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Operation of Cool Thermal Energy Storage to Increase Renewable Energy Utilization

Amy Van Asselt
University of Wisconsin, United States of America, avanasselt@wisc.edu

Douglas T. Reindl
University of Wisconsin, United States of America, dreindl@wisc.edu

Gregory F. Nellis
University of Wisconsin, United States of America, gfnellis@engr.wisc.edu

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Amy VAN ASSELT*, Douglas T. REINDL, Gregory F. NELLIS

University of Wisconsin – Madison, Department of Mechanical Engineering,
Madison, WI, USA
avanasselt@wisc.edu

* Corresponding Author

ABSTRACT

Recent international agreements on climate change aim to increase the production of electricity derived from renewable energy resources. Renewable energy generation can be pursued on both an individual building and utility scale. Due to the intermittent nature of renewables, some form of energy storage is essential to bridge diurnal mismatches between generation and demand. Air-conditioning loads associated with commercial buildings dominate peak electricity demand on the utility grid in some areas and climates. Therefore, Cool Thermal Energy Storage (CTES) is a relatively technically mature and inexpensive means of providing this "storage" and balancing supply/demand mismatches, thereby enabling the success of increased renewable energy penetration. Electrical energy generated by renewables during periods of higher availability can be used to run chillers that charge CTES systems. The stored thermal energy can subsequently be used to meet air-conditioning demand during periods of low renewable energy resource availability.

In this work, the U.S. Department of Energy Commercial Reference Building Model for a secondary school is used to obtain simulated cooling loads that are met by a combination of two chillers and a stratified chilled water thermal storage system. Control strategies are designed to charge the thermal storage system when renewable resources are available and discharge storage to meet building cooling loads during periods with low or no renewable energy resource. One optimization target is the fraction of the chiller energy consumption met by renewable power. This metric is one that may be of interest to electric utilities trying to manage a grid with increasing renewable penetration. An alternative optimization target is the net economic benefit to the building owner assuming on-site, small scale renewable generation and thermal storage. This metric is based on equipment costs, net electric demand after wind and/or solar generation offsets the chiller electric demand, and time-of-use electricity rate structures.

The results show that there is a trade-off between maximizing the use of renewable power and life-cycle cost, but a storage system designed to optimize either variable will be more cost effective and utilize the renewable resource better than a system without storage. The analysis is carried out for locations in Texas and California. These results suggest that CTES may be a technology enabling utilities to reach higher penetration of renewables while avoiding the so-called "duck curve" generation ramp caused by the time mismatch between the renewable generation and demand peaks.

1. INTRODUCTION

The demand for electricity varies significantly on both a seasonal and diurnal basis. This variation is driven by cooling load differences between winter and summer as well as the daily peaks that occur as a result of typical work schedules. Myers, et al (2010) evaluated the impact of varying penetration rates of solar energy technology to meet the aggregate load in Wisconsin. In 2002, the aggregate peak utility demand in Wisconsin was 13,200 MW. The analysis showed that the deployment of 6,600 MW of photovoltaic capacity (50% of the utility aggregate peak) only reduced the grid demand for electricity from traditional generation sources by 4.3%. The minimal reduction in peak electrical demand even with such a large renewable energy deployment is due to the mismatch between the peak solar energy electricity production (which occurs around noon) and the utility load peak (which occurs at approximately 4 p.m.). The authors of this work noted that the future success of large-scale penetration of renewable energy technology, such as photovoltaics, hinges on cost-effective and reliable energy storage technologies.

At a utility level, the intermittent nature of renewable energy production, coupled with the obligation to provide firm supply with a high degree of reliability, has created both operations and capital challenges. From an operations perspective, utilities have been challenged with significant grid dynamics created by the rapidly changing electricity production rates from renewable energy sources that occur coincidently with changing customer demand. Evidence of such dynamics includes utilities experiencing very high electricity production ramp rates and base load generation encroachment (over-generation). The California Independent System Operator (CAISO) region has been observing these specific issues due to increased solar electricity production as shown on the popular "duck curve" shown in Figure 1 (CAISO, 2013). From a capital perspective, utilities have not experienced a reduction in fixed asset generation or transmission/distribution requirements due to the growing deployment of renewable energy generation. On the contrary, utilities have had to increase investments in transmission, distribution, and grid controls in order to accommodate the increased renewable energy generation. They have not been able to forego investments in traditional generation assets due to the renewables' inability to provide firm generation capacity.

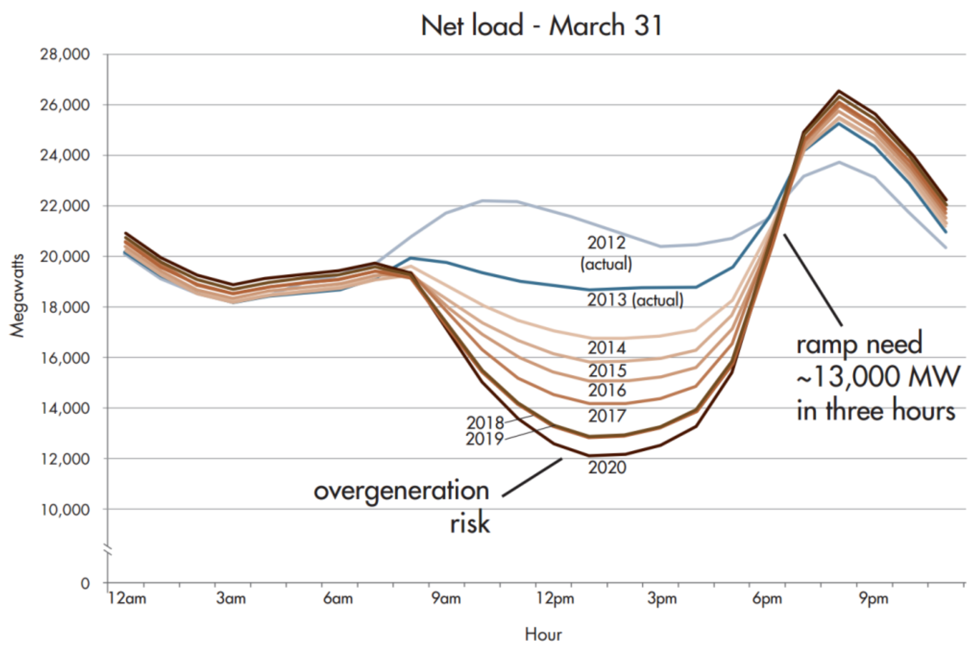

Figure 1 CAISO "duck curve" showing over-generation risk and ramp rate (2013)

