SOLAR COOLING WITH ICE STORAGE

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ABSTRACT

An investigation is undertaken of a prototype building-integrated solar photovoltaic-powered thermal storage system and air conditioning unit. The study verifies previous thermodynamic and economic conclusions and provides a more thorough analysis. A parameterized model was created for optimization of the system under various conditions. The model was used to evaluate energy and cost savings to determine viability of the system in several circumstances, such as a residence in Phoenix with typical cooling demand. The proposed design involves a modified chest freezer as a thermal storage tank with coils acting as the evaporator for the refrigeration cycle. Surrounding the coils, the tank contains small containers of water for high-density energy storage submerged in a low freezing-point solution of propylene glycol. The cooling power of excess photovoltaic and off-peak grid power that is generated by the air conditioning compressor is stored in the thermal storage tank by freezing the pure water. It is extracted by pumping the glycol across the ice containers and into an air handler to cool the building.

1. INTRODUCTION

Alternative energy sources, such as solar photovoltaic panels are receiving a great deal of research and development in order to decrease the amount of conventional energy sources being used, particularly fossil fuels. While photovoltaic technologies are decreasing in cost and increasing in efficiency [1], an obstacle that they still face concerning widespread adoption is their limited time-span for energy generation since they require incident sunlight. A technique for addressing this obstacle is storage of energy. This study analyzes the ability of a thermal storage method to improve the ability of solar energy to meet a full day's electric demand. This system relies on the high proportion of electrical use resulting from air conditioning demand. As a result, this is not an ideal system for users who do not have a large air conditioning demand, although a similar thermal storage design could be employed for users who have a high heating demand. In this system, an air conditioning compressor is modified with a second refrigerant loop that acts as a heat exchanger with a thermal storage tank. When the compressor is not being used for air conditioning, the flow of refrigerant switches to the loop that is in the storage tank and cools liquid that is inside. Liquid from in the tank can then be used for additional cooling on-demand by pumping it through an air handler.

The ratio of thermal energy output to electrical energy input generated by an ideal refrigeration cycle is given by the Carnot efficiency:

$$\eta_{Carn} = \frac{T_{evap}}{T_{cond} - T_{evap}} \qquad (1)$$

where η_{Carn} is the Carnot efficiency, T_{evap} is the evaporator temperature, and T_{cond} is the condenser temperature. The evaporator temperature is the temperature of the thermal storage when the compressor is charging the storage. As Equation 1 shows, the Carnot efficiency is highest when the condenser and evaporator temperatures are closest together. This means that cooling is most efficient at night when the outdoor temperature is lower and is less efficient when cooling the thermal storage than when cooling the relatively warmer indoor air space. For real-world air conditioners, a coefficient of performance, or COP, is used to measure the efficiency. COP for a refrigeration cycle is determined by:

$$COP_{ref} = \frac{Q_L}{W_{Net,in}} \qquad (2)$$

where Q_L is the amount of heat removed from the indoor, conditioned space and $W_{Net,in}$ is the net amount of electrical energy supplied to the air conditioner. To determine the heat removed, or cooling supplied, each hour, the ratio between the known COP and Carnot efficiency for given temperatures was used with the calculated Carnot efficiency for the average outdoor dry bulb temperature each hour [2]. This method was used to determine the efficiency of conditioning the indoor space and the thermal storage each hour.

The heat transferred into or out of a given mass depends on the total change in internal energy of the mass, and can be calculated by [3]:

$$Q = mc\Delta T \qquad (3)$$

where Q is the heat transferred, m is the mass, c is the specific heat of the mass, and ΔT is the difference between the final and initial temperature of the mass. The specific heat depends on the phase of the substance and Q must be calculated for the temperature change and specific heat in each phase and summed together. When the mass undergoes a phase change, the latent heat of the substance must be added to the total heat transferred. The rate of heat transferred into or out of a liquid passing through a heat exchanger is:

$$\frac{dQ}{dt} = \dot{m}c\Delta T \qquad (4)$$

where $\frac{dQ}{dt}$ is the rate of heat transferred, $\dot{m}$ is the mass flow rate of the liquid, c is the specific heat of the liquid, and ΔT is the difference in temperature of the liquid between the outlet and the inlet.

