Session 12-14

A TRNSYS Model of a Solar Thermal System with Thermal Storage and Absorption Cooling

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Abstract

A combined flat plate and vacuum tube solar thermal array on the roof of the University of New Mexico Mechanical Engineering building is used to produce hot water. The hot water fires a lithium bromide absorption chiller in the summer and flows through heating coils in the winter, providing cooling and heating respectively. To overcome problems associated with intermittent insolation, an insulated concrete tank is used for hot thermal storage. Additional concrete tanks without insulation are used to store chilled water. These cold storage tanks are used as the primary chilled water source to meet the cooling load, while the absorption chiller provides additional cooling during peak load periods. The cold storage tanks are cooled by a district chiller at night when district chilled water demand and the cost of electricity are low. TRNSYS, a transient systems simulation program with a modular structure, is used to model and predict optimal operating conditions of the solar array working in combination with the thermal storage system, absorption chiller and cooling system. This research enhances engineering education for undergraduate and graduate students at the University of New Mexico. Also, key concepts from this research are translated into standards-based middle school science curriculum.

Introduction

In response to concerns about sustainability, energy conservation, global warming, rising fuel prices and the current geopolitical climate, faculty and students in the Mechanical Engineering (ME) Department at the University of New Mexico (UNM) are taking steps to demonstrate methods which will result in drastic reductions in the carbon footprint of building operations. Often overlooked, building operations total close to 40% of primary energy consumption in the United States and Europe[1,2]. Moreover, there is ample scope for reducing the energy consumption in buildings due to the pervasiveness of wasteful practices and designs. This paper is focused on optimizing the operating parameters related to recent upgrades to the heating ventilation and air conditioning (HVAC) system in the UNM Mechanical Engineering building. These upgrades include the addition of flat plate solar collectors, vacuum tube solar collectors, an absorption chiller, a heat exchanger and the refurbishment of some thermal energy storage (TES) tanks. The optimized system will extract maximum useful cooling and heating from the solar array and deliver this energy to the building. A TRNSYS model is used to optimize the system by evaluating its performance with varying operating parameters. By providing heating and cooling to the building from this renewable energy source, both the carbon footprint and operating costs of the Mechanical Engineering building will be reduced.

Literature Review

Pongtornkulpanich *et al.*[3] describe a system installed in Thailand consisting of a 10 ton $LiBr/H_2O$ absorption chiller, 72 m^2 of vacuum tube solar collectors, stratified thermal storage (400 l of hot storage and 200 l of cold storage) and an auxiliary water heater. The auxiliary water heater allows the absorption chiller to be the only source of chilled water (CHW) to cooling coils under all environmental conditions. The control strategy for this system is based on the solar array outlet temperature. If the solar array outlet temperature reaches 75°C, then the absorption chiller is turned on. When insolation is low, this system is operated at the lower threshold of recommended absorption chiller hot water inlet temperature. The auxiliary heater ensures hot water supply is at least 70°C. The chiller is sized to cover 150% of the calculated maximum cooling load. This project demonstrates the technical viability of absorption chillers. The project economics were dominated by the capital cost of the absorption chiller and the solar collector array which, to date, are still very expensive. A conventional vapor compression cycle has lower capital costs that can be offset by the lower operating costs of an absorption chiller installation. Advances in absorption chiller technology and higher electricity prices would make solar absorption chillers more economically viable.

Running chillers and boilers off peak and storing hot or cold water in thermal energy storage can produce savings if the utility offers discounted off peak electrical rates. This practice also helps the utility to run efficiently by decreasing the difference between high and low demand peaks.

Wildin[4] describes the design and operation of the original UNM Mechanical Engineering building TES. He concludes that stratified thermal energy storage can be achieved for typical HVAC applications without the use of partitions inside the tank. Stratification is accomplished by the use of linear diffusers for both hot water inlet and cold water exit. For an approximately cubed shape tank, it is recommended that the diffusers have the same orientation where the hot diffuser is located at the top of one side of the tank and the cold diffuser is located at the bottom of the opposite side of the tank. This arrangement avoids mixing by producing low velocity, uniform temperature fluid flow in and out of the tank. The equipment that uses stored hot and cold stratified water must maintain the design temperature difference across storage inlet and outlet to avoid stratification degradation. This difference in inlet and outlet temperature must also be maintained during tank charging. Constant inlet and outlet temperatures help to maintain stratification. A stratified tank can store more useful energy than a mixed tank.

