,168	-8,868	$7,846	-$2,190	$39,910
17	-$17,031	-27,067	-10,149	-20,185	$1,204	-8,833	$8,086	-$1,950	$41,777
18	-$17,498	-27,535	-10,427	-20,464	$1,237	-8,800	$8,308	-$1,729	$43,644
19	-$17,931	-27,967	-10,685	-20,721	$1,267	-8,769	$8,513	-$1,523	$45,511
20	-$18,331	-28,368	-10,924	-20,960	$1,296	-8,741	$8,703	-$1,333	$47,378

Table 4.2.4: HACS NPV and Simple Cost of Cooling for no PV

In the last case, we explored a scenario where the HACS has no incentive for the PV. Which increases the CC dramatically, however we still get payback period in less than 20 years only for the fourth method (H.NPV4).



H. AC [kW]	2.35	PV [m^2]	67	H. AC [TR]	2.08	A. MC [$]	$500		
TES [Gal]	94.33	Excess [G]	10.4%	Jul. OC [$]	-$432	CC [$]	$53,963		
PV winter [$]/month		-$384	Jan. Heat [$/m]		$180	FeedIn Cap			
Tot Ann1	-$3,022	APR %	8%	SPB1	17.86	125%			
Tot Ann2	-$3,776	Tot Ann4	-$5,775	SPB2	14.29	PV Incentive ? "yes"			
Tot Ann3	-$5,021	SPB4	9.34	SPB3	10.75	no			
	Hybrid AC System (HACS)								
years	PV1	H.NPV1	PV2	H.NPV2	PV3	H.NPV3	PV4	H.NPV4	H.SCC
1	$2,798	-51,165	3,497	-50,466	$4,649	-49,314	$5,348	-$48,615	$50,941
2	$5,389	-48,574	6,734	-47,229	$8,954	-45,009	$10,299	-$43,664	$47,919
3	$7,788	-46,175	9,732	-44,231	$12,940	-41,023	$14,884	-$39,079	$44,897
4	$10,009	-43,954	12,508	-41,455	$16,630	-37,333	$19,129	-$34,834	$41,875
5	$12,066	-41,897	15,078	-38,885	$20,047	-33,916	$23,060	-$30,903	$38,853
6	$13,970	-39,993	17,458	-36,505	$23,212	-30,751	$26,699	-$27,264	$35,831
7	$15,733	-38,230	19,661	-34,301	$26,141	-27,822	$30,069	-$23,894	$32,809
8	$17,366	-36,597	21,702	-32,261	$28,854	-25,109	$33,190	-$20,773	$29,787
9	$18,878	-35,085	23,591	-30,372	$31,366	-22,597	$36,079	-$17,884	$26,765
10	$20,277	-33,685	25,340	-28,623	$33,691	-20,272	$38,754	-$15,209	$23,744
11	$21,574	-32,389	26,960	-27,003	$35,845	-18,118	$41,231	-$12,732	$20,722
12	$22,774	-31,189	28,459	-25,503	$37,839	-16,124	$43,525	-$10,438	$17,700
13	$23,885	-30,078	29,848	-24,115	$39,685	-14,278	$45,648	-$8,315	$14,678
14	$24,914	-29,049	31,134	-22,829	$41,394	-12,569	$47,615	-$6,348	$11,656
15	$25,866	-28,097	32,324	-21,639	$42,977	-10,986	$49,435	-$4,528	$8,634
16	$26,748	-27,215	33,427	-20,536	$44,443	-9,520	$51,121	-$2,842	$5,612
17	$27,565	-26,398	34,447	-19,516	$45,800	-8,163	$52,682	-$1,281	$2,590
18	$28,321	-25,642	35,392	-18,571	$47,056	-6,907	$54,127	$164	-$432
19	$29,022	-24,941	36,267	-17,696	$48,220	-5,743	$55,466	$1,503	-$3,454
20	$29,670	-24,293	37,078	-16,885	$49,297	-4,666	$56,705	$2,742	-$6,476

Table 4.2.5: HACS NPV and Simple Cost of Cooling with no PV Incentive.

CHAPTER 5

RESULTS, CONCLUSIONS AND FUTURE WORK

5.1 Results

The HACS shortest payback period is about 5.8 years (Table 4.2.3) based on the 4th method (Savings with no winter heat) with 150% FeedIn cap which is the best extreme case, where by that time the highest NPV of the CACS is about -$17.5K (C.NPV2). In other words, by that time (5.8 years) the HCAS would have paid back its CC (~ $28K) where the CACS' total cost by then is ~%17.5K, thus the HCAS would have saved the owner ~$45.5K (28+17.5) in less than 6 years at 8% APR.

However, this result will change when using a less aggressive TOU, and will also change with the increase of energy rates from the utility ($/kWh).

5.2 Conclusions and HACS Advantages

- The HACS proves to be a very competitive AC system and once the major calculation are validated with the actual system that is being built on the roof of building ECF at ASU in Tempe, AZ, the HACS will have a potential of becoming a remarkable marketable breakthrough in the HVAC field and refrigeration industry.
- Note that the relatively large payback from the PV is due to the fact that some of the excess PV power (based on the CAP) is used in the house, instead of buying that energy from the utility at peak rates,

which makes a big difference than the case where all that power is fed back to the grid on the lower rate (since the HACS AC is operating directly from the PV power before it goes back to the grid).

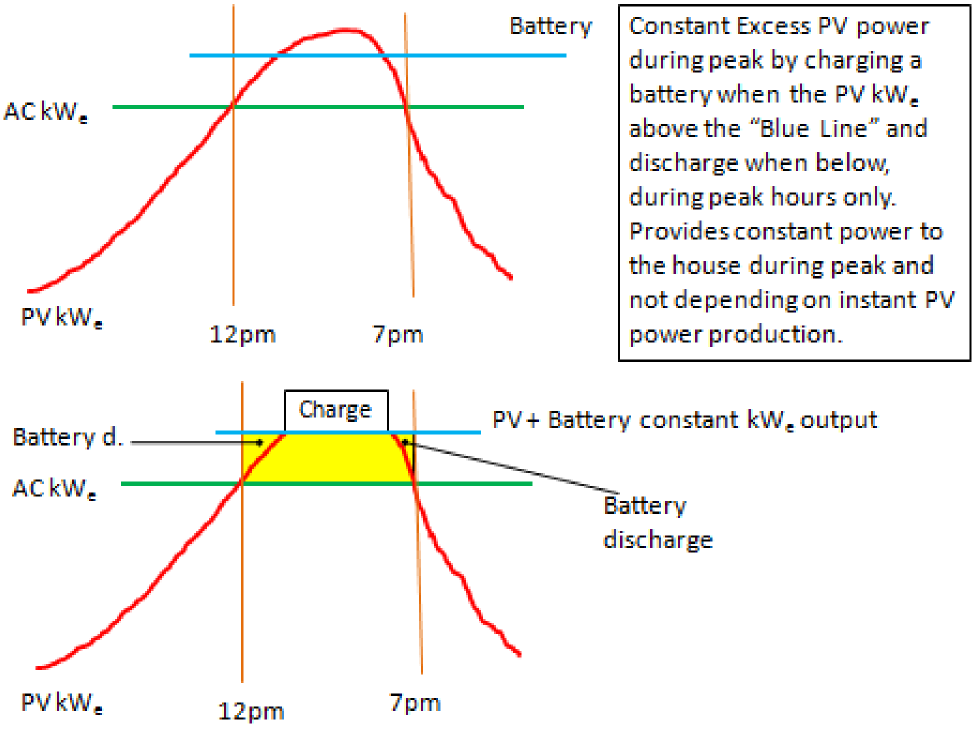
- With the advancement of the thin films industry and PV technology, it is expected that the PV cost will decrease with time, which will decrease the CC of the HACS dramatically (since most of the CC of the HACS is due to the high cost of the PV, even after the incentive) which will result on even lower pay back of the HACS and better NPV.
- In addition to the savings in money, the HACS eliminates the carbon emissions caused by operating peak (Brayton) power cycles (at the utility) during peak hours, which normally emit larger amounts of carbon than operating on base loads during off-peak hours of the power stations, since most of the peak load is generated by gas turbine cycles that are less efficient.
- Reducing or eliminating the peak power demand caused by air conditioning for the residential sector will reduce transmission losses from the utility to the end user / house. These losses are highest during super peak hours (3-5pm) when the outside air temperatures are high and the power draw (current [Amps]) in the transmission lines are also high and maximize the resistive losses that are relative to the temperature and the current in the wires (7%-12% losses, source: Rick - APS guest speaker at ASU ASME lecture).