1.1 Motivation

The combined air conditioning and thermal storage system is intended as a technology to increase the effectiveness of solar photovoltaic energy use. While it was originally designed as a concept for off-grid applications, the current study analyses its value in a grid-connected application as well.

The design of the system allows owners to better cope with peak energy rates by relying on solar power during the day and stored thermal energy during the evening. Photovoltaic energy collected during times of peak solar radiation can be stored and therefore can be accessed during peak energy rate hours to meet cooling load. Also, the thermal storage can be charged overnight when grid energy rates are lower so that it will supplement the cooling power provided by the PV panels as needed during peak rate times.

1.2 Objectives

This research is intended to expand on previous analytical work done on this system. The goal is to verify the viability of the system and study its performance such as grid energy savings and payback period for different circumstances. For instance, different climates with lower cooling loads may get less value from using such a system. This study also aims to create a versatile and user friendly computer model for optimizing the sizing of the system. Different conditions for the system can be easily input, and different parameters for optimum sizing can be used. The model created for this analysis meets these requirements.

2. OVERVIEW OF DESIGN

2.1 Solar Cooling

Solar cooling can use two different methods. One method, a thermal-driven system, uses the heat provided by the sun to drive an absorption refrigeration cycle and other cycles that require a heat input to be activated. In our system, we use the other method. Rather than using the thermal energy of the sun directly, this method uses the photovoltaic panels to convert sunlight to electricity which is used to power a refrigeration cycle, such as the vapor-compression cycle we are using [4].

While solar cooling can be provided without any storage capacity, our design is intended to make use of the high levels of sunlight during the peak irradiation time during the day in order to provide cooling during the subsequent period of peak cooling demand. Therefore, our design does utilize a method for storing energy for cooling as needed.

2.2 Thermal Storage

The refrigerant, R134a, is run through a parallel section of the system into a separate expansion valve and evaporator. This evaporator is located in a thermal storage tank. We used a 75 gallon chest freezer as the thermal storage tank for our prototype. The refrigerant is run through coils throughout the tank.

In order to store the energy of the refrigerant, the evaporator is used to absorb heat from the contents of the thermal storage tank. A phase change in a substance is ideal for storing thermal energy so water has been chosen for its availability and lack of health hazards.

However, to utilize the thermal energy, some of the chilled contents of the tank must be extracted and used to absorb heat from the space that requires conditioning. As a result, containers of water are being placed in the tank surrounding the evaporator coils. These containers are known as Cryogel Ice Balls, which are designed specifically for such applications [5]. They are sealed plastic balls containing water and have dimples to allow it to easily expand when the water freezes to ice. The Cryogel balls remain in the freezer, while a surrounding liquid is able to absorb the stored thermal energy from the balls as it passes over and use it to cool the conditioned space by running through an air handler. Since it would need to remain liquid at the freezing point of water, a weak propylene glycol-water solution has been chosen since it has a lower freezing point than water and is less toxic than alternative substances.

The thermal storage tank is considered fully charged when the Cryogel balls are all fully frozen and the glycol solution at its freezing point, frozen near the evaporator but still able to flow between the inlet of the thermal storage tank and the outlet and through the air handler.

We have discovered alternate containers for holding water in the thermal storage tank. Water bottles also effectively isolate water from the surrounding glycol solution while allowing a sufficient heat transfer between the water and the solution. Water bottles, although much cheaper and more readily available, may leak, may not be as durable as Cryogel balls under the pressures of the storage tank and the expansion of the ice, and may not expand as successfully as Cryogel balls. Depending on the dimensions of the thermal storage container and the evaporator coils, either the Cryogel balls or the water bottles may be preferable for optimum packing due to their different geometries. Some other containers are expected to have similar potential desirable characteristics.

Fig. 1: Prototype thermal storage tank and components.

The refrigerant is cycled through the evaporator in the thermal storage container when energy storage is desirable. Programmable thermostats are being used to control the path of the refrigerant through the parallel sections of the cycle by controlling valves that release or restrict the flow of the refrigerant in the appropriate path. When the temperature of the conditioned space is higher than it is programmed to be, the valve will send the refrigerant into the conventional air handler to cool the room. The conventional air conditioning unit is able to be a smaller size than it would be without the thermal storage because the glycol air handler can also be turned on and run using the stored cooling if the conventional air handler does not cool the room to the programmed temperature. This second air handler can supplement the cooling power of the first.

