Quantifying the Value of Unitary Thermal Energy Storage Systems (UTSS): A Modelling Study

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Abstract

An EnergyPlus object model for Unitary Thermal Storage Systems exists, but it is not currently available to OpenStudio (OS) for parametric analysis. This study presents an OS measure to apply UTSS to existing building models for the purpose of exploring design alternatives. Four metrics are proposed to quantitatively compare these systems: load shifting effectiveness, energy increase intensity, penalty ratio, and an effective *COP* for UTSS operation. Preliminary results show that applying the measure to retail and small office models, average annual site energy use increases relative to the shifted load by 17.3% and 16.3%, respectively. However, under example time-of-use utility rates, average annual energy bill savings of 8.0% for retail and 4.8% for small office are achieved with UTSS.

Introduction

The increased market penetration of distributed renewable energy generation poses several new challenges to the grid: (1) The intermittent nature of wind and solar power sources can lead to large, rapid variations in the electrical demand from the power grid throughout the day; (2) regions with large solar generation suffer from large end-of-day ramp requirements as residential loads increase coincidentally with sunset, creating the so called “Duck Curve” net demand profile. These two problems present a challenge to the growth of renewables in future energy generation portfolios. To combat these challenges, two approaches have been proposed: “fattening” and “flattening” the duck (Denholm et al., 2015). The first addresses the power generation system, the second addresses the power demand. It is the second approach with which this study is concerned.

One of several means to “flatten” the duck is to include building-level energy storage. The energy storage is charged during periods of excess renewable generation or during periods of low energy demand. It is then discharged during periods of high energy demand and low renewable generation—such as during the evening ramp. This study examines one possible means of energy storage: thermal energy storage (TES) using an ice storage device designed to integrate with existing, packaged direct-expansion air conditioners, called unitary thermal storage systems (UTSS) (AHRI, 2014). UTSS traditionally function by creating ice during cooler nighttime hours and discharging the ice in lieu of running the

air-conditioner (AC) during the mid-day peak cooling hours. The design and performance of UTSS depend on many factors and their operational characteristics are described in the literature (Willis and Parsonnet, 2010). However, little has been published on the application of UTSS in building energy modelling.

EnergyPlus includes three thermal storage models, two of which model centralized thermal systems. The third one, developed and added in 2013, models UTSS as a single coil object: `Coil:Cooling:DX:SingleSpeed:ThermalStorage` (Kung, et al., 2013). However, EnergyPlus uses a text-based input, and it primarily relies on graphical user interfaces (GUI) and OpenStudio Software Development Kit (SDK) for its broad use. Currently, OpenStudio does not include a component to make use of the EnergyPlus UTSS object. This has limited the performance analysis which has been conducted on UTSS to date.

This project addresses this shortcoming by making the UTSS object available to OpenStudio users through a measure enabling rapid parametric analysis. Using the new OpenStudio measure, this project also presents several new quantification metrics to help evaluate UTSS compared to baseline AC systems.

The purposes of this paper are four-fold: (1) present the OpenStudio measure used to model UTSS, (2) quantify the load shifting effectiveness of an example UTSS, (3) quantify the round-trip efficiency trade-offs of using UTSS compared to a standard rooftop AC unit, and (4) explore potential cost savings under two existing time-of-use commercial electricity rates.

Methods

OpenStudio Measure

The new OpenStudio measure for the EnergyPlus UTSS object (`Coil:Cooling:DX:SingleSpeed:ThermalStorage`) is called “Replace Cooling Coils with Packaged TES,” and operates on existing building models with heating, ventilation, and air-conditioning (HVAC) components that use `AirLoop:HVAC` or `CoilSystem:Cooling` EnergyPlus container objects.

The measure inspects the current OpenStudio model and allows user selection of thermal zones to which it will apply. Users may input capacities for the AC unit and the ice storage tank or may use the EnergyPlus autosize routines. A simple operating schedule may be created directly with user inputs. Several pre-defined schedules

are also available for selection. The measure removes the original coil objects and adds all required performance curves, schedules, nodes, and Energy Management System (EMS) controllers. Figure 1 below shows the user input screen for an example small office model.

Inputs

Select applicable zones:

☒ Perimeter_ZN_2 ZN

☐ Attic ZN

☒ Perimeter_ZN_4 ZN

☒ Perimeter_ZN_1 ZN

☒ Core_ZN ZN

☒ Perimeter_ZN_3 ZN

Input the AC unit cooling capacity [tons]
Typical systems support units between 3-20 tons. 'AutoSize' may return a value exceeding practical limits, verify result.