- The HACS could be more beneficial (economically profitable / effective) in other hot climates where the temperatures are still hot during the day but cool down significantly at night time (like in Temecula, CA) where the AC night time COP could be double than the day time COP.
- The HACS could be significantly more cost effective when used in commercial, office and industrial buildings where these buildings usually are not occupied during night time. During low occupancy times, more cooling energy can be stored from a smaller AC in a larger TES (due to a smaller cooling load assuming no or less internal heat gains from appliances, and higher internal temperature (above the human comfort zone) set by the controller since people / employees are not present).
- Having an AC system that runs continuously (without cycling off and on) will increase the efficiency and the life time of the system, by reducing mechanical wear (bearings of the compressor and the wiring coil / winding of the motor assembly (stator/rotor)) and other structural fatigues, caused by thermal expansion and shrinkage due to continuous temperature changes / fluctuations that are caused by cycling off and on for such a system.
- Due to the high latent (334 kJ/kg) and specific (4.2 kJ/kg/K for liquid and 2 kJ/kg/K for solid)) heat of the TES (water), a small (232 Gal or 0.877 m^3) size of TES for 13°C temperature difference is enough to

store 93 kW_c (26.5 TR), which is a relatively high energy density storage medium (~ 8.75 Gal / TR or 9 L / kW_c), a 232 gallons TES can store enough cooling for a no-PV HACS for a 1,600 ft^2 house in Phoenix, AZ.

5.3 Future Work

- The hourly distribution does not capture changes in between the hours thus it is recommended to perform the analysis on a higher frequency / resolution of time change (minutes vs. hours). However, the estimated increase in accuracy is not more than 10% and it mostly occurs when the rate plan peak and off-peak times start and end.
- Exploring other means of TES for storing heat during the winter will increase the efficiency of the HACS and decrease the payback period.
- Utilizing the heat from the AC during the winter when it's not heating the house to heat the hot water tank and the hot tub/swimming pools will also help in making the system more efficient and save energy.
- Adding a solar thermal collector to harness heat during the sunny days in the winter to heat the evaporator will also increase the overall efficiency and could also increase the economic effectiveness of the system.
- In the following figure we see another approach that can make the HACS even more efficient by using an electrical battery as described below



Constant Excess PV power during peak by charging a battery when the PV kW$_e$ above the “Blue Line” and discharge when below, during peak hours only. Provides constant power to the house during peak and not depending on instant PV power production.

Figure 5.3.1: The Battery Advantage

REFERENCES

[1] Thermodynamics**:** an engineering approach, Yunus A. Çengel, Michael A. Boles, McGraw-Hill Higher Education, 2006

[2] National Solar Radiation Data Base (NSRDB)
http://rredc.nrel.gov/solar/old_data/nsrdb/

[3] Solar Engineering of Thermal Processes, by John A. Duffie, William A. Beckman, 2006

[4] Application of indirect evaporative cooling to variable domestic cooling load, Energy Conversion & Management 41 (2000) 1931±1951,
www.elsevier.com/locate/enconman

[5] Time advantage super peak TOU plan from APS
http://www.aps.com/main/services/residential/rates/rates_29.html#ta7
And: www.aps.com/_files/rates/et-sp.pdf

[6] National Climatic Data Center (NCDC), National Oceanic and Atmospheric Administration (NOAA).
www.ncdc.noaa.gov

[7] U.S. Energy Information Administration (EIA)
www.**eia**.gov
http://www.eia.gov/consumption/residential/reports/air_conditioning09.cfm

[8] CSRSES: California Statewide Residential Sector Energy Efficiency Potential Study. Prepared by KEMA-XENERGY Inc. April 2003. Final Report # SW063. HVAC PAG White Paper - Pacific Gas and Electric Company.
www.pge.com link to file

[9] Off-Peak Energy Storage for Domestic Applications, Applied Energy 44 (1993) 259-281

[10] Analysis of ice cool thermal storage, M.J. Sebzali, P.A. Rubini, Energy Conversion and Management 47 (2006) 3417–3434.

[11] Case Study of Design and Implementation of a Thermal Energy Storage System, M.E.S. Farahani N. Saeidi Niroo Research Institute First International Power and Energy Conference PECon 2006.

[12] Optimized Dispatch of a Residential Solar Energy System, Patrick M. Corrigan and Gerald T. Heydt, 978-1-4244-1726-1/07/$25.00_c 2007 IEEE

[13] CRYOGEL Ice Ball Thermal Storage, San Diego, CA. www.cryogel.com , additional information and data files were received by email from Victor – CRYOGEL engineer.

[14] Home Builders Association of Central Arizona WWW.HBACA.ORG

[15] ASHRAE Handbook – Fundamentals 2009 – Chapter 18

APPENDIX A

HACS CODE FOR THE EXCEL PROGRAM

Selected formulas used to calculate some of the critical values in the Excel code

1. **FeedIn [$$] during peak hours, Cell N18:**

   ```
   =IF(I18>$I$4*$D$1,$I$4*$D$1*$I$2+(I18-
   $I$4*$D$1)*$I$3,IF(I18>$C$1,(I18-$C$1)*$I$2,$I$2*I18))
   ```

2. **FeedIn [$$] during super peak hours, Cell N21:**

   ```
   =IF(I21>$I$4*$D$1,$I$4*$D$1*$I$1+(I21-
   $I$4*$D$1)*$I$3,IF(I21>$C$1,(I21-$C$1)*$I$1,$I$1*I21))
   ```

3. **FeedIn [$$] during off-peak hours, Cell N7:**

   ```
   =IF(I7>$C$1,(I7-$C$1)*$I$3,I7*$I$3)
   ```

4. **HACS cost of cooling at 1am, Cell O7:**

   ```
   =IF(I7>$C$1,0,($C$1)*$I$3)
   ```

5. **TES to Cool, kWc, at 12noon, Cell Q18:**

   ```
   =IF($C$1>I18,F18,(IF(K18<0,ABS(K18),0)))
   ```

6. **FeedIn kWe, Cell R18:**

   ```
   =IF(I18>$C$1,(I18-$C$1),I18)
   ```

7. **PV production, $$ per month in Winter, Cell T4:**

   ```
   =IF($F$2*$F$3*6.5/15<=$I$4*$D$1*0.75,$F$2*$F$3*
   6.5*30*0.15,$I$4*$D$1*0.75*0.15*30*15+$F$2*$F$3*6.5*30*0.05)
   ```

8. **TES required volume in Liters for each kWc, Cell M7:**

   ```
   =L7*3600/(4.2*$L$3+334-2*$L$2)
   ```

9. **HACS Tot Ann4:**

   ```
   =H1-model1!T3*(1+2*0.95+2*0.85+2*0.65)
   +0*(1+2*0.9+2*0.7)+C3*(4+1*0.5)
   ```