Fig. 2: Prototype thermal storage extraction setup.

2.3 Similar Storage Technologies

Other technologies are sometimes used to store or use energy during low-cost off-peak times. In some cases, batteries are charged during this period and occasionally other technologies are used for storing thermal energy. For example, water heaters and chillers are sometimes run during the night to store the heated or chilled water until it is needed during the day, rather than using the electricity needed during the day at higher costs [6]. Energy generated through photovoltaic power is commonly used directly, without being stored. Our system uses the photovoltaic power directly, with as few losses as possible, by converting it directly to its end state of thermal energy without doing conversions in between, and storing it when it does not need to be used immediately as well as storing off-peak grid power. This avoids using on-peak grid power and problems associated either with storing power in a battery in the form of electricity or with the fact that sunlight is not consistent and not always provided during on-peak times and periods of high cooling demand during the early evening. A somewhat comparable technology that is currently on the market is the Ice Bear, which is designed for freezing water during off-peak times [7]. The Ice Bear uses a conventional air conditioner as necessary, except during on-peak times, when it circulates refrigerant through the ice and into an air handler to cool the conditioned space.

3. THEORETICAL MODELING METHODOLOGY

The theoretical model was developed from assumptions made in a previous analysis of the solar thermal storage system [2]. The model was designed to calculate the cost and energy use of the system under constraints input by the user for each unique circumstance. The model ultimately compares the cost and the energy use with that of a conventional air conditioning system and determines the payback period due to the upfront cost and the subsequent savings, as well as the savings after a given time period, so that the desired parameter can be optimized. The system setup for the optimized result is given, such as the size of the photovoltaic array, the size of the air conditioning unit, of the thermal storage tank, and of the battery if necessary.

To create the model, a general formulation for the flow of energy was created. This included an hourly distribution of the solar photovoltaic electricity to the air conditioning unit, which would be used to meet the cooling demand or stored (with corresponding COPs), and the excess to the hot water heater and to a battery. The thermal storage and battery were sized based on a calculation of the cooling that was required which was not met by the solar power.

The user is first prompted to input the rated cooling requirement for the conditioned space. The approximate square footage of a house corresponding to the rated cooling requirement is calculated based on the assumption that one ton of cooling is needed for 500 square feet of space [8]. This calculation is to provide a rough real-world perspective to the use of the model, and is not precise. An hourly profile for the cooling energy demand for a house during a typical July day in Phoenix is given [2], [9]. This profile can be modified to show a different cooling profile or can be calculated more precisely for the exact application by analysis of the specific conditions of the house. For this model, the profile is assumed to be appropriate for any house. The profile is then normalized so that the rated cooling requirement is the highest point of the profile, in units of kilowatts of thermal energy.

The significant values from a compressor manufacturer data sheet are input in the model and could be changed if different values apply to the specific compressor being considered. The COPs of the compressor cooling the conditioned space and cooling the thermal storage are calculated based on the values from the data sheet and Equation 2. The Carnot efficiency for each of the refrigerant loops is calculated based on Equation 1 from the data sheet values. The ratio of the COP to the Carnot efficiency for each mode of operation is calculated and they are averaged to find an approximate Carnot ratio. The dry bulb temperature of the outdoor air for a typical July day for Phoenix is given and can be modified for different climates [2], [9]. The Carnot efficiency is determined for both of the loops based on the dry bulb temperature. The actual COP is estimated based on the Carnot ratio and the hourly Carnot efficiency, as described in the Introduction, for the two modes of operation.

The profile of the grid electricity required to provide cooling is calculated from:

$$W_{CL} = \frac{Q_{CL}}{COP_{CL} * \eta_{rect}} \tag{5}$$

where W_{CL} is the AC electricity required, Q_{CL} is the normalized cooling load profile, COP_{CL} is the hourly profile of the COP for the compressor operating to meet the cooling load, and η_{rect} is the rectifier efficiency to convert the alternating current grid electricity to direct current. When the compressor is assumed to operate using direct current, which avoids the losses of inverting the photovoltaic energy to alternating current, the rectifier efficiency is assumed to be 98%, which is conservative to give a low estimate of the electricity used for a conventional air conditioning system.