Experimentation and models of smaller systems led to the conclusion that an optimum volume of a TES tank exists. A larger than optimal tank does not charge fast enough to reduce auxiliary equipment use. A smaller than optimal tank loses capacity too quickly. For one system modeled, the optimum storage volume is defined as 75 kg of water per square meter of collector area[5]. Li and Sumathy[6] found similar results of decreasing system coefficient of performance (COP) with an increase in tank volume. Conversely, an undersized storage tank is described as not being able to effect solar cooling in the late afternoon. With the results of these computer models and experiments in mind, storage tank volume can be considered an important design consideration regarding the reduction of grid peak electricity demand and solar heating/cooling system efficiency.

Absorption chillers are a mature technology with a range of medium to large scale capacities[1]. Absorption involves mechanical retention, as in the way that a sponge retains water[7]. In this application absorption refers to a liquid acting like an absorbent sponge to absorb a refrigerant, forming a liquid solution. This liquid solution is then pumped to a higher pressure. The high pressure solution is pumped into a generator that separates the solution into absorbent liquid and refrigerant vapor. Analogous to a sponge being squeezed to force out the water that it had absorbed, the refrigerant vapor is separated from the absorbent liquid by adding heat. The absorbent liquid goes back to the absorber to absorb more refrigerant and the refrigerant vapor is passed through to the condenser. Heat leaves the refrigerant in the condenser to cooling water before it goes through an expansion valve to an evaporator. In the evaporator heat is transferred to the refrigerant from water. Hence, CHW is produced. After that, the refrigerant is back where it started and is ready to be absorbed by the liquid absorbent once again[8].

Building

The ME building is located at the central campus of the University of New Mexico in Albuquerque, New Mexico, where sunshine is abundant and cooling loads dominate for well insulated buildings. The ME building was built in the late 1970s to demonstrate energy conservation technologies. It is a 6,040 m^2, 5 story building with high insulation and high thermal mass. The building has air locks at all entrances to reduce heating and cooling loads caused by infiltration during periods of high traffic. The window area of the building is relatively small at 5% of the floor area. Further, there exist 8 concrete TES tanks with a useful volume of 53 m^3 each[9].

System

Figure 1 shows the major components when the system is in cooling mode. CHW can be provided to the cooling coils from cold storage and from the absorption chiller, separately or in tandem. The flow rate of CHW from cold storage to the cooling coils is variable and can be set based on the cooling load and amount of CHW supplied from the absorption chiller.

The preferred source of energy for meeting the cooling load is with CHW from the absorption chiller. To produce CHW, hot water is drawn from the top of the hot storage tank to fire the absorption chiller. The water is then returned to the bottom of the hot storage tank at a lower temperature. Water from the bottom of the hot storage tank is pumped through the solar collector array, heated and returned to the top of the hot storage tank. The outlet temperature of the solar array water loop into the hot tank is maintained at a set temperature using a three way bypass valve. The control system calculates the amount of heat that is added to the hot storage tank. When a set amount of heat is added to the hot storage tank, the absorption chiller is started. While the absorption chiller is running it supplies CHW to the cooling coils, reducing the flow rate of CHW from cold storage. As long as there is a set minimum amount of insolation hitting the solar collectors, water continues to be pumped from the hot tank and through the solar array, adding more heat to the hot tank. The absorption chiller continues to run until the absorption chiller hot water supply drops below a set temperature. At this point, the absorption chiller is turned off and CHW from cold storage meets the entire cooling load while necessary. The cold storage tanks will be charged by rejecting heat to a district CHW system via a plate-and-frame heat exchanger at nighttime when the university can take advantage of reduced off peak electricity rates.