AutoSize

Select ice storage capacity [ton-hours]

AutoSize

Enter user-specified ice storage capacity [ton-hours]
Leave blank unless 'User Input' selected above

Select ice storage control method

EMSControlled

Select the operating mode schedule for the new TES coils
Use the fields below to set a simple daily ice charge/discharge schedule. Or, select from pre-defined options.

Select the operating mode schedule for the new TES coils
Use the fields below to set a simple daily ice charge/discharge schedule. Or, select from pre-defined options.

Simple User Sched

☐ Run TES on the weekends?
Select if building is occupied on weekends.

Input start time for ice charge (hr:min)
Use 24 hour format

23:30

Input end time for ice charge (hr:min)
Use 24 hour format

07:00

Allow zone cooling during ice charge period?

No

Input start time for ice discharge (hr:min)
Use 24-hour format. If 'AutoSize' is selected for ice capacity, these inputs set an ice capacity sizing factor. Otherwise, these only affect discharging schedule.

13:00

Input target end time for ice discharge (hr:min)
Use 24 hour format

17:00

Allow AC unit to run during ice discharge period?
Currently Cooling and Discharge Mode is Unavailable

No

Figure 1: User Inputs for OpenStudio UTSS Measure.

This study uses publicly available performance curves for the UTSS, taken from the EnergyPlus 8.9 example file titled "RetailPackagedTESCoil.idf." The curves were empirically developed using field test data (Kung, et al. 2013). Performance curves are hardcoded in the measure but may be added or modified within the resource file (TESCurves.idf) to perform custom analysis.

This study considers two different DOE prototype buildings, each modelled to meet ASHRAE 90.1-2013: stand-alone retail (2300 m² / 24700 ft²) and small office (510 m² / 5500 ft²). The building models are created using the OpenStudio "Create DOE Prototype Building" measure available on the Building Component Library. The HVAC systems in the small office models are slightly modified to ensure they use measure-compatible HVAC container objects. Both building types are analysed using typical meteorological year (TMY3) weather files for each climate zone as defined by ASHRAE Standard 169-2013, shown in Table 1 below. Both building types are run in these 15 climate zones using a five-minute simulation timestep.

Table 1: Climate Zones and Weather Locations.

Climate Zone Number	Description	Weather File Location (TMY3)
1A	Very Hot-Humid	Miami, FL
2A	Hot-Humid	Houston, TX
2B	Hot-Dry	Phoenix, AZ
3A	Warm-Humid	Memphis, TN
3B	Warm-Dry	El Paso, TX
3C	Warm-Marine	San Francisco, CA
4A	Mixed-Humid	Baltimore, MD
4B	Mixed-Dry	Albuquerque, NM
4C	Mixed-Marine	Salem, OR
5A	Cool-Humid	Chicago, IL
5B	Cool-Dry	Boise, ID
6A	Cold-Humid	Burlington, VT
6B	Cold-Dry	Helena, MT
7A	Very Cold	Duluth, MN
8B	Subarctic	Fairbanks, AK

The building models also include a 1°C [1.8°F] thermostat hysteresis to more accurately capture the variations in power requirements of the building. This is accomplished by modifying the "ZoneControl: Thermostat" objects for each zone, setting the "Temperature Difference Between Cut-out And Setpoint [C]" field to a value of 1.0. This is added independently of the measure and is not required for measure functionality.

UTSS Operating Strategy

Typical implementation of TES systems includes multiple modes of operation depending on the weather, utility rates and load-shifting objectives. In this study the operating strategy is determined by analysing the daily cooling load in the baseline models and selecting the times of maximum cooling energy use as the TES discharge period, assuming a full storage system. Future work will look at optimizing the actual operation of the UTSS. The UTSS object model in EnergyPlus has six available modes of operation:

- Mode 0: System Off. All HVAC systems are off.
- Mode 1: Cooling Only. All cooling is done by the AC unit.
- Mode 2: Cooling and Charge. The UTSS is providing cooling to the building while also making ice (charging the system).
- Mode 3: Cooling and Discharge. The UTSS is providing cooling by means of the AC and by melting ice (discharging the system).
- Mode 4: Charge Only. The UTSS is fully dedicated to making ice (charging the system). No cooling is supplied to the building.
- Mode 5: Discharge Only. All cooling loads are met by melting ice (discharging the system).