Cool thermal energy storage technology is a cost-effective, mature, and high efficiency energy storage technology that has the potential to bridge mismatches between renewable energy production and utility aggregate demands. By operating energy-intensive building chilling systems to charge thermal storage systems during periods when renewable energy resources are available and then discharging the stored thermal energy with chillers idle to meet building air-conditioning loads during periods of resource unavailability, CTES offers the potential to enable a more effective utilization of electricity produced from renewable energy resources. Our hypothesis is that, beyond electricity cost savings, CTES can cost-effectively enable a significantly greater penetration of renewable energy production than currently exists today. The overall objective of this work is to evaluate the potential benefits of thermal energy storage as an enabling technology that will allow a more effective penetration of renewable energy generation.

2. MODELING

2.1 System Models

A chiller plant that directly meets the facility load without storage is used as a baseline comparison for CTES system options. This system is referred to as the no-storage case throughout this work. The chiller for the non-storage system operates anytime the building experiences a cooling load. The fluid flow rate is variable and adjusted to maintain a chilled water temperature differential of 10°F (5.5°C). The installed chiller capacity is sized to meet the annual peak cooling load. The model consists of two equally sized chillers for both redundancy and improved efficiency at part-load operation.

Figure 2 shows the CTES system modeled in this work with a storage tank decoupling the cooling load from the air-cooled chillers. In a stratified chilled water storage system, a single tank stores thermal energy by utilizing water's natural tendency to stratify – warmer, less dense fluid gathers at the top and cooler, more dense fluid moves to the bottom. During a charge cycle, cool water from the chiller is supplied to the bottom of a tank where it is available to subsequently be withdrawn from the bottom of the tank and supplied to meet building loads during its discharge cycle. The discharge cycle can proceed with or without chiller operation. The CTES-based chilling system is designed to operate with a 20°F (11°C) water temperature differential.

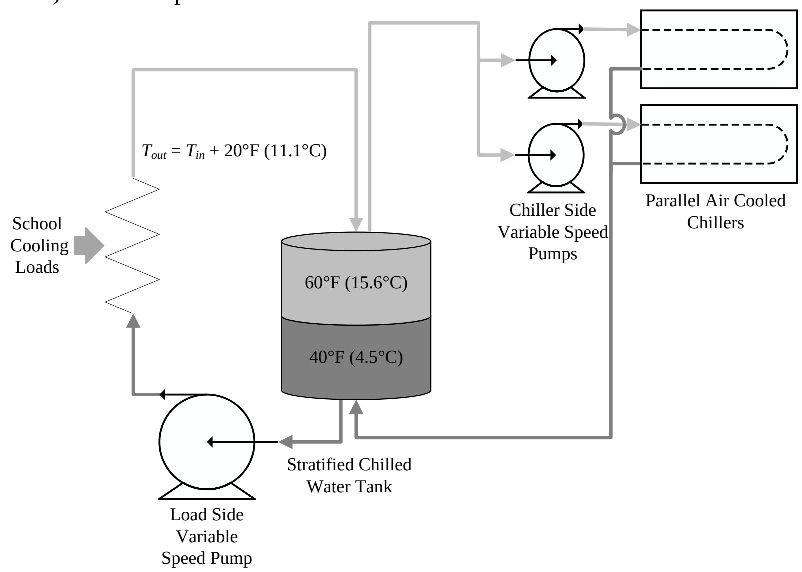

Figure 2 Stratified chiller water storage system schematic

The air-cooled chillers modeled in this work use screw compressors and therefore exhibit coefficients of performance (COP) of 3.0 or better at full-load conditions. However, their part-load performance is poor and leads to a COP of less than 1 at extremely low part-load ratios (PLR). In order to operate less frequently at these poor performance conditions, two equally sized chillers are assumed to be installed in parallel. In this case, each chiller is run at equal part-load ratios down to half of the overall building part-load ratio. Once the building part-load ratio dips below half, only one chiller is in operation and the system performance follows the single chiller performance curve. The performance curves for the overall chilling system are shown in Figure 3. The system is technically capable of running at as little as 7.5% of the two-chiller full-load capacity which corresponds to one chiller operating at 15% of its full-load capacity limit.