APPENDIX B

[HEAT LOSSES EQUATIONS FOR THE TES AND PICTURES]

Simple overview of heat losses equations for the TES and pictures

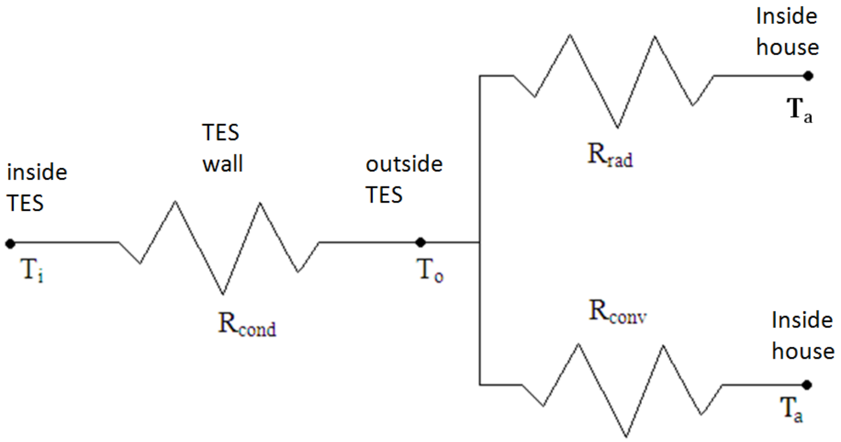


Figure B1: TES Thermal Losses Flow

$Q_{cond} = Q_{rad} + Q_{conv}$

$Q_{\text{cond}} = ({}_{o} - T_i) / R_{wall},\quad R_{wall} = L / (k \times A)$

$Q_{rad} = A \times \varepsilon \times \sigma \times ({}_{a} - T_o)^4$

$Q_{\text{conv}} = ({}_{a} - T_o) / R_{conv},\quad R_{conv} = 1 / (h \times A)$, reference [3]