The OpenStudio UTSS measure works for all these modes; however, not all modes may be available for a specific commercial product. This study only uses modes 1, 4, and 5 to characterize device performance in a general manner.

For the general application of our proposed metrics, we select a four-hour ice discharge period of 14:00 to 18:00 for all climate zones. This timeframe is not geographically optimized but ensure that the ice typically discharges during the hours of greatest cooling energy requirements. It also agrees with current marketing information on commercially available UTSS, which indicates that some devices are designed to provide cooling four- to six-hour periods (Ice Energy, 2018). For the retail model, the UTSS operates seven days a week. For the small office, the UTSS only operates Monday-Friday. An alternate, cost-focused strategy is employed for the financial comparisons at the end of this paper, where UTSS scheduling is tied to the utility pricing.

For all models, ice charging is enabled during the cooling season from midnight to 7:00 a.m. This window allows sufficient time for ice tank recharge each day throughout the cooling season and coincides with typical off-peak electric rates. Additionally, ice charging is only enabled once the state-of-charge is lower than 70%. This helps maximize the use of the ice storage tank and reduce the number of compressor cycles for ice charging purposes. The minimum state-of-charge permitted in the ice tank is 5% to maintain 0°C [32°F] tank temperature.

Models are first simulated for all climate zones with the UTSS operating all year. After initial simulation and cooling load analysis, the operating seasons are uniquely set for each building type and climate zone (discussed in Results below).

Load Shifting Effectiveness

The primary purpose of UTSS is to shift electricity demand for cooling purposes out of a given time period. Therefore, the first metric of interest in assessing UTSS performance is a measure of load shifting effectiveness. Load shifting effectiveness is an aggregate cooling-season metric that describes how much of the potentially-shiftable load from the baseline case is shifted by the UTSS model.

Prior to determining the device effectiveness, we determine the load shifting potential for each of our buildings and locations. This load shifting potential provides an initial indicator of the possible value of using thermal energy storage.

Load shifting potential is defined as the total electricity used for cooling purposes (excluding supply fan energy) in a baseline case over a user-specified time period coincident with the proposed daily ice-discharge period for the storage model. It describes the upper limit of cooling electricity that can possibly be shifted from a given time period each day. This is similar to another paper that looked at potential cost savings for energy storage (Lanahan, et al, 2019). In this study, the potential is a function of both the daily ice-discharge period and the locally-specified UTSS cooling season for each building and climate zone.

The shifting effectiveness is then defined as the actual shifted load divided by the load shifting potential during the designated TES discharge period.

$$\epsilon_{load\ shift} = \frac{Shifted\ Load\ [kWh]}{Load\ Shifting\ Potential\ [kWh]} \quad (1)$$

This effectiveness term requires baseline and UTSS simulations for each building model and can be calculated on daily to annual timeframes.

Round-Trip Efficiencies

All energy storage systems incur an energy penalty due to round-trip inefficiencies. In the case of ice storage, this cost is primarily manifest in the heat transfer effectiveness between the ice storage and the refrigerant loop to the cooling coil. Additionally, the lower refrigerant temperatures required for making ice reduce the efficiency of the compressor when charging the ice storage tank. We characterize the UTSS performance on a site energy basis relative to a baseline AC system using three metrics: energy increase intensity (*EII*), penalty ratio (*PR*), and an effective coefficient of performance for UTSS operation (*COP_{UTSS}*).

Ambient losses from the ice tank are small relative to building loads but do contribute to total system inefficiency. An estimated heat transfer coefficient of 0.667 W/m²-K [0.1174 Btu/hr-ft²-°R] for the ice tank is used in the model.

To minimize system losses (or inefficiencies) UTSS operation strategies typically take advantage of diurnal temperature changes by charging at night. The lower outdoor air temperatures help reduce the energy requirements from the compressor. In this study, the energy penalty is assessed by calculating the change in annual total electricity use when using the UTSS and be defined as a floor-area-normalized energy increase intensity:

$$EII = \frac{(Energy_{UTSS} - Energy_{Baseline})}{Floor\ Area} \quad (2)$$

where, *Energy_{xx}* is the total annual site energy of the building for the UTSS and baseline cases. This term is analogous to an Energy Use Intensity (*EUI*) but is calculated in reference to a baseline model.