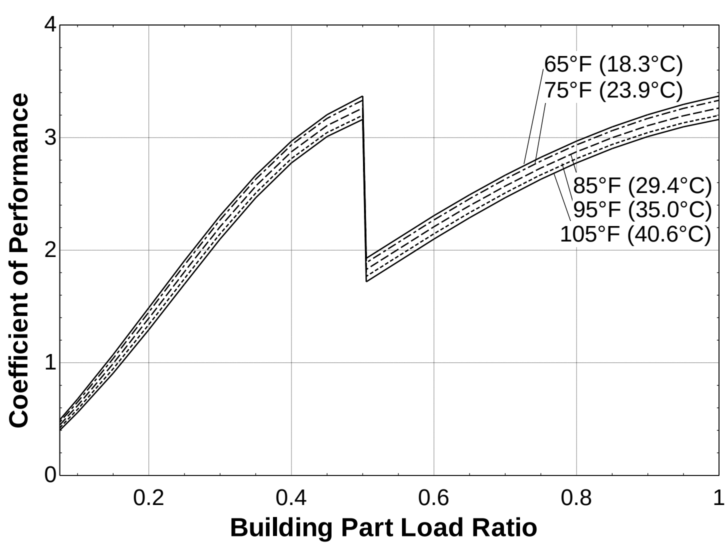

Figure 3 Air-cooled chiller performance curves for two equal sized chillers (CUSCST, 2011)

2.2 Cooling Loads and Equipment Sizing

Cooling loads met by the systems are derived from the Commercial Reference Building model developed for a secondary school by the US Department of Energy (2011). Energy simulations are run for both Amarillo, TX and Los Angeles, CA, each with weather data and building construction parameters that are representative of these climates. The simulations provide cooling loads at 10-minute intervals which then must be met either using chillers directly or the CTES system.

For this work, the sizing of the chiller plant system and stratified chiller water storage tank are based on a partial storage strategy. This strategy determines to the minimum capacity or size of each piece of installed equipment. The integrated design day cooling load, or load on the day with the largest cooling load, is divided by 24-hours in order to determine the minimum required chiller capacity. This implies that the chiller will be running at full-load throughout this day. The resulting chiller capacity for Amarillo is 630 kW (180 tons) and for Los Angeles it is 470 kW (134 tons). The storage tank is the minimum capacity tank that will allow the chiller system to meet the cooling load, 5,200 kWh (1,480 ton-hrs) for Amarillo and 4,500 kWh (1,280 ton-hrs) for Los Angeles.

2.3 Weather, Generation, and Cost Data

The weather data utilized for the Commercial Reference Building energy simulation is Typical Meteorological Year version 3 (TMY3) data (NREL, 2008). The energy model requires temperature, relative humidity, and solar radiation data for solar gain calculations, this data is referred to here as the cooling load weather data. TMY3 weather is also used to estimate the solar resource. A four parameter photovoltaic model uses the total radiation on a tilted surface to predict the solar power data using only parameters provided by panel manufacturers (Duffie and Beckman, 2013). The wind speed data in TMY3 is collected at a height of 33 ft (10 m) and, although it is possible to estimate the equivalent wind speed at other heights using a wind shear exponent that is a function of terrain, data gathered at heights of 164 ft (50 m) or higher are more accurate for estimating the wind resource. The hub-height wind data used in this work comes from White Deer, TX and Kern County, CA (AEI, 2012; NREL, 2015b). Wind turbine power output is then modeled using a characteristic power curve from NREL's System Advisor Model (2015a). The geographic locations for the three weather data types are shown in Figure 4 for the Los Angeles region (a) and the Amarillo region (b).

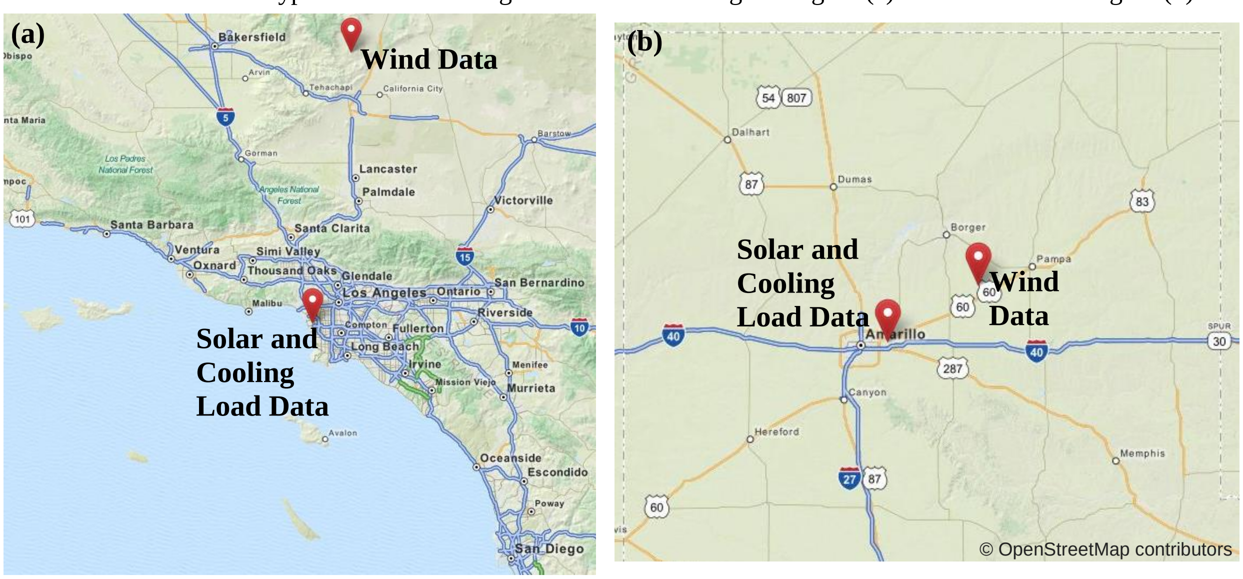

Figure 4 Cooling load, solar, and wind data locations for (a) Los Angeles and (b) Amarillo

Cost data for stratified chilled water storage tanks have been obtained from a consulting firm that specializes in thermal storage systems (J. Schuett, personal communication, April 12, 2016). The air-cooled chiller cost data is obtained from RS Means Mechanical Cost Data for rotary-screw type water chillers with integrated condensers (2015). Capital cost for installed wind turbines is based on the US DOE's Wind Technology Report and cost for solar photovoltaics is reported by the US DOE's SunShot Photovoltaic System Pricing Trends for non-residential systems (2015a, 2015b). A single representative commercial time-of-use electricity rate is used for both locations in order to enable consistent life-cycle cost comparisons. During the summer months, the on-peak rate between the hours of 3 p.m. and 8 p.m. is 16.5 ¢/kWh and the off-peak rate during all other hours is 7.16 ¢/kWh. During the winter months the rates are the same, but there is an additional on-peak period between the hours of 6 a.m. and 8 a.m. (CoServ, 2015). No demand charges are considered. When calculating the present value of the electricity costs over a 20-year period, a discount rate of 8% and an inflation rate of 5% are taken into account.