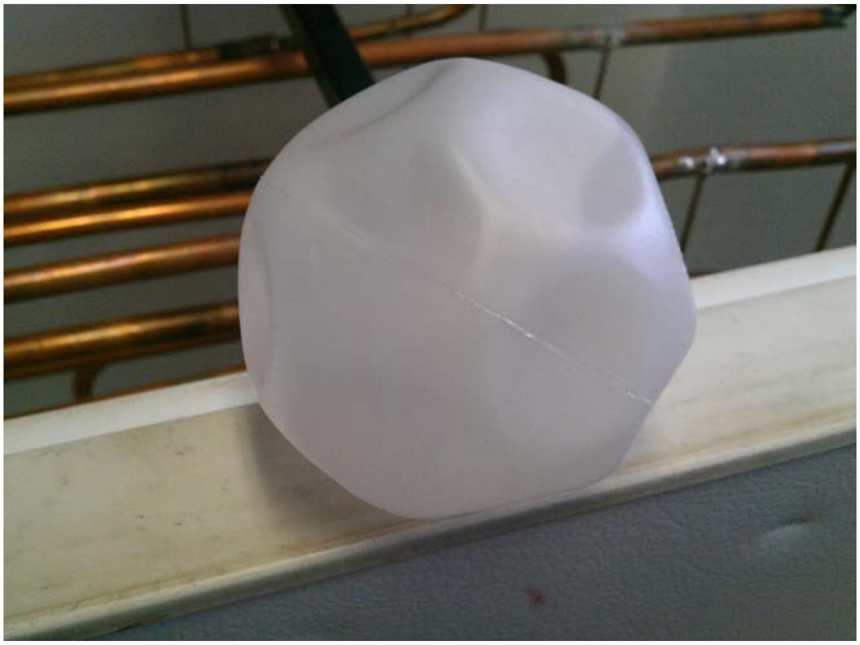


Figure B2: Cryogel Ice Ball

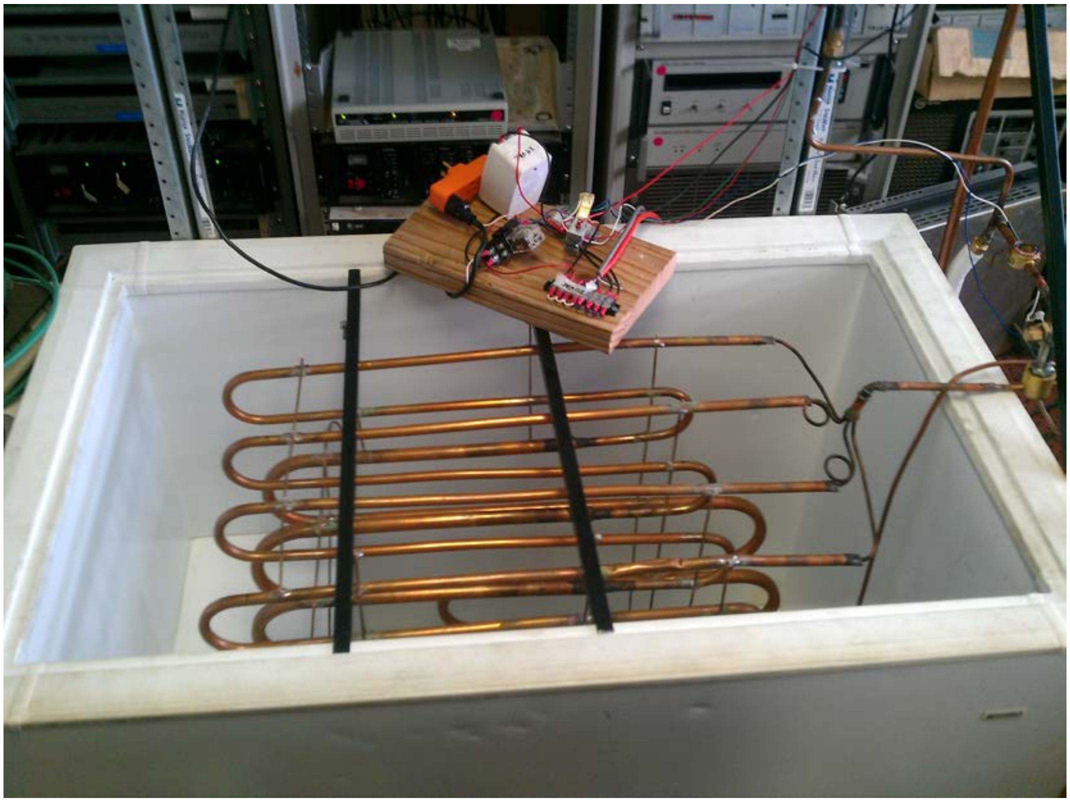


Figure B3: TES

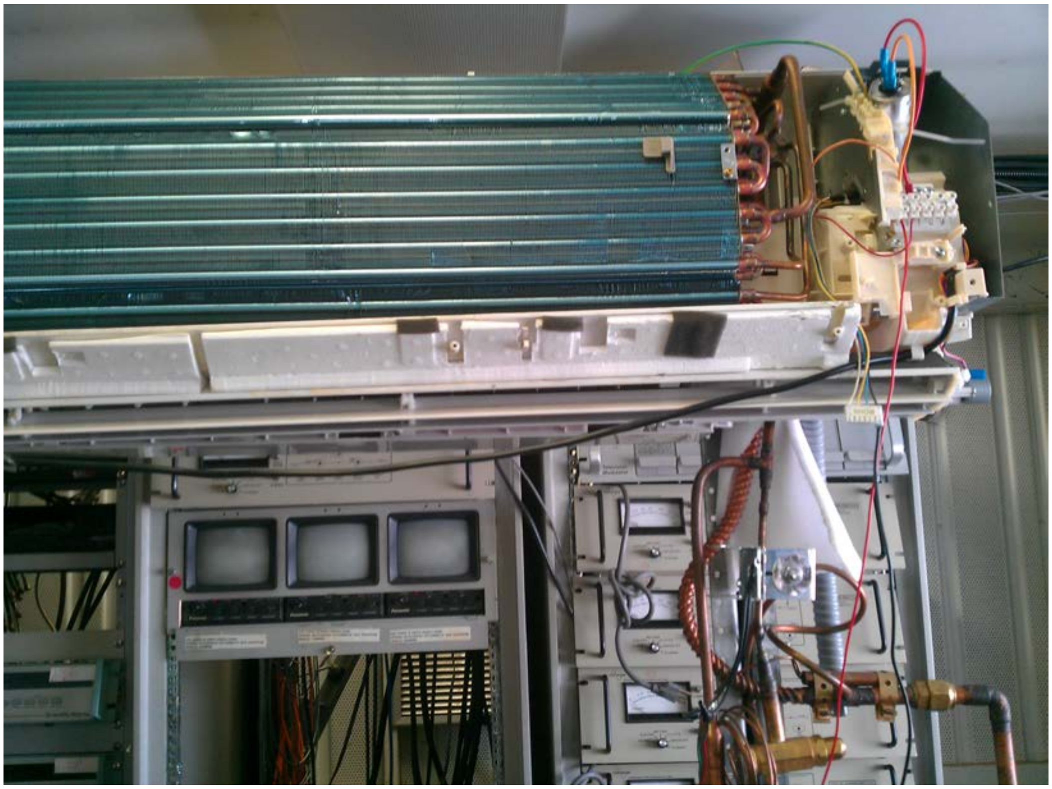


Figure B4: Air-Side Evaporator

APPENDIX C

[RADIATION FOR AZIMUTH AND INCLINE ANGLES]

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	Radiation [Wh/m^2] for Azimuth (Gamma) = 0														
0	111.0	384.0	608.0	762.0	860.0	919.0	929.0	958.0	961.0	929.0	859.0	752.0	616.0	386.0	115.0
5	103.6	358.4	567.5	746.6	857.8	924.5	938.2	969.4	972.7	938.8	864.6	751.0	605.9	366.5	109.2
10	95.5	330.5	523.3	726.6	850.4	924.5	942.0	975.2	978.8	943.1	865.1	745.6	591.9	344.7	102.7
15	86.9	300.5	475.7	702.1	837.8	919.1	940.4	975.5	979.2	941.9	860.3	735.6	574.3	320.9	95.6
20	77.6	268.6	425.2	673.2	820.2	908.2	933.5	970.1	973.9	935.1	850.4	721.2	553.2	295.1	87.9
25	67.9	235.0	372.1	640.2	797.6	891.9	921.2	959.2	963.0	922.8	835.5	702.5	528.6	267.6	79.7
30	57.8	200.1	316.8	603.4	770.2	870.5	903.7	942.9	946.5	905.1	815.5	679.7	500.8	238.6	71.1
35	47.4	164.0	259.7	563.0	738.3	843.9	881.1	921.1	924.6	882.1	790.7	652.9	470.1	208.3	62.1
40	36.7	127.1	201.3	519.3	702.1	812.6	853.5	894.2	897.4	854.0	761.3	622.2	436.6	177.0	52.7
45	25.9	89.7	142.0	472.7	661.8	776.6	821.2	862.3	865.1	821.1	727.6	588.1	400.6	144.9	43.2

Table C1: Radiation for Azimuth 0° (South facing)

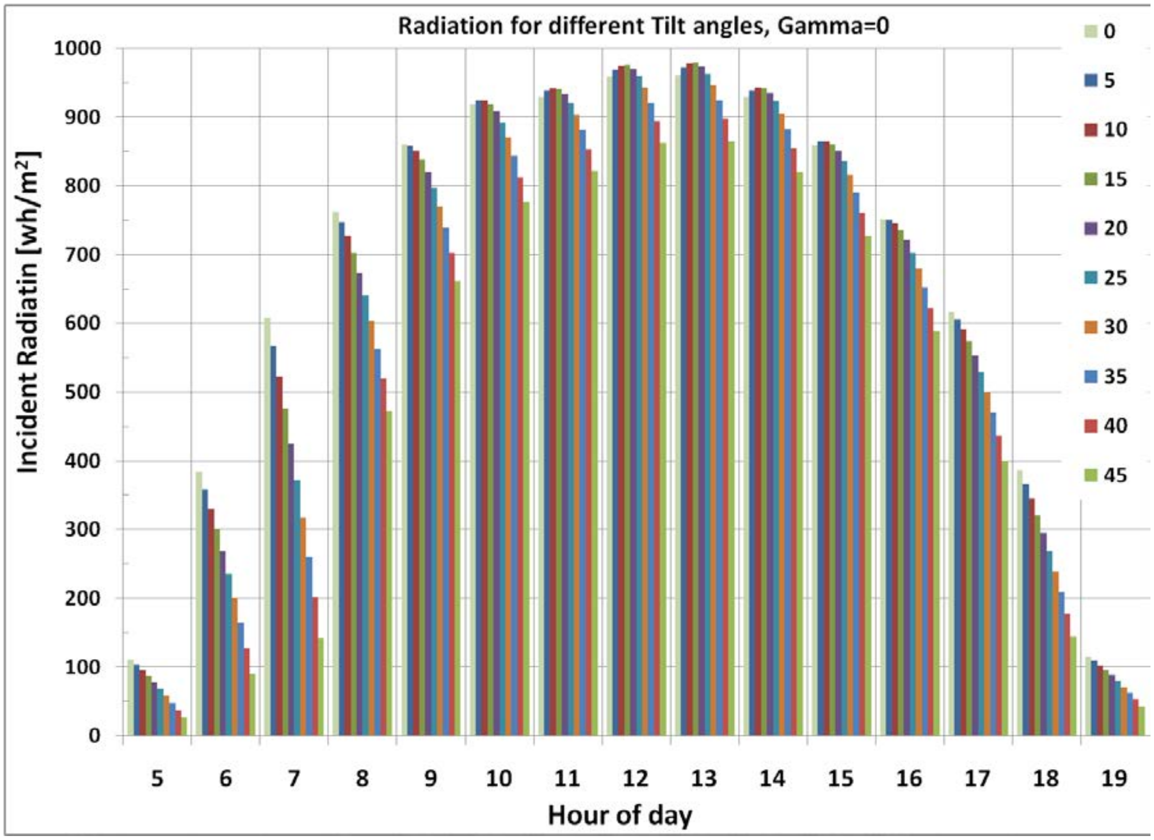


Figure C1: Radiation for Azimuth 0° (South facing)