A second efficiency metric for UTSS performance is the penalty ratio (PR). This value is defined by dividing the energy increase when using the UTSS by the amount of shifted load. Though it is possible under ideal conditions to obtain a negative penalty ratio (i.e. total energy consumption is reduced by employing the UTSS), typically this is not the case. The term is defined such that increasing positive values are less desirable.

$$PR = \frac{\text{Energy Increase [kWh]}}{\text{Shifted Load [kWh]}} \quad (3)$$

The penalty ratio may be calculated over any analysis timeframe in which both a TES discharge and subsequent charge cycle are included. Daily or weekly PR values may be used to evaluate specific operating strategies, while annual PR values provide a broad measure of the system's round-trip efficiency compared to the baseline AC unit.

The third efficiency metric is an effective Coefficient of Performance (COP), calculated at each HVAC system timestep. These values measure coil performance only and do not include fan power. This metric is useful for informing detailed control strategies.

$$COP_{UTSS} = \left[\frac{1}{COP_{Charge}} + \frac{1}{COP_{Discharge}} \right]^{-1} \quad (4)$$

The COP for ice charging is calculated based on the rate of heat transfer into the tank divided by the electrical power used by the coil object:

$$COP_{Charge} = \frac{\text{Ice Charging Rate [kW]}}{\text{Coil Power [kW]}} \quad (5)$$

This equation is applied at each simulation timestep when the ice tank is in charge mode (the middle of the night).

During direct zone cooling, COP values are calculated according to a discharge formula:

$$COP_{Discharge} = \frac{\text{Supply Air Cooling Rate [kW]}}{\text{Coil Power [kW]}} \quad (6)$$

Equation 6 is used at every timestep when the ice tank is discharging; it is also used when the AC unit is providing direct zone cooling. Cooling and charging rates are calculated at the device to avoid including duct losses.

The model uses performance curves that are a function of ambient temperature, flow fraction, and ice tank state-of-charge (SOC). The publicly available performance curves do not include an SOC variation and generate a uniform ice discharge COP value of 63.6 during all discharge timesteps. However, actual system values will not be constant, especially as the ice tank approaches complete discharge. This necessitates the use of an average value, $\overline{COP}_{Discharge}$ in the COP_{UTSS} calculation. This decouples the calculation from the discharge ambient conditions.

UTSS performance during ice charging is only a function of ambient temperatures in the available curves. However, they do capture the efficiency penalty imposed on the compressor in order to achieve the lower evaporator temperature needed to make ice.

These COP_{UTSS} values can then be plotted at each timestep to visualize the device efficiency variations throughout the day.

Financial Analysis

Energy storage systems typically use more on-site energy than a system without storage. Thus, TES only makes economic sense when local utility rates sufficiently incentivize their use. Under high time-of-use (TOU) energy and/or demand charges, annual electricity bill savings can be achieved, yet this must be weighed against capital and maintenance costs of the system. This study uses two current TOU rates that apply to small/medium commercial customers and have variable energy and demand charges with peak TOU periods in the mid/late afternoon. Both rates also use seasonal variation, with high rates charged during summer months.

The rates used are: (1) Salt River Project E-32 (SRP), taken from the greater Phoenix, Arizona area; and (2) the Pacific Gas and Electric (PG&E) E-19 rate which is available in much of central and northern California (Utility Rate Database, 2018). Figure 2 below illustrates the time variability of energy charges for each rate, and Figure 3 shows the time variability of the demand charges for summer season. Additional service fees are considered but not illustrated.

For the financial analysis, alternate operating seasons and schedules are used that operate the ice storage only during the on-peak cooling seasons and times. For the SRP rate, the ice is discharged from 2-7 pm daily; under the PG&E rate, ice is discharged from 12-6 pm daily. Ice charge times remain midnight to 7 am. The operating season under both rates is from June 1 to October 31.

Figure 2: Time-of-Use Energy Charges for Two Example Utility Rates During Summer Months.

Figure 3: Time-of-Use Demand Charges for Two Example Utility Rates During Summer Months.

Utility bill calculations are made using the U.S. National Renewable Energy Laboratory's System Advisor Model (SAM) software and utility data files from the U.S.

Department of Energy's Utility Rate Database at OpenEI.org.