The efficiency of the photovoltaic array used is 15% based on a typical current industry value, although this could be increased for a higher solar array cost or to address future changes in the industry [1]. Industry values for derating factors are used and can also be modified to accommodate changes in the solar industry [10]. The solar irradiation profile that is used is for the tilt that provides the highest output during peak hours, at a 35° Azimuth and 70° Zenith, for Phoenix in July [2], [9]. Other profiles can be used to evaluate different tilts or levels of insolation. The peak energy hours and the time-of-use prices according to the utility company are provided by the user, and a matrix is generated.

Since the model is analyzing a DC system, the photovoltaic energy that is not used for cooling can be stored in a battery or used in a DC appliance. A typical home appliance, a 64 gallon hot water heater, is assumed to use 15 kW of electricity each day [11]. This is conventionally provided by off-peak grid power, but can be instead supplied by excess photovoltaic power.

The cooling load and the COP profile are used to calculate the grid energy required for conventional cooling. The peak rate profile is used to find the cost for cooling during weekdays, the off-peak rate is used to find the cooling cost during weekends and for water heating each day, and they are proportionally summed to calculate the conventional cost of cooling and water heating during the 31 days of July. The corresponding total amount of energy is calculated for each day and multiplied by 31 to give the corresponding energy used during July.

Since water is the principal thermal storage medium, the specific heat capacity of liquid water and ice, the latent heat of fusion, the minimum thermal storage temperature of -3°C and maximum effective temperature of 10°C are used to calculate the specific energy of the thermal storage across the full charge and discharge cycle using Equation 3. The user is prompted to input a maximum capacity of water for the thermal storage tank that they would be capable of installing, most likely due to space limitations. This is converted to a mass of water contained in the tank and multiplied by the specific energy of the water across the full charge to find the total thermal energy that the tank could store.

Based on these inputs and calculations, the model then runs a series of simulations evaluating possible system setups to create a chart with the results and to select the one that optimizes the desired output parameter.

As the first input parameter that the model runs, it prompts the user to input a maximum available area for the photovoltaic array and runs the model at ten intervals of array size. The direct current electricity that it generates is calculated using the irradiation profile, the efficiency of the panels, and the derate factors. The rating of the array is given by the maximum electricity output before the derate factors are included. The cost of the array is calculated using $2000/kW for the array's rating [1].

The next parameter is the size of the compressor, where the rated electrical demand corresponds to the cooling power by its COP. The amount of electrical energy available for storage as thermal energy is the difference between the rating of the compressor and the electrical demand corresponding to the cooling demand each hour [2]. As a result, the compressor size can only be decreased to the mean value of the electrical demand profile for the conventional air conditioning system, with an extra quarter size as a buffer.

The electric profile of the compressor during peak hours is the next parameter, where the maximum it can be decreased is the corresponding electrical demand for the full allowable thermal storage capacity, divided across the peak hours. The profile of the photovoltaic energy powering the compressor is evaluated as the compressor's electrical demand if the solar energy is greater than this demand, for each hour. Excess solar energy is the difference between the photovoltaic energy profile and the solar-to-compressor profile.

Next, the profile for the normalized thermal energy demand is compared to the thermal energy provided by the rated compressor each hour. For hours when the demand is larger, the cooling from the rated compressor is its full value and the cooling from the thermal storage is the difference divided by the efficiency for extraction. If the demand is not as large, the cooling from the compressor is the value of the demand. The extra energy is available for storage. The difference between the cooling that the compressor can provide and the demand is converted into electricity by the corresponding COP and back to thermal energy by the COP for the thermal storage at that hour, multiplied by the efficiency for storage. The efficiency for storage and extraction are estimated to be 90% and require more rigorous thermodynamic analysis.

The cooling during peak hours that is not provided by photovoltaic energy is considered from battery, thermal storage, and grid. The demand profile is modified accordingly. The mass flow rate is determined using Equation 3 where the heat transfer is the maximum load on the thermal storage. The optimum profile for storing thermal energy is created by comparing the total required capacity with the available energy for storage each hour, beginning with the end of the charging time to ensure the energy is stored for as short a time as possible. A minimum amount of extra capacity is required for extreme loads. The full capacity of the storage is calculated by setting the capacity to the minimum amount and adding the net input of thermal energy to the previous capacity for each hour. The photovoltaic power that is not used directly by the compressor is determined. First, this power is allotted to the hot water heater load, and the remainder is allotted to battery storage. The profiles for energy from the grid is used to find the total energy consumption, and the peak rate plan is used to find the cost of operation, considering that weekends have no peak rates. The size of the system components are used for estimations of the upfront cost. A payback period is calculated from the cost and yearly savings, where savings decrease for cooler months [2]. A chart is generated with the results for each configuration.