The parameters available for optimization in cooling mode are solar array exit temperature, temperature differential through the absorption chiller, solar collector tilt angle, hot storage tank volume, amount of heat collected in the hot tank before absorption chiller activation, absorption

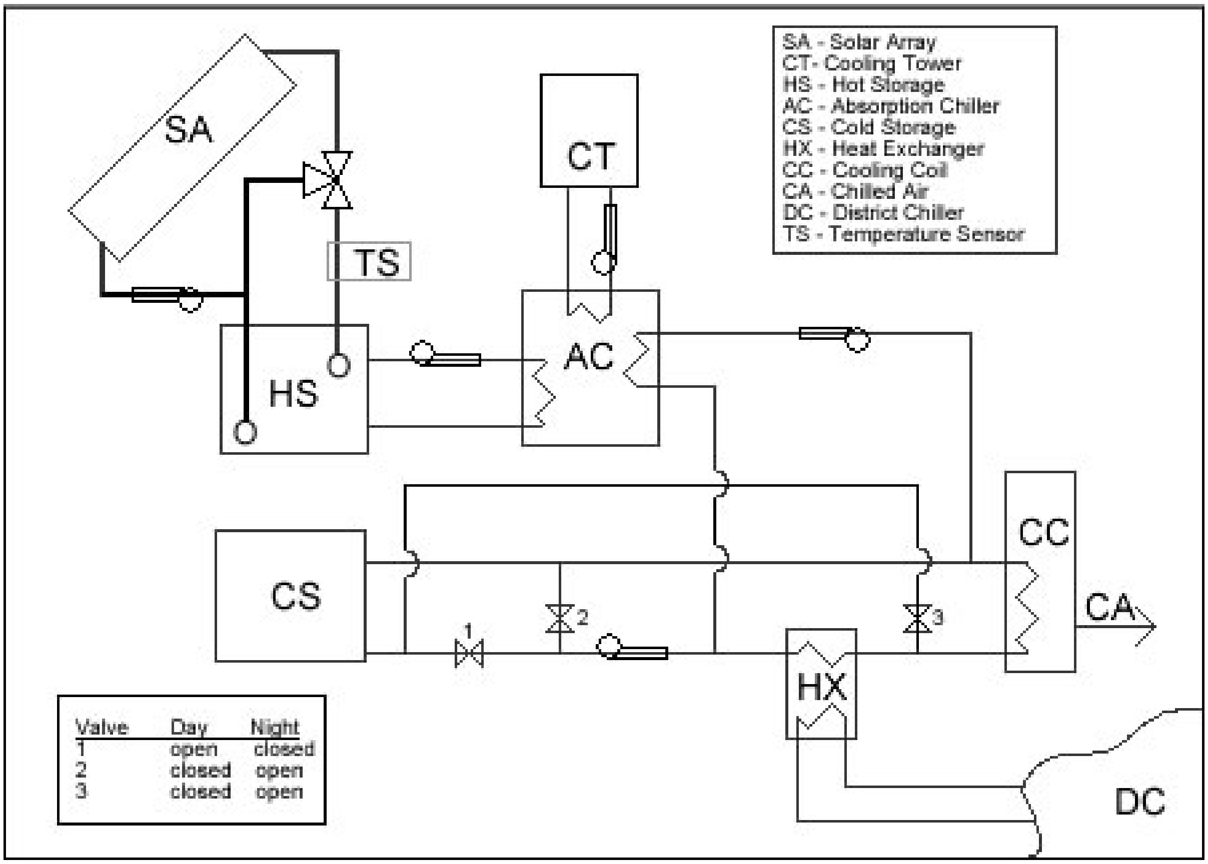

Figure 1: Cooling mode schematic

chiller hot water supply shut off temperature, amount of sufficient insolation to run solar loop, cold storage tank volume, amount of nighttime district chilling necessary for the next day and the flow rate to the cooling coils from cold storage.