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	Radiation [Wh/m^2] for Azimuth (Gamma) = 10														
0	111.00	384.00	608.00	762.00	860.00	919.00	929.00	958.00	961.00	929.00	859.00	752.00	616.00	386.00	115.00
5	102.00	367.62	582.07	729.50	845.51	916.20	933.53	967.57	973.79	942.89	871.66	760.59	618.47	379.70	113.12
10	96.82	348.96	552.51	692.46	825.89	907.98	932.73	971.59	980.93	951.23	879.08	764.57	617.06	371.05	110.55
15	91.05	328.15	519.57	651.17	801.29	894.42	926.61	970.05	982.37	953.94	881.19	763.93	611.76	360.10	107.28
20	84.72	305.35	483.48	605.94	771.89	875.62	915.20	962.96	978.11	951.01	878.00	758.65	602.63	346.95	103.36
25	77.90	280.75	444.52	557.11	737.91	851.71	898.61	950.36	968.17	942.46	869.51	748.79	589.74	331.68	98.82
30	70.62	254.52	402.99	505.06	699.63	822.89	876.95	932.35	952.63	928.36	855.80	734.41	573.17	314.42	93.67
35	62.95	226.86	359.20	450.18	657.31	789.36	850.40	909.08	931.60	908.80	836.96	715.63	553.07	295.30	87.98
40	54.93	197.99	313.49	392.89	611.30	751.39	819.14	880.71	905.26	883.95	813.15	692.59	529.57	274.46	81.77
45	46.65	168.13	266.20	333.63	561.93	709.27	783.43	847.47	873.79	853.99	784.54	665.47	502.87	252.06	75.10

Table C2: Radiation for Azimuth 10 degrees

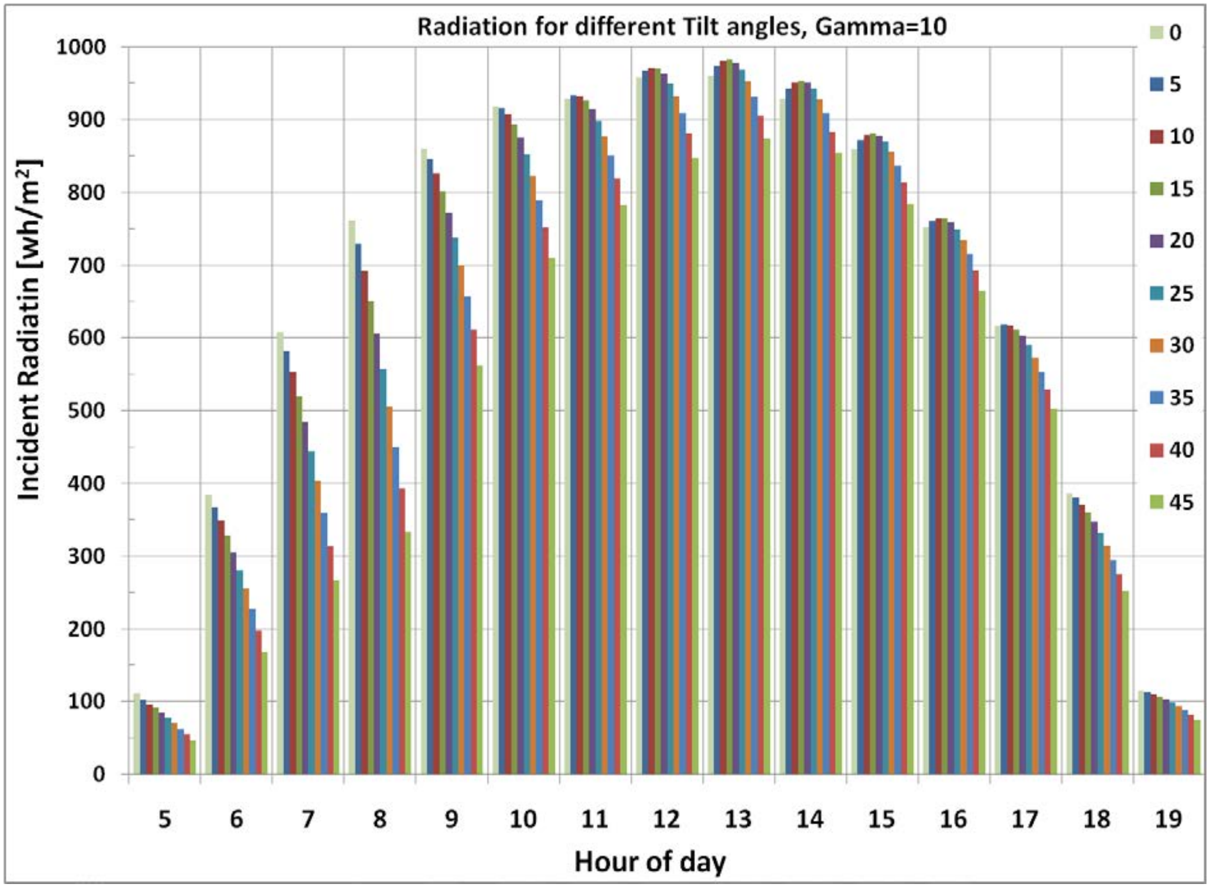


Figure C2: Radiation for Azimuth 10 degrees

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	Radiation [Wh/m^2] for Azimuth (Gamma) = 20														
0	111.00	245.00	608.00	762.00	860.00	919.00	929.00	958.00	961.00	929.00	859.00	731.00	551.00	321.00	148.00
5	74.43	188.00	519.51	713.27	833.57	907.91	928.65	965.36	974.38	946.45	878.22	739.92	553.65	329.54	150.88
10	61.28	119.95	427.70	660.13	802.09	891.46	923.01	967.20	982.12	958.31	892.15	752.40	562.90	333.10	152.51
15	47.75	93.47	333.28	602.97	765.82	869.80	912.12	963.50	984.15	964.50	900.68	760.33	568.69	334.66	153.23
20	33.95	66.46	236.97	542.25	725.01	843.08	896.06	954.30	980.46	964.96	903.74	763.67	570.97	334.20	153.02
25	19.98	39.12	139.49	478.41	679.99	811.51	874.96	939.67	971.07	959.70	901.32	762.38	569.73	331.73	151.89
30	17.21	33.68	120.11	411.95	631.10	775.32	848.97	919.70	956.06	948.75	893.43	756.47	564.97	327.26	149.84
35	14.34	28.08	100.11	343.37	578.70	734.80	818.30	894.57	935.54	932.20	880.14	745.99	556.73	320.84	146.90
40	11.41	22.34	79.65	273.20	523.20	690.24	783.17	864.45	909.67	910.17	861.54	731.02	545.07	312.50	143.08
45	8.44	16.51	58.88	201.96	465.01	642.00	743.86	829.58	878.64	882.83	837.77	711.68	530.08	302.32	138.42