4. RESULTS AND DISCUSSION

For the main analysis, a Phoenix house that requires 4 tons of cooling, uses a time-of-use super-peak rate plan [12], and needs a new air conditioner is used. The house does not have a photovoltaic array area or thermal storage size limitation.

The profile for the solar irradiation incident on photovoltaic panels is shown in Figure 3, where the first hour of the day corresponds to the time between midnight and 1 o'clock in the morning.

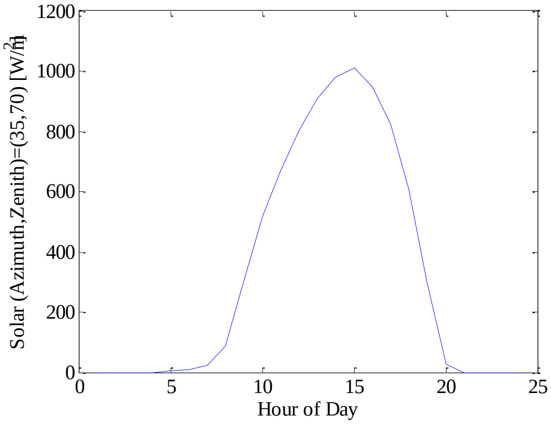

Fig. 3: Solar irradiation profile, Phoenix.

The profile of the outdoor dry bulb temperature is given in Figure 4.

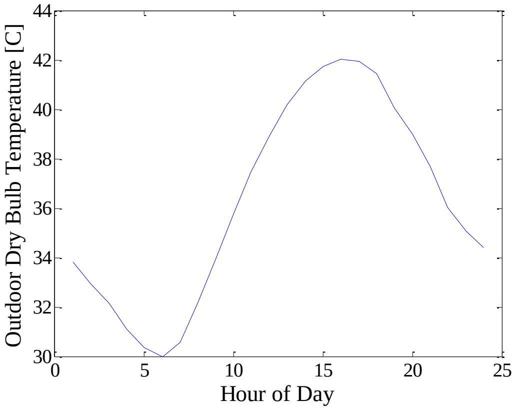

Fig. 4: Outdoor dry bulb temperature.

The profiles of the compressor operating with the cooling load and with the thermal storage are shown in Figure 5.

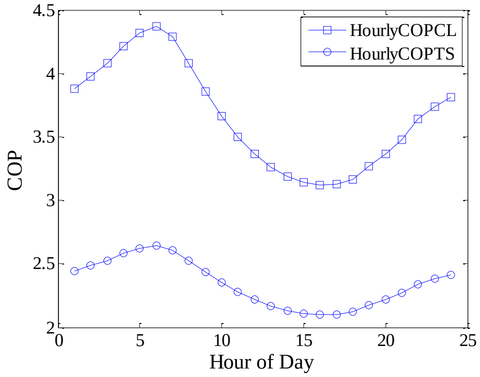

Fig. 5: Hourly COP for cooling load and thermal storage.

In Figure 6, the cost for electricity from the weekday super-peak rate plan for each hour is shown, where time 0 gives the cost for the hour following midnight.

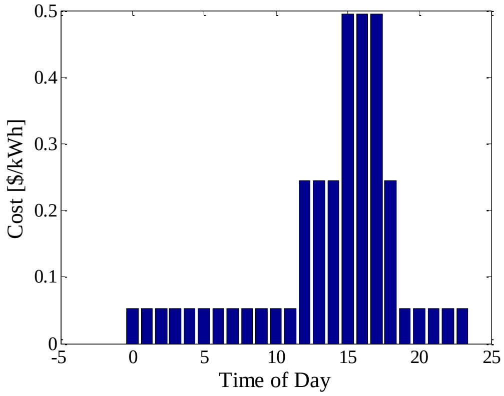

Fig. 6: Peak rate plan.

For a conventional system, the usage is given in Table 1. The upfront cost for purchase and installation of the air conditioner is estimated to be $5400.