Figure 2 shows the major components when the system is in heating mode. In heating mode hot water is pumped from hot TES through heating coils to meet the heating load. This water is heated by being pumped from the bottom of the hot storage tank through the solar array and then back into the top of the hot storage tank. If required, the water extracted from hot TES is heated additionally by steam from district waste heat recovery or a district boiler. The outlet temperature of the solar array water loop in heating mode is controlled in the same fashion as in cooling mode except that the set temperature into the hot tank is about 30° C lower. As long as there is a set minimum amount of insolation hitting the solar collectors, water continues to be pumped from the hot tank and through the solar array, adding more heat to the hot tank. To avoid freezing, when the outside temperature drops to 5° C and solar irradiation is below a set limit, (typically at night) water is pumped from the cold tanks through the solar array and then back into the cold tanks.

The parameters available for optimization in heating mode are the solar array exit temperature, solar collector tilt angle, hot storage tank volume and amount of sufficient insolation to run the solar loop. Finally, the carbon footprint can be further optimized by the appropriate choice of transition points between heating and cooling modes.

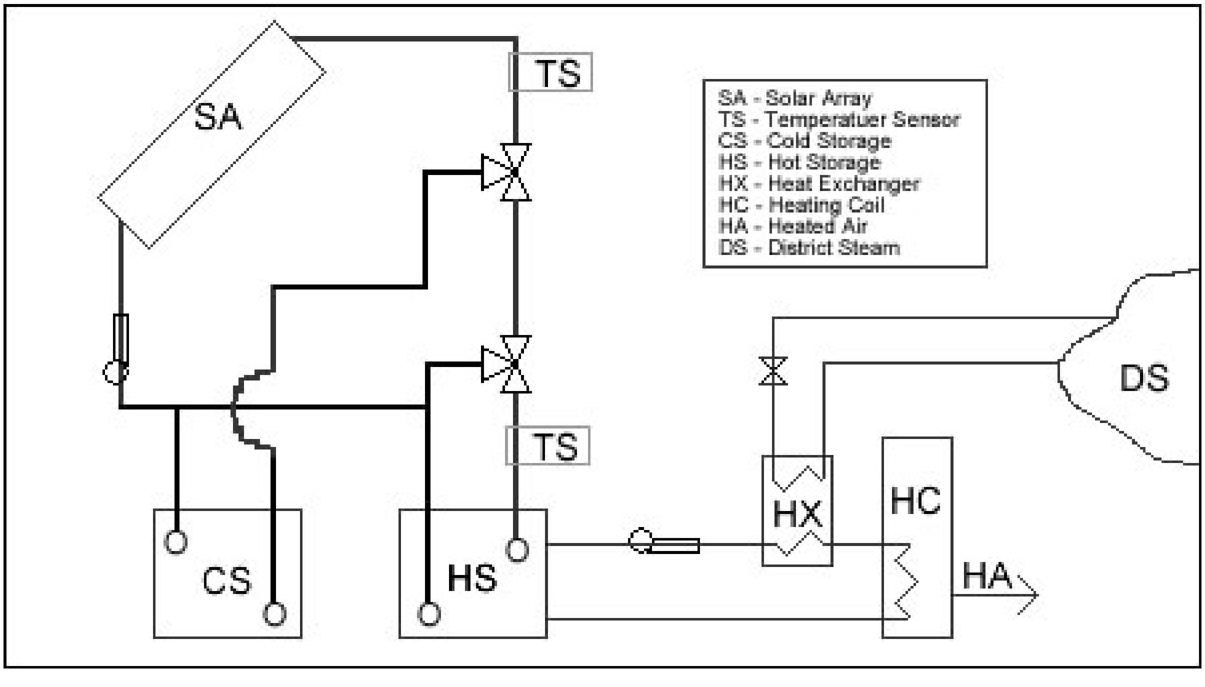

Figure 2: Heating mode schematic

Solar Array

The solar array consists of 126 m^2 of flat plate collectors and 108 m^2 of vacuum tube collectors mounted on the roof of the UNM Mechanical Engineering building. The flat plate collectors are legacy double glazed Lennox LSC18. The vacuum tube collectors are Sunda Seido 1-16. The tilt angles of the Lennox and and Sunda Seido collectors are 25° and 35° respectively. This is slightly biased toward maximization of heat absorbed by the flat plate array in summer, when the cooling load is highest. Water from the hot storage tank is first routed through the flat plate array, then to the vacuum tube array to maximize efficiency.