Table C3: Radiation for Azimuth 20 Degrees

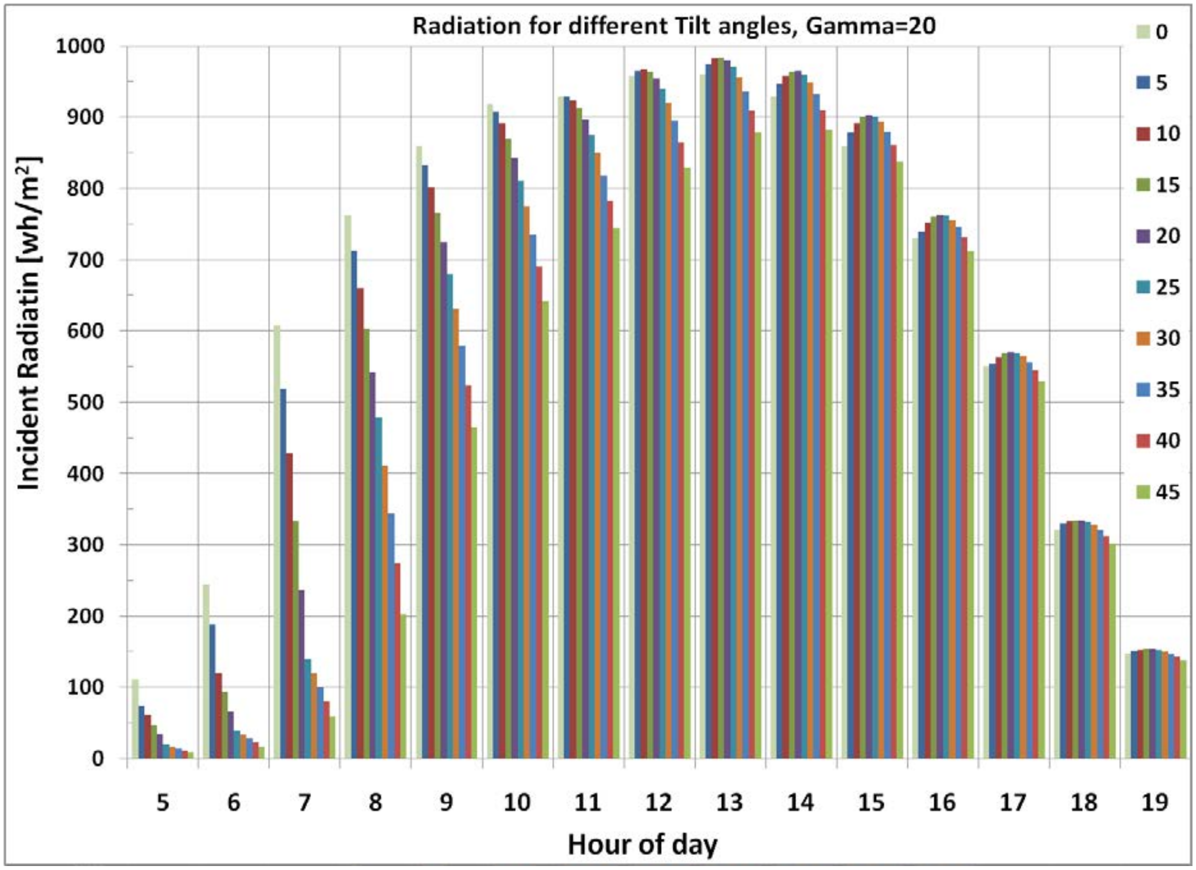


Figure C3: Radiation for Azimuth 20 Degrees

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	Radiation [Wh/m^2] for Azimuth (Gamma) = 30														
0	111.00	384.00	608.00	762.00	860.00	919.00	929.00	958.00	961.00	929.00	859.00	752.00	616.00	386.00	145.00
5	91.12	315.23	499.12	698.45	822.35	899.87	923.71	962.85	974.49	949.39	884.12	778.40	642.91	406.19	171.00
10	70.67	244.47	387.08	630.59	779.74	875.45	913.16	962.19	982.34	964.17	903.90	800.05	665.74	423.81	178.42
15	49.79	172.25	272.73	558.96	732.49	845.94	897.43	956.05	984.47	973.23	918.19	816.81	684.33	438.75	184.71
20	28.65	99.12	156.94	484.09	680.97	811.54	876.65	944.45	980.88	976.51	926.89	828.54	698.53	450.87	189.81
25	24.06	83.24	131.80	406.54	625.57	772.54	850.97	927.49	971.59	973.96	929.92	835.14	708.23	460.09	193.69
30	19.35	66.94	105.99	326.92	566.72	729.22	820.59	905.29	956.68	965.63	927.27	836.58	713.37	466.35	196.33
35	14.55	50.34	79.70	245.83	504.84	681.91	785.74	878.04	936.25	951.56	918.96	832.83	713.89	469.58	197.69
40	9.70	33.56	53.13	163.89	440.43	630.97	746.68	845.93	910.46	931.87	905.04	823.94	709.80	469.77	197.77
45	4.84	16.73	26.49	81.71	373.97	576.80	703.72	809.20	879.52	906.70	885.62	809.95	701.13	466.92	196.57