3. CONTROL STRATEGIES

Two CTES control systems are compared: "Renewable Control" and "Cost Control." Renewable Control runs the chillers whenever there is sufficient renewable power available to operate the chillers as well as a need for the cooling that is produced (either to directly meet building cooling loads or for charging storage). The level of renewable power required to run the chillers is an independent variable that can range from the full load chiller power down to the minimum individual chiller part-load ratio of 15%. Figure 5 illustrates a flow chart of the Renewable Control strategy for the case where wind power is the renewable energy source that is being exploited. The first branch, activated when there is insufficient wind power to run the chiller(s), demonstrates one constraint that requires that the storage tank be fully recharged by the beginning of the next day. This decision assumes perfect knowledge of the facility cooling load for the remainder of the day.

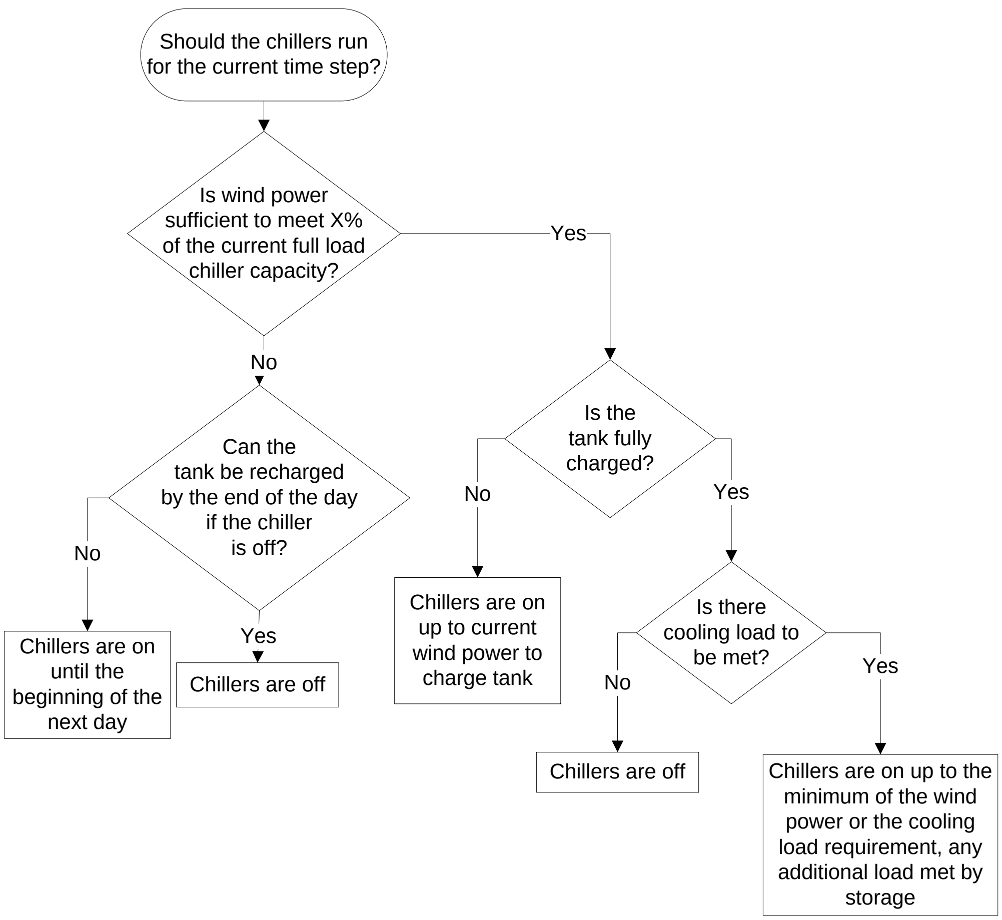

Figure 5 Flow chart for the Renewable Control strategy based on wind

The Cost Control strategy is similar to Renewable Control except that the trigger for operating the chillers is related to off-peak time-of-use electricity rate rather than the level of renewable energy that is available. The chillers will run during the on-peak period only if necessary in order to fully charge the tank by the beginning of the next day.

4. DESIGN PARAMETERS AND METRICS

In order to accomplish the system optimization, the two independent variables (or design parameters) examined are the hour of the day by which the storage tank must be recharged and the chiller system minimum part-load ratio. For each of the strategies utilizing the solar resource, the optimal storage tank recharge hour was found to be noon while for those strategies utilizing wind, the optimal recharge hours was found to be 8 a.m.

Two metrics have been developed for carrying out optimization of the control strategies. The first is the fraction of the chiller power that is met by the renewable resource, defined as the chiller electrical consumption met by renewable divided by the total chiller electric consumption over the simulation year. The second metric is the cost of owning and operating the system for a period of 20 years. This cost includes capital costs for chillers, storage tanks, renewable generation equipment, and the discounted operating cost, as described previously in Section 2.3. Figure 6 shows the method for calculating the daily operating cost for 250 kW of installed solar power with (a) no storage and (b) storage. The top-most plot shows the chiller power consumption over 24 hours as a negative quantity, the second to the top is the positive solar power produced, and the third is the sum of the two, corresponding to the net utility impact. The discontinuities apparent in the chiller power consumption plot are due to the transition between one and two chiller operation which is governed by the performance curve in Figure 3. At each timestep, the time-of-use electricity rate in effect is applied to the net utility impact to get the net electricity value that is shown in the bottom plot. The shaded region represents the time of on-peak rates and discontinuities in the net electricity value are apparent at the beginning and end of this time period. The integration of the net electricity value over a year gives the operating cost. The operating cost does not account for on-going maintenance costs or solar panel performance degradation over time.