Thermal Storage

The thermal storage tanks have been part of the building since construction. Each of the seven cold tanks has a volume of 53 m^3. The refurbishment of the tanks includes the addition of liners to prevent leaks. The hot storage tank is insulated with an 8 inch thick exterior layer of polystyrene foam and a 4 inch thick interior layer of polyurethane foam. These layers of insulation are set between the concrete and the plastic liner, reducing the volume of the tank to 35 m^3.

We will take advantage of thermal stratification, where buoyant warm water naturally rises to remain at the top of the tank, while dense cold water sinks to the bottom of the tank[4]. This improves overall system efficiency as water from the top of the tank, with the highest possible energy content, is used to fire the absorption chiller. Similar efficiency advantages are at work in the solar loop, the cooling loop and the heating loop.

The TES tanks have the potential to reduce utility costs through load management[4], to allow independent energy collection and extraction, and, to reduce the effects of intermittent sunlight on the system[1]. Wildin[4] saw the entire daily cooling load for the summer of 1982 met by three cold tanks. Increased building load resulting from increased occupancy and increased use of electronic devices may require additional tanks in the current system.

Wildin[4] defined thermal efficiency for a TES tank as the integrated capacity supplied by storage during discharging, divided by the integrated capacity supplied to storage during charging. The thermal efficiencies of the storage tanks in the UNM Mechanical Engineering building were studied in the 1980s. 81% was the highest monthly efficiency achieved during winter for a hot tank without insulation. The average monthly efficiency during winter for a hot tank without insulation was 73%. Cold storage tank thermal efficiencies were found to range from 80% to 90% during summer.

Absorption Chiller

The absorption chiller is a Yazaki single effect LiBr/H_2O model SH20. Water is the refrigerant and lithium bromide is the absorbent. This vapor absorption cycle (VAC) has four liquid flows that interact with other HVAC system components. Hot water from the hot storage tank supplies heat to the VAC generator. The VAC absorber and condenser have separate water inlets and outlets for cooling water that extracts heat from these VAC components. This warmed cooling water is circulated through a cooling tower. Lastly, CHW flows from the VAC evaporator to cooling coils to meet the cooling load.

This 20 ton absorption chiller is designed to work with hot water supply temperatures in the range from 70°C to 95°C, with the COP increasing with temperature. However, since the solar collector efficiency decreases with higher temperature, the optimal operating temperature for the system as a whole is not necessarily achieved by using the highest temperature to fire the absorption chiller. We plan to calculate the optimum operating temperature using TRNSYS and verify the results with long-term performance monitoring of the real system.

TRNSYS Model

TRNSYS is modular simulation software that models thermodynamic interactions over time. TRNSYS can be used to model a vast array of energy/building systems, and is particularly suited to solar energy applications. Typical meteorological year data for a number of locations is available in the TRNSYS libraries to simulate weather conditions. A comprehensive library of components are available as separate interactive modules[10]. Creating a TRNSYS simulation consists of identifying the modules that will accurately model the components in a system, connecting these modules appropriately and setting the parameters to mirror the operating conditions of each module in the real system.

A working model of the UNM ME Building has been created in TRNSYS. The solar loop portion of this simulation is shown in figure 3. As an example optimization, with all other parameters constant, the tilt angle of the solar thermal collectors in this solar loop were varied from 5° to 40° in search of the position that maximizes insolation in July. Figure 4 shows data collected for 9°, 20° and 30°. 9° was found to have the most useful energy gain in July.