Table C4: Radiation for Azimuth 30 Degrees

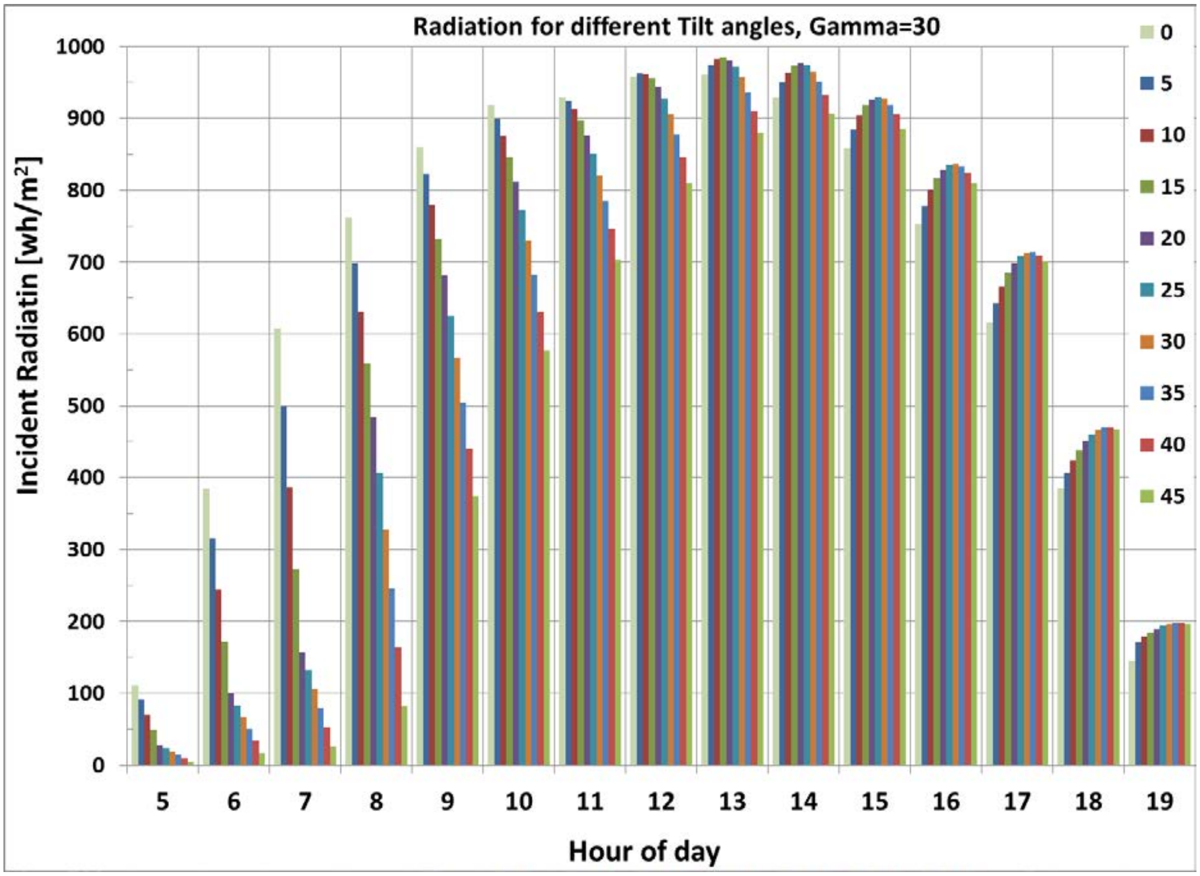


Figure C4: Radiation for Azimuth 30 Degrees

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	**Radiation [Wh/m^2] for Azimuth (Gamma) = 40**														
0	111.00	234.00	608.00	762.00	860.00	919.00	929.00	958.00	961.00	929.00	859.00	742.00	533.00	296.00	125.00
5	66.00	145.00	481.97	685.48	812.19	892.33	918.84	960.11	974.11	951.63	889.18	766.00	573.17	349.65	155.00
10	40.59	72.02	352.92	604.77	759.50	860.43	903.46	956.73	981.56	968.63	913.98	783.33	601.79	373.17	176.05
15	25.51	45.26	221.82	520.46	702.33	823.55	882.98	947.90	983.32	979.88	933.21	806.44	626.66	394.38	186.05
20	10.31	18.30	89.67	433.22	641.11	781.97	857.55	933.69	979.36	985.29	946.74	824.59	647.57	413.12	194.90
25	4.67	8.29	40.60	343.69	576.32	735.99	827.37	914.19	969.72	984.82	954.45	837.66	664.38	429.25	202.50
30	0.00	8.49	34.00	252.56	508.44	685.98	792.67	889.56	954.46	978.47	956.29	845.54	676.95	442.64	208.82
35	0.00	5.39	26.43	160.52	438.00	632.30	753.71	859.99	933.70	966.30	952.24	848.17	685.19	453.20	213.80
40	0.00	0.00	0.00	111.00	365.52	575.38	710.79	825.70	907.61	948.38	942.34	845.53	689.03	460.83	217.40
45	0.00	0.00	0.00	81.71	291.56	515.64	664.23	786.96	876.38	924.87	926.65	837.64	688.45	465.49	219.60

Table C5: Radiation for Azimuth 40 Degrees

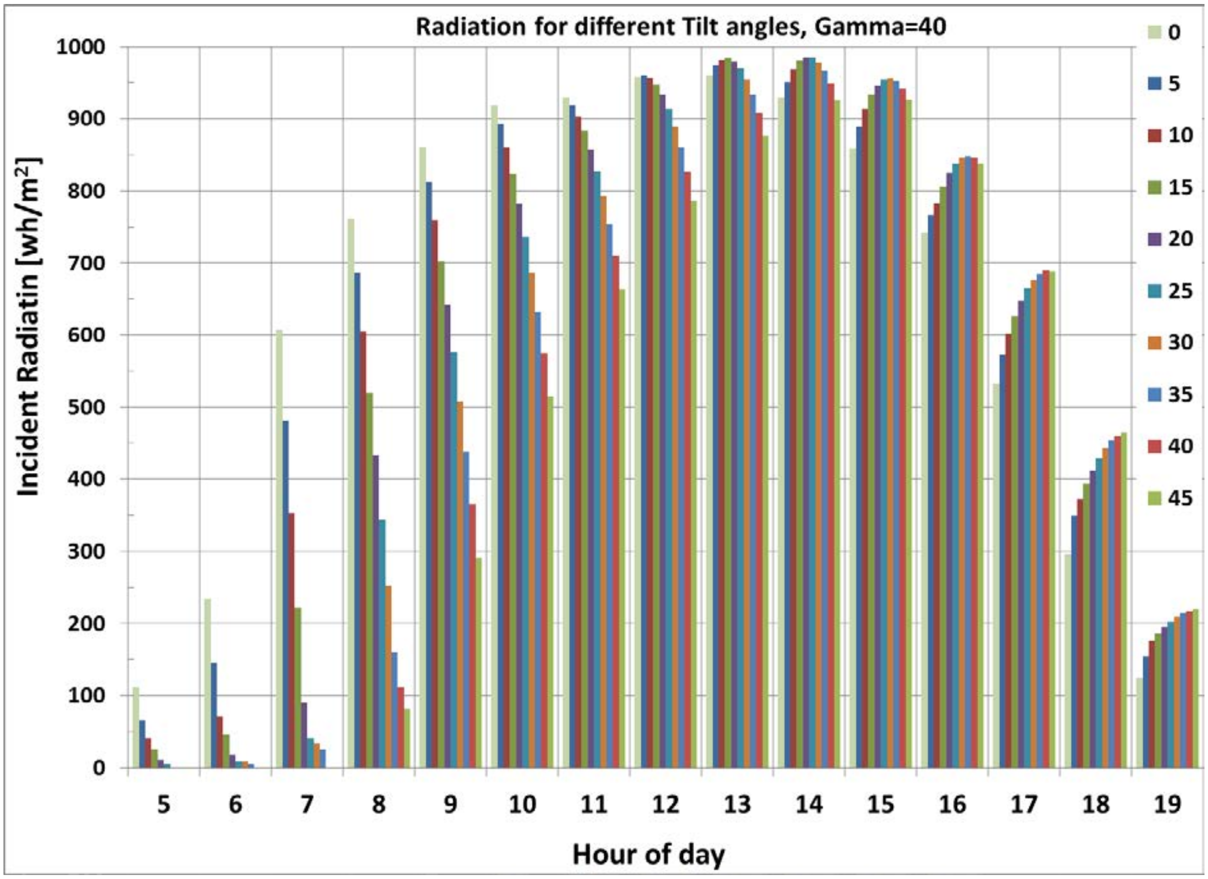


Figure C5: Radiation for Azimuth 40 Degrees

Hr	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Tilt	Radiation [Wh/m^2] for Azimuth (Gamma) = 50														
0	111.00	234.00	608.00	762.00	860.00	919.00	929.00	958.00	961.00	929.00	859.00	742.00	533.00	296.00	125.00
5	59.00	122.00	468.60	674.77	803.40	885.52	914.20	957.22	973.24	953.10	893.24	761.74	581.53	358.64	171.49
10	27.31	59.62	326.27	583.43	742.00	846.87	894.22	950.98	979.83	971.56	922.07	795.88	618.45	391.09	187.01
15	15.24	33.28	182.10	488.66	676.24	803.33	869.20	939.32	980.74	984.25	945.27	825.14	651.49	421.09	201.35
20	7.51	16.39	89.67	391.18	606.64	755.24	839.35	922.35	975.95	991.06	962.68	849.31	680.39	448.41	214.42
25	3.40	7.42	66.87	291.75	533.72	702.97	804.88	900.18	965.50	991.95	974.14	868.20	704.92	472.85	226.10
30	0.00	7.60	43.81	191.11	458.05	646.91	766.06	872.99	949.47	986.90	979.59	881.66	724.92	494.23	236.32
35	0.00	6.38	36.79	160.52	380.18	587.49	723.19	840.98	927.98	975.97	978.97	889.61	740.21	512.37	245.00
40	0.00	0.00	22.69	99.00	300.73	525.16	676.58	804.39	901.20	959.22	972.29	891.97	750.70	527.15	252.07
45	0.00	0.00	18.73	81.71	220.29	460.40	626.60	763.52	869.33	936.79	959.61	888.73	756.29	538.44	257.47