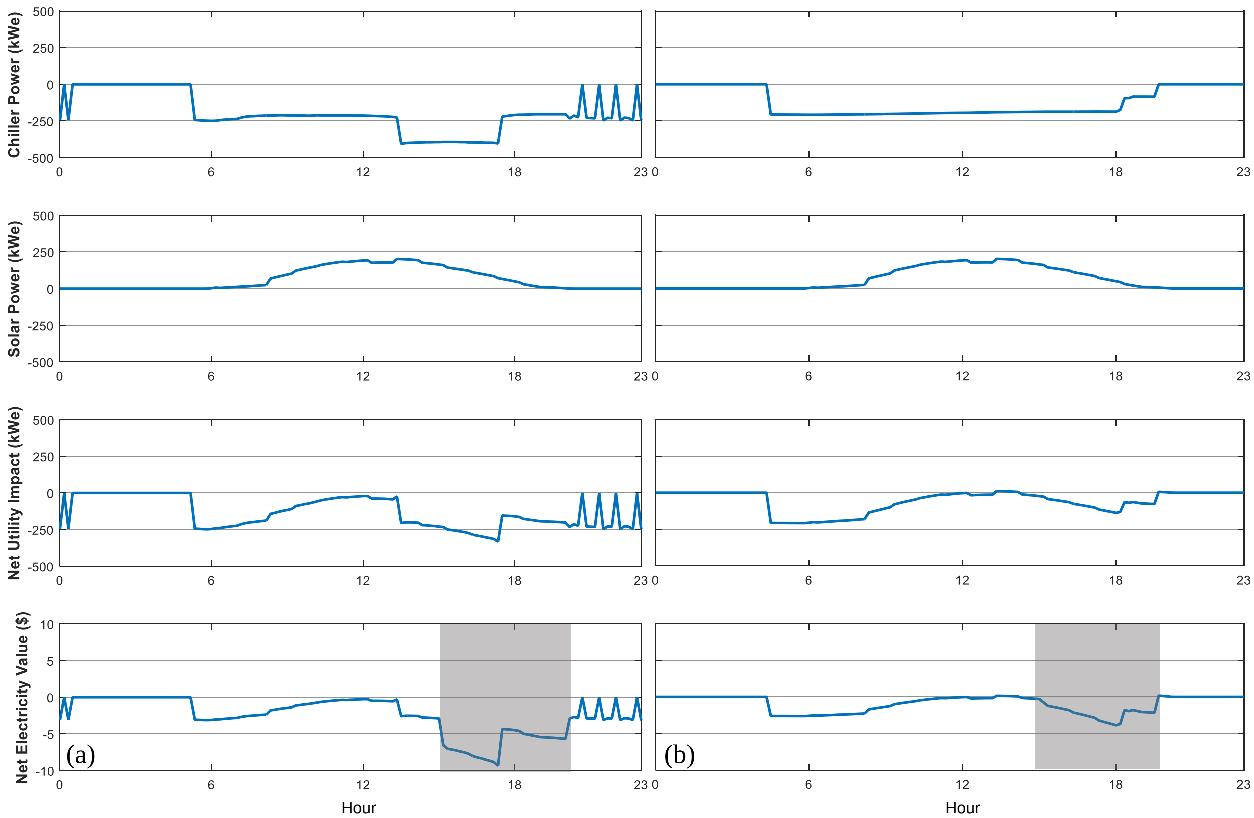

Figure 6 Example day showing net annual electricity value metric for (a) 250 kW of Solar Power without storage and (b) with storage, shaded region shows peak time-of-use rates

5. RESULTS

5.1 Individual Facility Results

Figure 7 shows several results, all as a function of chiller system part-load ratio. Both the fraction of chiller energy consumption met by renewable and life-cycle cost (LCC) are shown in Amarillo, TX and Los Angeles, CA using both the Renewable and Cost Control strategies with the wind resource utilized as the renewable. The installed nameplate renewable capacity is fixed at 250 kW. LCC is calculated using the sum of the present value of 20 years of net operating cost (as described in section 4) as well as the chiller, storage tank, and wind turbine capital costs. Negative LCC indicates that more wind energy was produced than chiller energy consumed, and the operating costs show a gain that outweighs the capital costs. The results in Amarillo show that if the chiller system is restricted to run at a part-load ratio of not less than 0.3, then 84% of the chilling system energy can be met by wind using the Renewable Control strategy as shown by point (1) in Figure 7a. However, the trade-off is that over a 20-year span, the system costs $120,000 more to operate using Renewable Control than it does with the Cost Control strategy if the optimal part-load ratio of 1 is used. This is shown by the difference between point (2) in Figure 7d and point (1) in Figure 7c. On the other hand, point (2), which optimizes cost, results in only 57% of the chiller energy consumption being met by wind. As a point of comparison, to meet the same cooling load without a storage system, the cost is $291,000 more than Renewable Control (-$49,000 for no-storage minus -$340,000 in point (1)) and $411,000 more than Cost Control (-$49,000 minus -$460,000 in point (2)). The no-storage system results in just 50% of the chiller energy met by wind (shown as point (3) in Figure 7). Similarly, for the Los Angeles system without storage, the cost is $254,000 more than Renewable Control (-$86,000 for no-storage minus -$340,000) and $374,000 more than Cost Control (-$86,000 minus -$460,000) with just 56% of the chiller energy met by wind as shown by point (4).