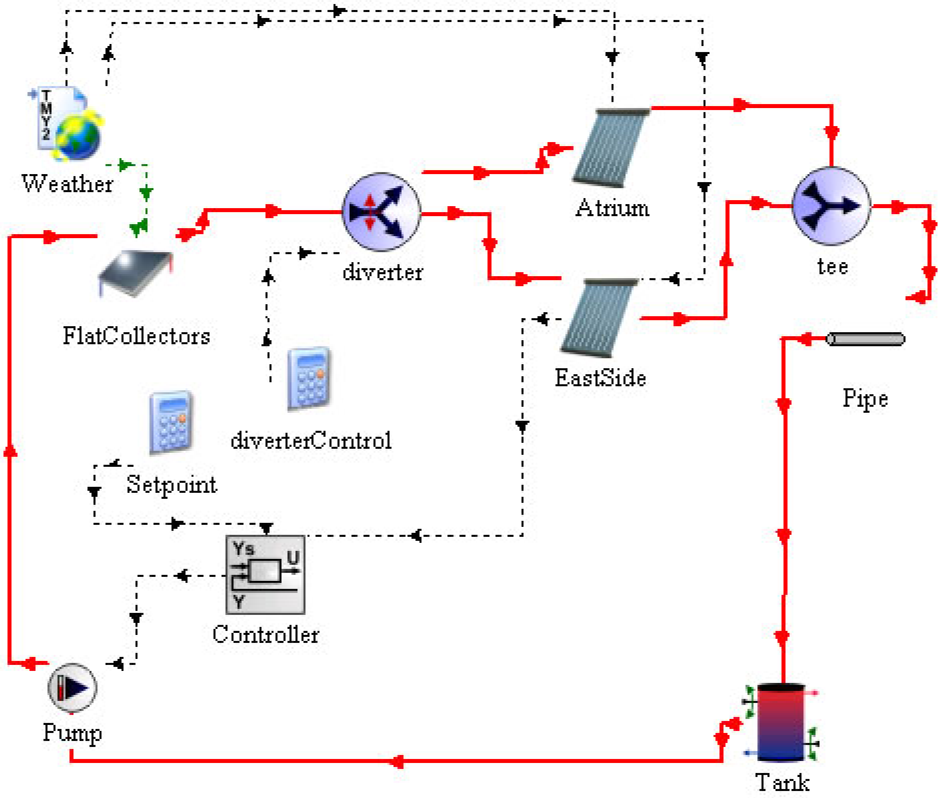

Figure 3: TRNSYS solar loop

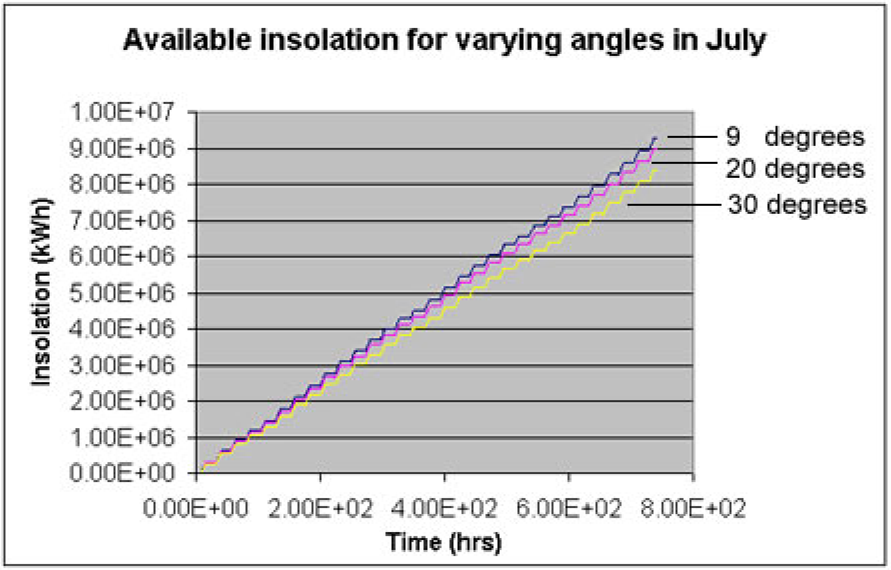

Figure 4: Available insolation at different angles for the month of July

Carbon Footprint

A vapor absorption cycle (VAC) offers environmental benefits over a vapor compression cycle (VCC). The average specific volume of the liquid solution in a VAC is much less than that of refrigerant vapor used in a VCC. This means that less work is required to pump the solution in an absorption chiller using a VAC compared to the work required to compress gas with a VCC[8]. Further, the VAC has a thermally driven generator in place of a mechanically driven compressor in the VCC. The VAC can be driven by thermal energy from solar collectors or from the waste heat of industrial processes[3]. VAC can provide effective cooling with less electricity input than with VCC.