Results and Discussion

UTSS Operating Seasons

While a fixed ice discharge window of 14:00 to 18:00 is used for all models, the differing cooling seasons of each climate zone necessitate some UTSS schedule customization. We attempt to minimize the ice production during non-cooling months in order to avoid energy waste from unnecessarily maintaining the ice tank charge.

The months of system operation (i.e. the UTSS cooling season) are determined based on the daily cooling energy use in the baseline models during our selected ice discharge period, 14:00-18:00. We arbitrarily select to begin using the ice storage when the daily cooling load during peak hours consistently exceeds 20% of the total peak load. Figure 4 illustrates the selection of UTSS cooling seasons for a stand-alone retail model in climate zone 3B: March 19th to October 27th.

Figure 4: Daily Percent of Peak Period Electric Load Associated with Cooling, Retail, CZ 3B.

Table 2 below summarizes the periods of operation selected for each climate zone and building type.

Table 2: Seasonal UTSS Operating Periods by Building Type and Climate Zone.

Zone	Retail Schedule (# Days)	Small Office Schedule (# Days)
1A	01/01 - 12/31 (365)	01/01 - 12/31 (365)
2A	01/27 - 12/22 (330)	02/20 - 12/07 (291)
2B	02/18 - 11/28 (284)	02/22 - 11/20 (272)
3A	03/22 - 10/30 (222)	04/16 - 10/29 (196)
3B	03/19 - 10/27 (222)	04/17 - 10/17 (183)
3C	05/23 - 10/05 (135)	05/31 - 09/14 (106)
4A	03/26 - 10/16 (204)	05/08 - 10/01 (146)
4B	03/30 - 10/10 (194)	05/13 - 10/05 (145)
4C	04/16 - 09/29 (166)	05/02 - 09/28 (149)
5A	04/12 - 09/27 (168)	04/15 - 09/27 (165)
5B	04/04 - 10/03 (182)	05/02 - 10/02 (153)
6A	05/21 - 09/26 (128)	04/19 - 09/14 (148)
6B	05/20 - 09/18 (121)	06/13 - 09/14 (93)
7A	05/15 - 09/16 (124)	05/16 - 08/31 (107)
8B	06/01 - 08/25 (85)	06/19 - 08/10 (52)

Load Shifting Effectiveness

Figure 5: Normalized Total Cooling Site-Energy that May be Potentially Shifted Based on UTSS Operating Season and Ice Discharge Window, CZ 1A-8B.

Figure 5 shows the load shifting potential for each building type and climate zone on a floor-area-normalized basis. For the default internal loads associated with the DOE prototypes used here, the stand-alone retail buildings require substantially more cooling relative to small offices and present a greater opportunity in general for cooling load shifting. Climate zones 1A-3B present strong potential for this modelled UTSS, while zones 3C and 8B indicate almost no benefit.

In all cases, the load shifting effectiveness of the modelled UTSS was consistently 92%-93%, with no significant variation observed across building types and climate zones. This indicates that the system, from a technical standpoint, is effective at accomplishing its primary purpose.

Efficiency Comparisons

Both buildings in all climate zones generally exhibit an increase in energy use when employing the UTSS compared to the baseline system.

Figure 6: Annual Energy Increase Intensities and Relative Annual Energy Increases Associated with UTSS Operation Compared to Baseline Models, CZ 1A-8B.

Figure 6 depicts the EII for each building in all climate zones. The relative importance of occupancy schedules and total cooling load can be observed in the differences between the retail and small office models. In two climate

zones, 3C and 7A, the small office models with UTSS exhibited a very slight reduction of total electricity use; this is manifest as negative *EII* values. This figure also visually depicts the differing “penalties” of using a UTSS in various climate zones. Used with the load shift potential data in Figure 6, this can inform the decision to explore UTSS options during HVAC system design.

Load shifting potentials and *EII*'s together provide a high-level snapshot of the potential benefit of adding a UTSS and can be used to determine if detailed UTSS modelling should be explored for a given building.

The penalty ratio provides a more useful aggregate metric to compare system performance across building types and climate zones. It can be calculated over any timespan that includes both an ice discharge and associated recharge cycle. Extremely large positive or negative values may be obtained whenever these two are temporally decoupled. Examples include: initial ice tank charge; the final day of UTSS usage in the season; any day in which the ice discharge failed to reach the 70% state-of-charge trigger; and the corresponding days when the ice storage was not full at the cycle start but was recharged fully. These instances occur frequently and appear when the Penalty Ratio is calculated on a daily basis. Calculating the *PR* on a weekly or monthly basis provides a more consistent depiction of system performance.