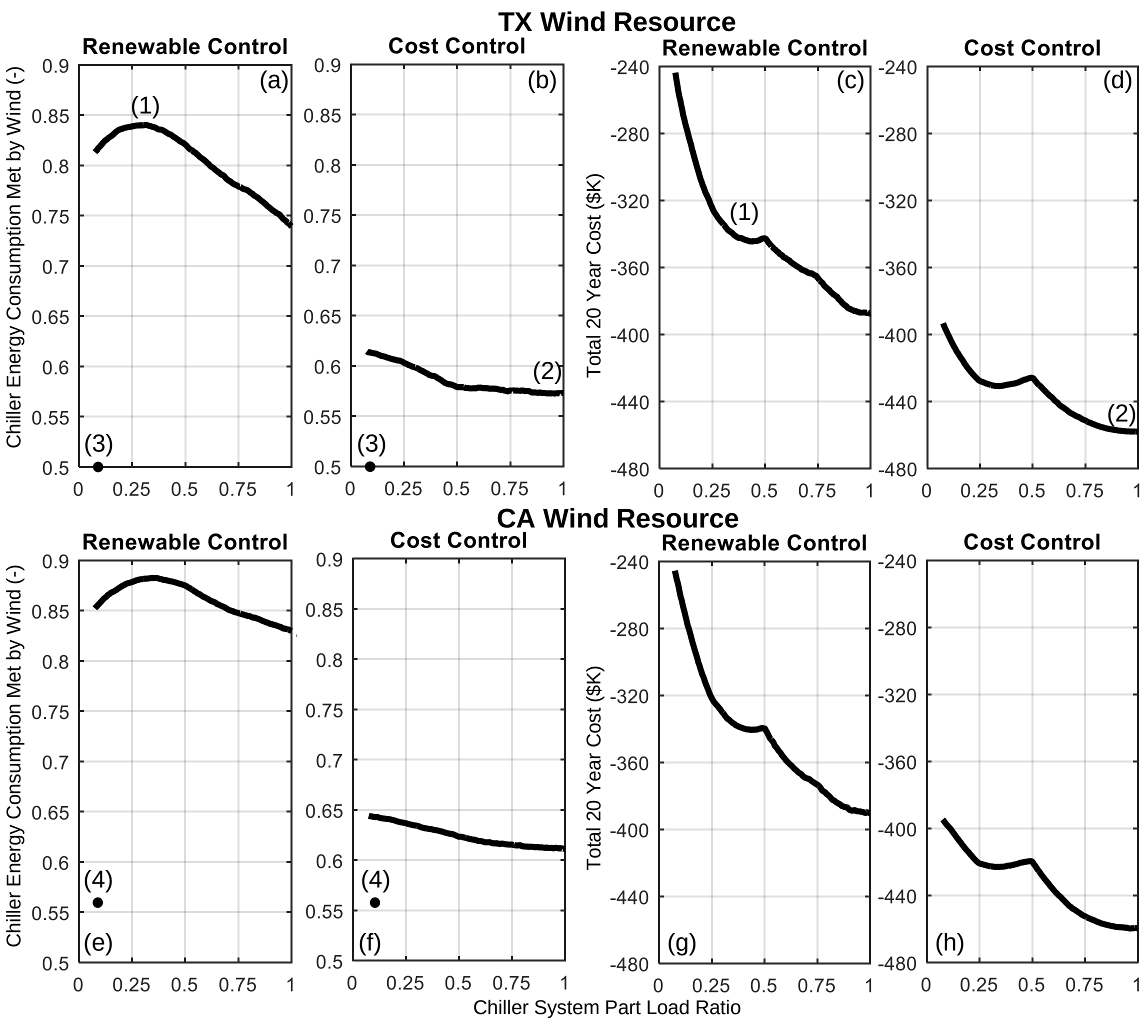

Figure 7 Results for wind resource (single points indicate no-storage values)

Figure 8 displays the same results but using the solar resource. In Amarillo, the capacity factor for the 250 kW of solar PV is less than that for the 250 kW of installed wind power, and therefore the maximum achievable fraction of the chiller energy met by solar is less than that for wind. Looking at Los Angeles in plots (e) through (h), restricting the minimum chiller part-load ratio to 0.3 results in the best utilization of the renewable resource with 82% of the chiller energy consumption being met by solar (see point 1 in Figure 8e). This strategy costs $80,000 more over 20 years than operating with the Cost Control strategy at a part-load ratio of not less than 1 which is shown by the difference between point (2) in Figure 8h and point (1) in Figure 8g. The Cost Control strategy only results in 54% of the chiller energy consumption met by solar (shown as point (2) in Figure 8f). For the Los Angeles system without storage, the 20-year cost is $420,000 more than Renewable Control ($1,100,000 for no-storage minus $680,000 for point (1)) and $500,000 more than Cost Control ($1,100,000 minus $600,000 for point (2)). The no-storage system results in 54% of the chiller energy consumption met by solar (shown as point (3) in Figure 8). In Amarillo, the no-storage 20-year cost is $330,000 more than Renewable Control ($970,000 for no-storage minus $640,000 for Renewable Control) and $405,000 more than Cost Control ($970,000 minus $565,000 for Cost Control) with 44% of the chiller energy consumption met by solar (shown as point (4) in Figure 8). In both locations, the no-storage system has at least as much chiller energy consumption met by solar as the Cost Control system. This is because the Cost Control strategy aims to keep the chiller system off when the on-peak rates are in effect from 3 p.m. to 8 p.m. Solar power is still significant in this timeframe and goes unused by the chiller system. All methods of operating the storage system are effective from a cost and renewable utilization standpoint as compared to a system without storage.