It may be expected that chilling water over night and storing it for daytime use might increase the carbon footprint of the ME building due to losses during storage. In a previous study, the cold tanks were found to have a thermal efficiency up to 90%[4]. There are clear losses to the surroundings. There are three factors that can offset this energy loss during storage. First, off peak energy is, in general, produced more efficiently on a large scale, in contrast to smaller systems that are started up in the daytime to meet peaks in demand. This is dependent on the mix of local utility electricity sources. Second, in New Mexico there exist wind generating plants which have zero carbon emission. Since nighttime charging matches peak wind energy production, energy lost during cold storage is not energy that comes from burning fuel. Lastly, cooler nighttime outside temperatures make the nighttime cold TES charging with electric chillers more efficient than in the daytime due to higher cooling tower efficiency.

Economics

In this life cycle analysis of the UNM ME building HVAC system, 4 different possible cooling configurations are analyzed. Fuel and capital expenses are normalized with present value calculations. Capital costs are paid in cash at time zero. We assume that the cooling season runs from March to October inclusive. For this period, thermal energy collected from solar collectors is used to fire the absorption chiller, producing 1440 hours of 20 ton cooling capacity in a year. Only non-negligible energy purchased from the utility to produce cooling is included in the fuel costs. Electricity used to run the solar pump is included in the cost calculations. The benefits related to reduced heating costs in configurations making use of solar energy are not considered in this cost comparison. Heated water supplied to the heating coils in the building is considered free energy from one of two different sources, the solar collectors and heat recovery from district electricity generation.

The first configuration is what was actually implemented. It includes solar thermal collectors, absorption chilling, cold and hot water storage along with chilled water supplied from a district chiller. The second configuration is the same as the first except that cold storage is not included. Not having cold storage decreases the capital costs and increases the electricity rate since the district chiller would supply chilled water during peak electricity demand. Conversely, the use of cold storage increases capital costs and takes advantage of lower off peak electricity rates by charging TES at night. The third configuration excludes absorption chilling and simply considers using district chilled water along with cold storage. The last configuration involves just district chilled water supplied directly against the cooling load.

Table 1 displays itemized capital costs included in this project. Table 2 is a calculation of fuel costs associated with the 4 configurations. A fuel inflation rate of 10% and a discount rate of 7% were used in these calculations. Almost 45% savings in fuel costs are seen with configurations that use TES. Table 3 gives totals for capital costs that would be a part of each different configuration. Configurations that do not include cold storage do not have cold storage costs added to that configuration's capital costs.

Table 4 shows the total fuel costs added to capital costs for each of the four configurations. A minimal savings in total cost is achieved with the configuration that employs the district chiller with TES. This savings can be attributed to special electricity rates afforded to UNM. The peak and off peak electricity rates can vary widely in the U.S. Larger district utility users can negotiate these rates with the utility. The larger the difference between peak and off peak electricity rates, the higher the savings that can be achieved by using TES. Options that use absorption chilling are much more expensive.

Educational Value

Future energy use can be influenced by energy education provided to mechanical engineers of the future. The UNM Mechanical Engineering Solar Project is more than renewable energy. It is an educational example of renewable energy. The solar project has already enhanced the graduate education of students focusing on energy related topics. Integration of renewable energy and sustainability topics into undergraduate classrooms is a way to promote wise use of natural resources to a large number of future engineers[11]. Through the GK-12 Fellowship, a National Science Foundation funded grant, energy topics related to this research have been taught by graduate students and education professionals in K-12 classrooms.