Table C6: Radiation for Azimuth 50 Degrees

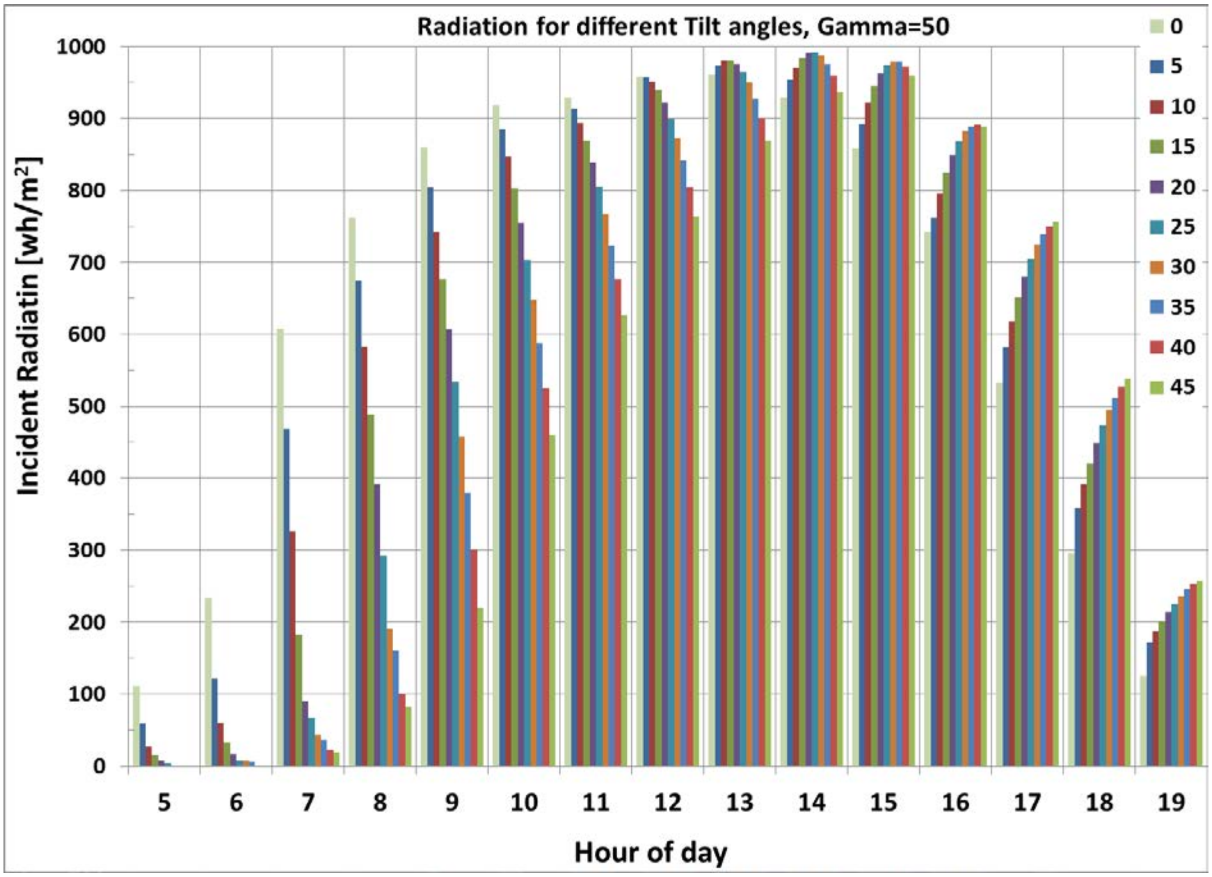


Figure C6: Radiation for Azimuth 50 degrees

Hr	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Tilt	**Radiation [Wh/m^2] for Azimuth (Gamma) = 60**														
0	111.00	234.00	608.00	762.00	860.00	919.00	929.00	958.00	961.00	929.00	859.00	742.00	533.00	296.00	125.00
5	45.00	93.00	459.40	666.64	796.26	879.65	909.93	954.27	971.91	953.75	896.18	766.80	588.61	366.55	177.43
10	20.81	48.56	307.94	567.22	727.76	835.16	885.71	945.10	977.19	972.86	927.93	805.95	632.56	406.85	196.94
15	10.46	24.41	154.77	464.50	655.02	785.88	856.53	930.57	976.81	986.19	954.02	840.15	672.51	444.57	215.20
20	6.06	14.14	89.67	359.27	578.60	732.19	822.59	910.78	970.75	993.63	974.23	869.14	708.17	479.45	232.08
25	3.08	7.20	45.64	252.31	499.08	674.48	784.18	885.88	959.08	995.12	988.42	892.70	739.25	511.21	247.46
30	0.00	0.00	33.44	144.45	417.06	613.20	741.57	856.07	941.87	990.66	996.48	910.66	765.53	539.61	261.20
35	0.00	0.00	23.42	85.63	333.16	548.82	695.09	821.57	919.26	980.27	998.34	922.87	786.81	564.43	273.22
40	0.00	0.00	0.00	68.28	248.03	481.83	645.09	782.65	891.43	964.04	994.00	929.25	802.91	585.49	283.41
45	0.00	0.00	0.00	0.00	162.32	412.73	591.96	739.59	858.58	942.10	983.49	929.74	813.73	602.62	291.70

Table C7: Radiation for Azimuth 60 degrees

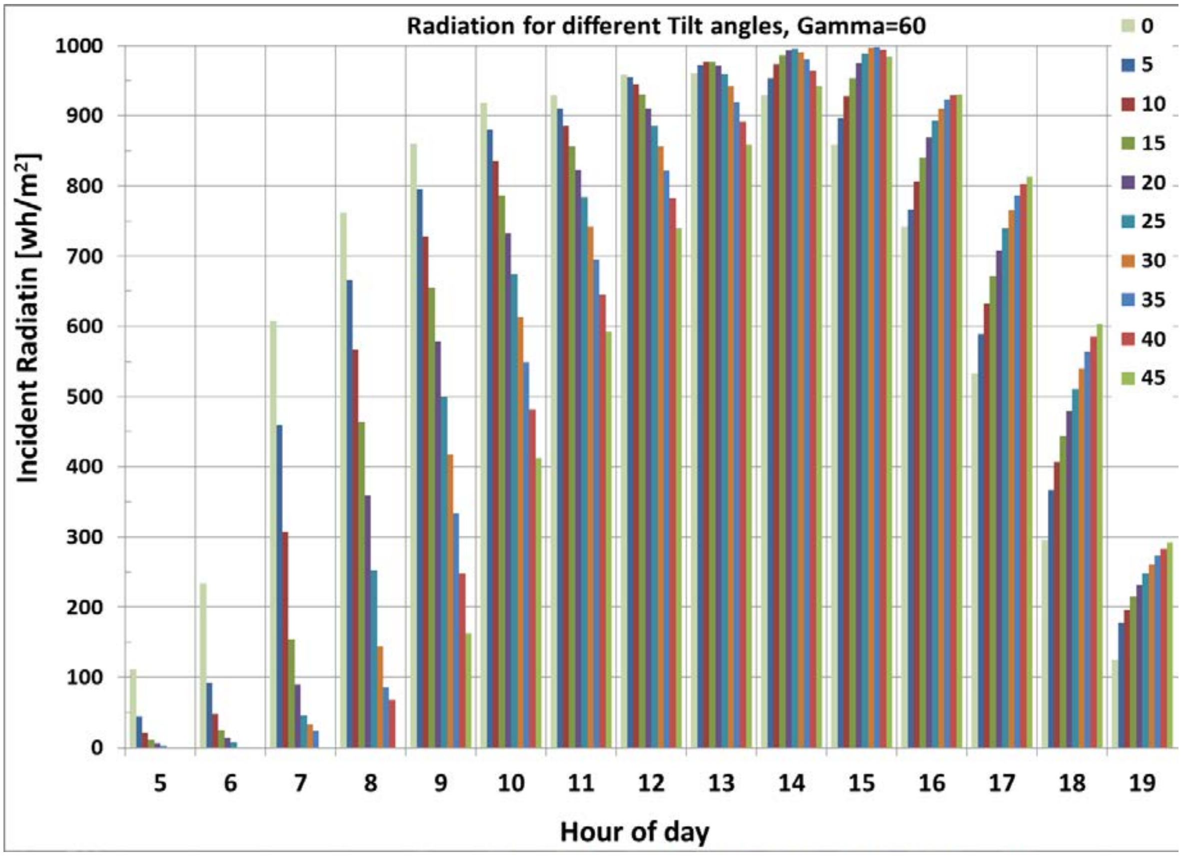


Figure C7: Radiation for Azimuth 60 degrees