Figure 7: Penalty Ratio and Total Shifted Load Calculated on a Weekly Basis, Retail, CZ 3B.

Figure 7 shows the weekly *PR* variation for a retail building in climate zone 3B with its associated shifted load during the weeks-of-the-year of UTSS operation. Once the building's cooling requirements become consistently large, around weeks 16-17 (end of April), the weekly *PR* values stabilize. This information may be used to further refine the UTSS operating schedule, to ensure that periods of minimal benefit and maximum penalty are avoided. On an annual basis, depicted in Figure 8 below, the *PR* provides a general snapshot of the round-trip efficiency of employing UTSS.

Figure 8: Penalty Ratios Calculated on an Annual Basis for Both Building Types, CZ 1A-8B.

No obvious correlations appear between *PR* and climate zone, though trends may be obscured by the selected operating schedules. Annual values range from 1.5% to 42.5% (17.3% average) for the retail models and -6.5% to 38.1% (16.3% average) for the small offices. The negative *PR*'s obtained for the small office models in CZ's 3C and 7A are due to the negative *EII*'s observed in Figure 6. Though this implies that energy use would be reduced from the base cases by adding a UTSS at these zones, both locations exhibit low load shifting potentials (Figure 5), which must also be considered when evaluating ice storage options.

Penalty ratios provide an energy comparison between UTSS and a baseline AC unit. This study performed the calculation on a site energy basis in order to focus on device efficiency. However, additional benefits of storage associated with the grid and emissions can be captured by calculating this metric on a source energy basis, or by reformulating the ratio to include emissions factors.

Figure 9: COP Comparison for July 9th-10th, Illustrating the Reduced Round-Trip Efficiency of the Modelled UTSS for these Conditions, Retail, CZ 3B.

Figure 9 compares the *COP* calculated at every timestep of the AC unit operating for the baseline model with the

effective COP of the UTSS in a retail model for climate zone 3B over July 9th and 10th.

The individual five-minute data points appear as smooth curves when zero values (between system cycles) are hidden. The baseline AC unit, shown in red, operates intermittently from 8 am to 7 pm, and forms a bucket corresponding to the times of hottest, most-humid ambient conditions. The blue indicates the calculated COP_{UTSS} values.

Despite the ideal discharge time from an efficiency perspective, the effective COP of using the UTSS falls well below the average value for AC unit use during the discharge window. This is due to the penalties associated with having a lower evaporating temperature required to make ice. It also explains the typically positive results for penalty ratio discussed above.

Plotting the COP_{UTSS} against the baseline AC values is useful for examining the relative performance of the UTSS on a timestep basis. Such a comparison may be useful for performing control optimizations, especially over a moving horizon.

Potential Financial Savings

Despite the increased use of energy, the use of this UTSS results in annual utility bill savings for all buildings and climate zones, though those with negligible cooling loads (i.e. 8B) present minimal value.

Figure 10 below show the floor-area normalized [$\$/m^2$] savings on the annual electricity bills for both buildings in each climate zone relative to the baseline models. Under both rates, for both models in all climate zones, savings are achieved.

Figure 10: Floor-Area-Normalized Annual Energy Bill Savings Using PG&E and SRP Rates, CZ's 1A-8B.

Under the SRP rate, which is characterized by higher TOU energy charges and lower demand charges compared to the PG&E rate, greater variation in cost savings is observed. The example retail building has annual savings between \$0.32 and \$2.14 per m^2 , while the example small office saves between \$0.17 and \$1.39 per m^2 .

Under the PG&E rate, which is characterized by higher demand charges and lower TOU energy charges, the

variation in cost savings across climate zones is less, though the overall magnitude is higher. The example retail building has annual savings between \$0.64 and \$2.58 per m^2 , while the example small office saves between \$0.32 and \$2.04 per m^2 .

Figure 11: Relative Annual Energy Bill Savings Using PG&E and SRP Rates, CZ's 1A-8B.