There are three graduate students that are pursuing projects related to the Mechanical Engineering Solar Project. The topics being studied are measurement and optimization of

Component Number	Component	Cost $1000
1	Flat Plate Collectors	30
2	Vacuum Tube Collectors	45
3	Absorption Chiller	28
4	Pumps and Batteries	10
5	Roof Piping	50
6	Building Piping	100
7	Controls	50
8	Heat Exchanger	20
9	Storage Tanks	32.5
T	Total	363

Table 1: Individual component capital cost

Configuration	Fuel Cost $1000
Absorption Chiller And District Chiller With Storage	16
Absorption Chiller And District Chiller No Storage	36.5
District Chiller With Storage	27
District Chiller No Storage	61

Table 2: Present value of fuel cost over 30 years of operation

Configuration (Included Components)	Capital Cost $1000
Absorption Chiller And District Chiller With Storage (T)	365.5
Absorption Chiller And District Chiller No Storage (1-8)	333
District Chiller With Storage (6-9)	177.5
District Chiller No Storage (6-8)	145

Table 3: Present value of capital cost for different configurations (Component number referenced from table 1)

Configuration	Fuel And Capital Cost $1000
Absorption Chiller And District Chiller With Storage	381.5
Absorption Chiller And District Chiller No Storage	369.5
District Chiller With Storage	204.5
District Chiller No Storage	206

Table 4: Present value of fuel and capital costs over 30 years of operation

solar-assisted heating/cooling, building performance simulation and the holistic economics of solar thermal energy when the system is actively interacting with the electricity grid. The scope of the system is wide enough that many more topics may be explored[11].

Incorporating renewable energy topics into core undergraduate mechanical engineering curriculum makes these courses more interesting and introduces students to a wider array of energy problems and solutions. Students in the heat transfer class have completed a project where they designed efficiency tests for solar thermal collectors. The possibility exists for the heat transfer class to be enhanced by conduction, convection and radiation labs based on solar thermal collectors. All mechanical engineering graduating seniors at UNM are required to take a senior design course. The solar system is available for interested senior design teams[11].

A graduate student working on the solar project is employed as a GK-12 Fellow. This student works as a visiting scientist in Albuquerque Public School science classes. GK-12 Fellows research and create labs and assist students and teachers with science learning and understanding. Energy topics related to the solar project have been taught at a middle school level. It is the goal of all parties involved with the GK-12 program to inspire scientists and engineers of the future. The Mechanical Engineering building solar project along the GK-12 Fellowship have the potential of steering careers toward one of the most important challenges facing society today.

Conclusions

1. The life cycle analysis for the UNM ME buildiing shows minimal cost savings as a result of energy storage. This savings would be greater in the absence of the reduced peak electricity rates charged to UNM. The district chiller with TES was found to be the most economical of the configurations studied. In general, bigger differences between peak and off peak electricity rates would make use of TES through nighttime charging more attractive. A small or absent difference between peak and off peak electricity rates makes TES systems less attractive because of unrecoverable capitol costs.

2. Advantages other than economic may result from widespread use of thermal energy storage, including more efficient energy infrastructure operations and possibly lower overall building operations carbon footprint.

3. Although wind generated electricity is currently the lowest cost renewable energy source, it has the problem of being in high supply when demand is low. Nighttime charging of cold storage tanks shifts the demand for wind energy to a time when wind energy is in supply.

4. Total district steam and electricity used to heat and cool the UNM Mechanical Engineering building will be decreased as a result of the HVAC system upgrades.

5. Thermal energy storage tank size is an important design consideration. TES tank size affects system efficiency and the ability to reduce utility peak electricity load.

6. The UNM Mechanical Engineering building solar project, used for research and studies as an integral part of engineering education, makes the UNM ME department a scholastic center of renewable energy and sustainability education. The UNM ME building solar project enhances engineering education and recruitment.

7. With the current electricity rates available to UNM, solar fired vapor absorption chilling capital costs are not recovered by lower running costs.

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