TABLE 1: CONVENTIONAL SYSTEM

	July Energy	July Cost
Air Conditioning	1611 kWh	$269
Water Heating	483.6 kWh	$25.4

For a system optimized to have the highest return after 10 years, the system component sizes are given in Table 2. This requires the thermal storage to be discharged at 0.007 gal/s, to meet the cooling load.

TABLE 2: SYSTEM COMPONENT SIZES

Compressor (DC)	2.707 kWe
Chest Freezer	24.8 ft^3 (0.7 m^3)
Volume of Water	148.3 gallons (561.4 L)
Capacity of Battery	0 W
Solar array size	0 ft^2 (0 m^2)

The corresponding upfront costs are provided in Table 3.

TABLE 3: UPFRONT COSTS

Compressor Install	$400
Compressor Cost	$3384
Thermal Storage Install	$200
Thermal Storage Cost	$744
Total	$4728

Table 4 gives the energy and cost of running this system. The savings compared to the performance of the conventional system are also included in Table 4.

TABLE 4: SYSTEM USAGES

	July Grid Energy	July Cost
Air Conditioning	1427 kWh	$75
Water Heating (DC)	483.6 kWh	$25.4

Total Used	1911 kWh	$100.4
Total Saved	175 kWh	$194

This system has a relatively low upfront cost of $4728 due to the smaller compressor and a high savings as a result of replacing grid power with the stored thermal energy during peak rate hours. For a period of 10 years, the expected savings compared to a conventional system is $6700.

Based on the assumptions about the thermal storage insulating efficiency, approximately 11 kWh of energy is lost from the thermal storage. If the thermal storage is located in the cooled space, this will only contribute to the space cooling. Otherwise, this is lost energy, and the efficiency could be even lower if the tank is in a warmer space.

The electricity required for cooling using the conventional, full-sized air conditioner is shown as Conventional Demand in Figure 7. For the system setup optimized by the model, the maximum amount of cooling supplied from the compressor is shown by System Cooling. Since in this case, the demand during peak hours is met entirely for thermal storage, the lower System Cooling during that time is irrelevant. The lack of photovoltaic output for this system is also shown in Figure 7.

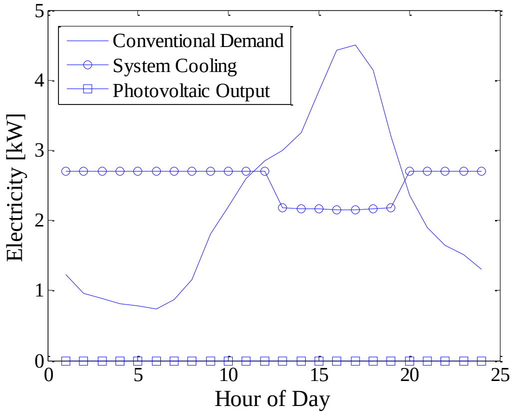

Figure 7: Electricity for cooling.

The actual electricity that is used to meet the cooling load of the indoor space is shown in Figure 8.

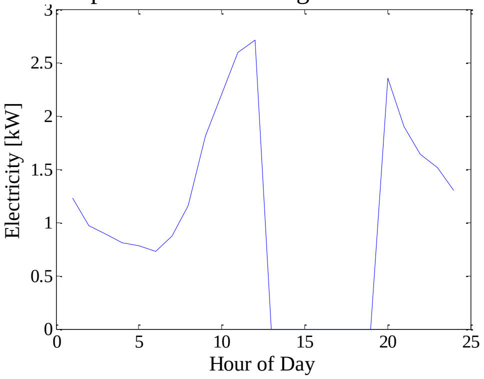

Fig. 8: Grid electricity to meet cooling load.

The electricity that is not needed for the cooling load is used to generate thermal energy for storage, which occurs according to the profile in Figure 9.

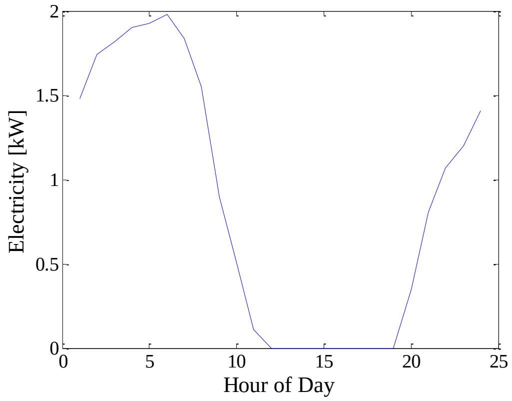

Fig. 9: Grid electric demand to charge thermal storage.