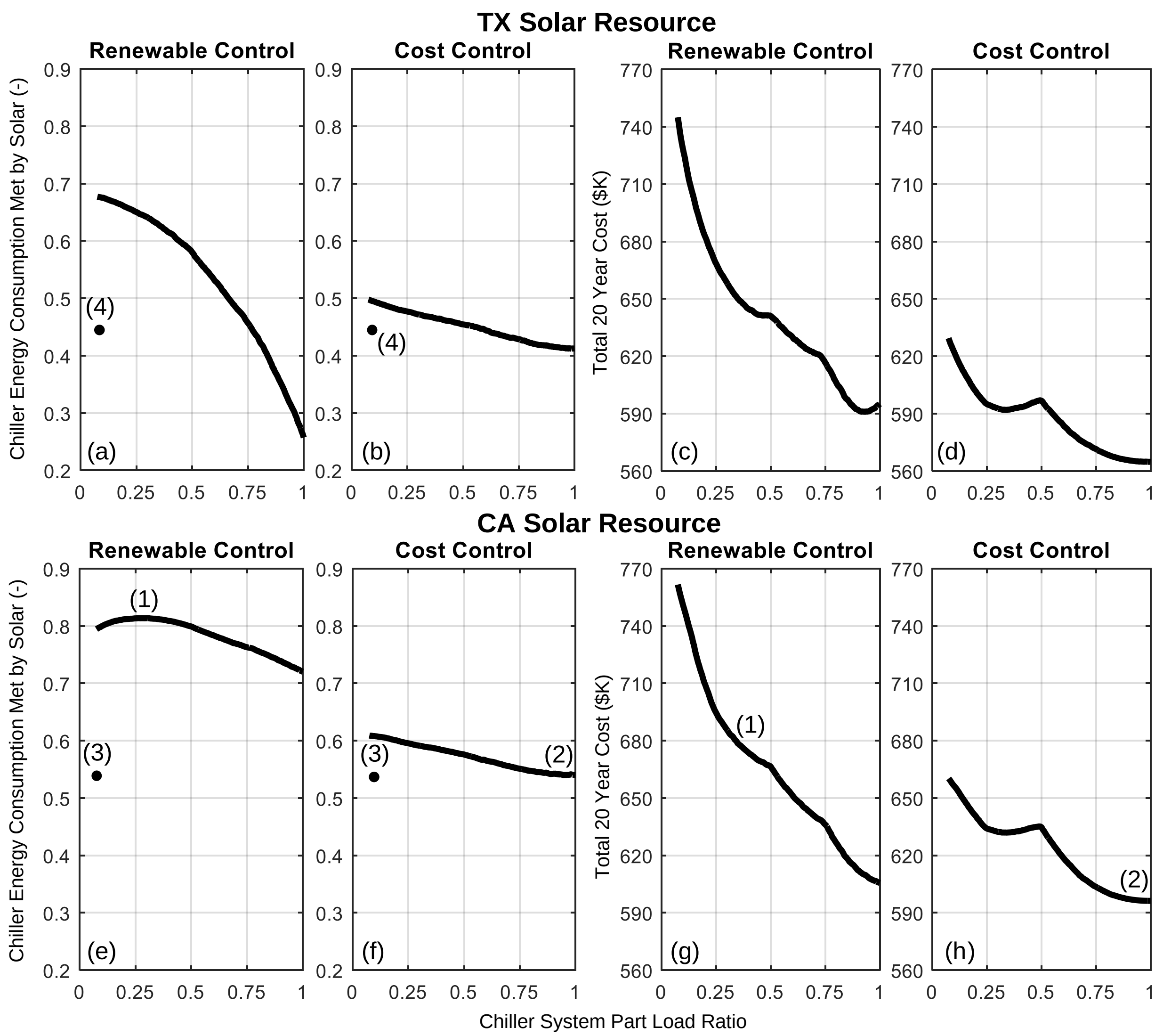

Figure 8 Results for solar resource (single points indicate no-storage values)

5.2 Aggregate Results

The results for an individual secondary school have been aggregated in order to begin to consider how large scale implementation of CTES systems might impact the utility aggregate demand (i.e. mitigate the "duck curve" problem). There are 4,495 secondary schools in California and each is assumed to use an air-cooled chiller system (High-Schools.com, 2015). The total installed solar PV capacity is 250 kW per school or approximately 1,125 MW. Figure 9 illustrates various impacts on the CAISO system on March 31st, the day used for the classic duck curve figure. Each plot shows the total CAISO load as a solid line. Plot (a) shows the impact of the 1,125 MW of solar capacity or the "net load" referred to in the duck curve in Figure 1. Plot (b) shows the net impact of 1,125 MW of solar PV offset by the addition of no-storage chiller systems for each of the 4,495 schools. Plots (c) and (d) show the net impact of exchanging the no-storage chiller systems for CTES systems operating using Renewable Control and Cost Control, respectively. The no-storage case in (b) shows much of the solar power being utilized, but adding the school chiller systems increases the peak evening load by nearly 700 MW as shown by point (1). The secondary schools equipped with CTES and operating with a Renewable Control storage system in (c) shows that some solar power is still left in the middle of the day, encroaching on the base load and fattening the "belly" of the duck. On the other hand, this strategy adds no load during the peak periods and meets the same cooling load with less energy overall. Lastly, the schools equipped with CTES and operating with Cost Control in (d) also use less energy than the no-storage systems and utilize much of the solar power. The time-of-use rate structure used causes some solar power to go unused around 7 a.m. during the on-peak period as shown by point (2). Point (3) shows where it also causes a short peak at 8 p.m. when the off-peak period begins. This shows that by shifting on-peak and off-peak schedules, this rate structure could be better optimized for utilization of the solar resource as well as reduction of peak demand.