Figure 11 shows the relative savings on the annual electricity bill for the UTSS models compared to their respective baselines for both utility rates. The average total electricity bill savings across all climate zones for the retail models is 8.0%, while small offices see an average decrease of 4.8%. These savings occur primarily due to reduced demand charges achieved by shifting the cooling load out of the peak periods. Table 3 below summarizes the percent reduction in annual demand charges for each building when the UTSS is used with both the SRP and PG&E rates.

Table 3: Annual Percent Reduction in Demand Charges for Each Building Type Using Both Utility Rates.

Zone	Retail [%]		Small Office [%]	
	SRP	PGE	SRP	PGE
1A	25.2	21.5	29.3	20.7
2A	28.5	23.3	20.6	18.0
2B	28.1	21.0	28.1	22.6
3A	28.6	23.1	16.6	14.7
3B	24.2	20.1	17.4	15.8
3C	16.7	15.0	8.4	8.4
4A	27.4	21.5	13.3	11.8
4B	21.5	18.2	10.5	8.2
4C	23.8	19.9	10.3	10.5
5A	24.4	19.4	10.2	8.8
5B	23.5	20.2	8.7	7.4
6A	22.0	17.6	8.1	8.0
6B	19.4	17.0	4.5	3.7
7A	20.0	16.7	6.8	5.4
8B	11.2	9.9	2.1	2.4

In addition to effectively shifting cooling loads, UTSS may provide a financial advantage compared to a baseline case. Under the TOU and variable demand charge rates analysed in this study, the UTSS does result in significant annual energy bill savings; however, this must be weighed against the original capital expenditure required for these

systems. Locations with negligible cooling loads do not appear promising for UTSS.

Conclusion

This paper presents a new OpenStudio measure that allows users to easily model a Unitary Thermal Storage System (UTSS) in OpenStudio or Parametric Analysis Tool. This measure is applied to two DOE Prototype Building types across 15 climate zones, and four UTSS performance metrics are presented: load shifting effectiveness, energy increase intensity, penalty ratio, and a timestep calculation of the effective *COP* for the UTSS.

Preliminary results show this UTSS effectively shifts more than 92% of the cooling load from the periods of ice discharge but incurs some round-trip inefficiencies. These inefficiencies are captured on a high level with the energy increase intensity (*EII*) and penalty ratio (*PR*) calculations. *EII*'s ranging from 0.1 to 7.9 kWh per m² for the example stand-alone retail models, and -0.1 to 3.6 per m² for the example small office models are observed. Average annual *PR*'s for retail buildings range from 2% to 42% (17.3% average); for small offices, *PR*'s range from -0.5% to 38% (16.3% average). An effective *COP* for UTSS operation is proposed and compared to the *COP* values for AC unit operation. These values illustrate why the penalty ratio exists and can also inform predictive control strategies designed to optimize device efficiency. Finally, a brief financial analysis shows that an average annual electric bill savings of 8.0% for retail buildings and greater than 4.8% for small offices can be achieved by using the UTSS under example TOU electric rates.

While round-trip efficiency metrics can inform scheduling optimization, they do not capture another potential benefit of UTSS: building integrated energy storage for on-site renewable energy generation. If used to store excess photovoltaic generation, the UTSS would likely be operating under adverse ambient conditions. Yet, if net metering is not permitted, or the utility is forced to curtail energy exports, UTSS may be an excellent option. This may be especially advantageous for any building with large end-of-day cooling loads.

Future work in the area of ice thermal energy storage includes the optimization of controls to maximize the building load flexibility in the presence of grid-interactive control signals; comparison of UTSS with central chiller/ice-tank systems; and a study of how to effectively employ UTSS to store excess renewables.

Acknowledgements

The authors would like to thank Colorado School of Mines for supporting this study and the National Renewable Energy Laboratory for their plethora of open source modelling tools. Additional funding support was provided by the ASHRAE Grant-in-Aid program for graduate students.

Nomenclature

- AC – Air Conditioner
- *COP_{Charge}* – Coefficient of Performance for UTSS Coil While Making Ice
- *COP_{Discharge}* – Average UTSS coil *COP* While Melting Ice
- *COP_{UTSS}* – Effective *COP* for UTSS Operation
- CZ – Climate Zone
- *EII* – Energy Increase Intensity
- $\epsilon_{\text{load shift}}$ – Load Shifting Effectiveness
- *PR* – Penalty Ratio
- *SOC* – State of Charge for the UTSS Ice Storage Tank
- TES – Thermal Energy Storage
- UTSS – Unitary Thermal Storage System

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