The resulting capacity that is stored in the thermal storage tank at each hour provided in Figure 10, where the minimum capacity occurs at the end of the peak rate hours.

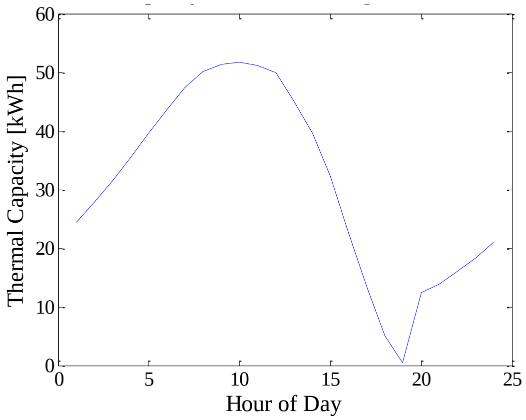

Fig. 10: Thermal storage daily capacity profile.

The charge and discharge of the thermal storage is shown in Figure 11, where the integrals of the two curves are approximately equal.

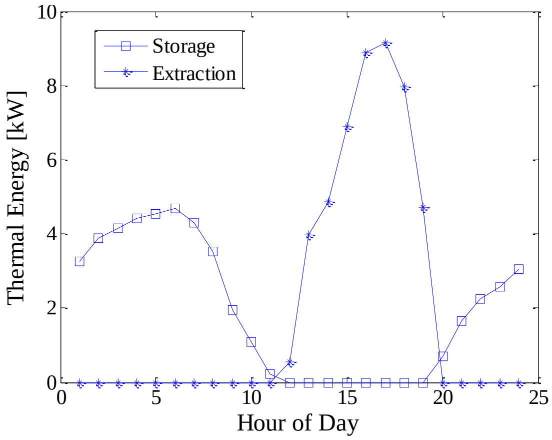

Fig. 11: Storage and extraction profile.

The output of the model is not only the design of this system but also a chart providing the performance of each of the system setups that it analyzed. As a result, it is possible to review the chart to find a preferred system setup or compare the results for different system designs.

When the model was run with no peak rate, the thermal storage was ineffective at providing cost savings. For a lower cost of solar panels or a higher cost of thermal storage, the system design would instead include a solar array. The energy saved would be much higher in this case, and a smaller size thermal storage tank could be used. If the optimized parameter is energy saved instead of cost, the solar array would be in the chosen system.

The high battery cost also limits the feasibility of battery use in the system, although for a lower cost it would be an effective storage system. The system does effectively use storage to offset the peak energy demand and therefore contribute to grid-scale smoothing of the energy demand curve.

For a house that has a cooling demand which is low during the peak hours, but very high immediately afterwards, such as a house where people are gone during the daytime, this system would not provide as much cost savings. However, the thermal storage could supplement the air conditioner in order to cool the house faster or allow a smaller air conditioner to be used. If the owner desires a photovoltaic array, but wants to use the generated electricity, this system would store the energy for them to use. For a house located in a climate with a lower cooling load, the savings would be correspondingly lower. However, using the system for heating and heat storage is a possibility for cold climates.

5. CONCLUSION

The solar powered ice thermal storage system is effective for some circumstances. The model is useful for evaluating whether the system would work and what its cost and savings would be for each situation.

6. FUTURE WORK

In order to fully evaluate the proposed system, testing on a prototype needs to be completed to support the assumed performance characteristics. The full system also needs more development of the control system to optimally utilize the photovoltaic power generated and to optimize charging of the thermal storage system to be most effective in real-world situations. The system is also a heat pump which can run in forward (cooling) and reverse (heating) directions, which can be included in the model. The model could also be expanded to include a comparison with the costs and benefits of an AC compressor. Better analysis of the heat transfer losses in the thermal storage tank would improve the model. In addition, analysis of design improvements for increasing the efficiency of the thermal storage heat transfer, such as using a barrel-shaped tank, would help to improve the system. An in-depth thermodynamic model along with experimental data would allow for a complete understanding of the advantages of the system.

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