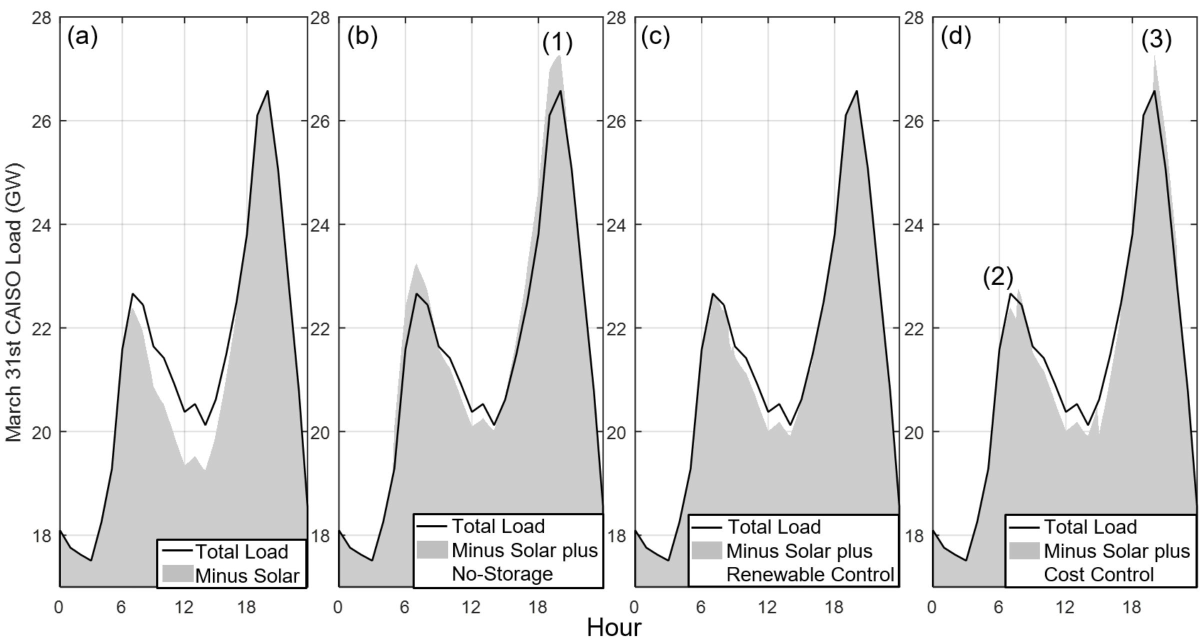

Figure 9 (a) Total CAISO load minus 1,125 MW of solar capacity, (b) total load and net of 1,125 MW of solar capacity and 4,495 schools with no storage, (c) Renewable Control storage, and (d) Cost Control storage

6. CONCLUSIONS

- A CTES system utilizing the Cost Control strategy has a positive externality of increasing the portion of the chiller energy consumption met by wind (by at least 10%), but this is not the case for the solar resource because the system without storage consumes more energy during the day to meet the same cooling load
- Either control strategy implemented with a storage system will be more cost effective than a no-storage system
- Renewable Control of a storage system results in at least 40% more of the chiller energy consumption being met by wind and at least 50% more met by solar as compared to the Cost Control strategy
- Implementing CTES systems with Renewable Control has the potential to reduce the duck curve peak load by approximately 700 MW if implemented solely on the secondary schools in California

NOMENCLATURE

CAISO	California Independent System Operator
COP	Coefficient of performance
CTES	Cool thermal energy storage
ERCOT	Electric Reliability Council of Texas
LCC	Life-cycle cost
NREL	National Renewable Energy Laboratory
PLR	Part-load Ratio
TMY3	Typical Meteorological Year, version 3
USDOE	United States Department of Energy

REFERENCES

Alternative Energy Institute (AEI). (2012). *Wind Data: White Deer, TX*. Retrieved from http://www.windenergy.org/datasites/. Last accessed June 2015.

California Independent System Operator (CAISO). (2013). *What the Duck Curve Tells us about Managing a Green Grid* (CommPR/HS/10.2013). Folsom, CA.

California Utilities Statewide Codes and Standards Team (CUSCST). (2011). *2013 California Building Energy Efficiency Standards: Final Measure Information Template – Chiller Minimum Efficiency*.

Duffie, J. A. & Beckman, W.A. (2013). *Solar Engineering of Thermal Processes* (4th ed.). New York: John Wiley & Sons, Inc.

High-Schools.com. (2015). *California High Schools.* Retrieved from http://high-schools.com/directory/ca/. Last accessed April 2016.

Myers, K.S., Klein, S.A., & Reindl, D.T. (2010). Assessment of high penetration of solar photovoltaics in Wisconsin. *Energy Policy, Volume 38*(11), 7338-7345.

National Renewable Energy Laboratory (NREL). (2008). *User's Manual for TMY3 Data Sets*. Retrieved from http://www.nrel.gov/docs/fy08osti/43156.pdf. Last accessed April 2016.

National Renewable Energy Laboratory (NREL). (2015a). System Advisor Model (Version 2015.6.30) [Software].

National Renewable Energy Laboratory (NREL). (2015b). *Western Wind Dataset.* Retrieved from http://www.nrel.gov/electricity/transmission/western_wind_methodology.html. Last accessed April 2016.

RSMeans. (2015). *RSMeans 2016 Mechanical Cost Data*. Rockland, MA: RSMeans Construction Publishers.

United States Department of Energy (USDOE). (2011). *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock* (NREL/TP-5500-46861). Golden, CO.

United States Department of Energy (USDOE) (2015a). *2014 Wind Technologies Market Report* (DOE/GO-102015-4702).

United States Department of Energy (USDOE) (2015b). *SunShot Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections* (NREL/PR-6A20-64898).

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