Abstract (231 of 250 words max):

With the increasing interest in grid-interactive efficient buildings, energy storage technologies in buildings are being re-evaluated for their role in the future grid. Ice thermal energy storage (TES) has a large potential to provide load flexibility to a grid dominated by variable generation assets but requires careful design, analysis, and control to be effective. This evaluation is possible using building energy simulations but is not often done because of the complexity (and added time) related to add ice storage to building simulation models. The objectives of this study are two-fold: (1) automate the addition of ice energy storage to building models through OpenStudio measure scripting and (2) evaluate the load flexibility potential of various TES design and control strategies. This paper presents a new OpenStudio measure that provides the ability to rapidly and accurately model a variety of potential design options and common control schemes. After applying this measure, we then bound the ability of the building to increase or decrease its predicted future electric load over 1, 2, 4, and 6-hour windows using chiller and ice storage performance constraints at each simulation timestep. Results showing the upper and lower limits of facility demand flexibility (kWe) for each timestep are presented to illustrate this potential. Preliminary results indicate that storage-priority control strategies produce more consistent daily flexibility profiles over the cooling season. Our methodology provides a means to quantify and visualize the available electrical flexibility at a given point in time for a building using ice TES.

Intro:

The increased variability of the grid due to the growth of renewable generation assets and distributed energy resources (DERs) requires dynamic demand response for buildings. One of the largest electrical end-uses within buildings is space conditioning, accounting for 9% of the total U.S. electricity production (CITE), and up to 50% of a building’s total electricity demand (CITE). This vast amount of energy use is theoretically controllable through the use of thermal energy storage. Ice has traditionally been used to shift on-peak daytime cooling loads to off-peak nighttime hours, providing significant energy cost savings (CITE); and if properly sized and controlled, a reduction in total energy use (decreased EUI) (CITE). In a grid dominated by renewables however, this strategy may be insufficient – the flexibility of a given system’s design and control sequence should also be assessed.

Building demand flexibility is currently characterized by DOE BTO as (1) energy efficiency, (2) load shifting, (3) load shedding, and (4) load modulation (CITE). The traditional design approach to ice systems is based on load shifting evaluated over a design-day (CITE). Chillers may then be downsized, thereby decreasing capital cost and improving device efficiency during part-load operation. These factors then impact the building’s overall efficiency, with potential to reduce EUI. Ice storage does not lend itself to load modulation as the timesteps (RANGE of s) are too small

Alternatively, ice storage does provide an opportunity for load shedding within a building. Even operating with a traditional load-shifting strategy, the ice available within the storage tank at each point in time can be converted into a temporary reduction in building electrical demand. Conversely, a partially discharged ice tank and/or a chiller operating with a demand limiter provides an opportunity for a temporarily increase in building demand while saving the stored ice for later. This may be a useful service in the event of excess renewables that might otherwise be curtailed. Thus, ice storage system designs and controls should be evaluated for their ability to provide both load shed and load add in a grid-interactive manner.

In order to perform these assessments, detailed whole-building energy modeling that incorporates the ice energy storage model with accurate controls is required. While most BEM software include an ice storage model (CITE), implementation is a time-consuming, custom endeavor, which limits parametric analysis potential. Furthermore, controlling the ice storage models often requires scripting within the HVAC iteration loops in order to achieve performance similar to real-world applications. These challenges have limited the analysis of ITS to date.

It is the objective of this paper to present a method to automate the implementation of ITS within BEM and allow users to quickly define and evaluate a wide variety of potential control schemes, even permitting the testing of a system during a simulated demand response event. This allows rapid parametric analysis of possible ice storage system designs and control strategies. We demonstrate the measure on a single building model, but explore several configuration and control options, examining the impacts on building energy efficiency, load shifting, and load shed/add potentials.

Overview of ITS Modeling – Ref. Memo to NREL/DOE

* Current industry approach (Design Guide)
  + Cite quote on modeling limitations
* E+ and OpenStudio capabilities
* Challenges to getting a working model

Modeling Approach

The BEM engine used for this project is DOE’s EnergyPlus, using the ThermalStorage:Ice:Detailed object (CITE), accessed through the OpenStudio SDK (CITE). The OpenStudio user interface is used for model articulation with integration of ITS configurations and controls is achieved through an OpenStudio measure (aka script). The measure can be implemented directly within the GUI, from the command line, or as part of a workflow (CITE).

The goal of this measure is to provide users access to typical configuration and control options. Configuration (aka hardware) options available to the user include:

* Ice tank position relative to chiller;
* Ice tank capacity;
* Chiller capacity multiplier;

Control strategies possible through the measure are:

* Full Storage;
* Partial Storage:
  + Load Leveling
  + Demand Limiting
  + Chiller Priority
  + Storage Priority

Through this measure, the impacts each design decision may be evaluated at timesteps down to 1 minute, the minimum simulation step for EnergyPlus. Chiller, ITS, pump, fan, and zone temperature values may simultaneously be observed.

Flexibility Evaluation

A variety of building demand flexibility metrics have been proposed in recent years. For this paper will apply the following four metrics: (1) Energy Efficiency, (2) Load Shifting, (3) Load Shed Potential, and (4) Load Add Potential. The first two metrics are evaluated against the baseline building. Load Shed/Add are evaluated for each model that includes ITS.

Building energy efficiency (EE) is a common characterization of a building’s energy performance and is usually presented in terms of Energy Use Intensity (EUI), which is total building site energy use over an annual period divided by floor surface area. ITS may either reduce or increase building EUI depending on equipment type and sizing, local weather patterns, and applied control strategy/sequences of operation.

EUI Equation

Obtaining EE with ITS is a function of the chiller’s change in performance. The variables of interest are the change in annual chiller energy use, total chiller runtime hours, and average annual chiller efficiency, defined by COP here:

Chiller COP Equation

Load shifting is the fundamental application of any energy storage system, and is the predominant design consideration for installing ITS. It must be measured over a complete charge/discharge cycle for the energy storage, which is usually a 24-hour cycle in typical ITS applications. Both maximum change in facility power and total energy shifted are of interest in quantifying load shifting. Benefits for a building owner are best captured through the potential reduction in electricity bills provided by the ITS performing daily load shifting. Load shifting may also be assessed on a seasonal or annual period, though this is most useful from a qualitative perspective by examination of the facility electricity load duration curve.

Average Daily Shifted Load

Percent of Total Load Shifted ea Day

With the development of a future, interactive grid, particularly in the presence of high renewable generation, the paradigm of daytime on-peak, nighttime off-peak may no longer be sufficient. Instead a decoupling of the shedding and addition portions of the traditional load shift metric may be more useful for flexible demand response. Load shedding events become dynamic, occurring in response to grid signals. Similarly, in the event of excess renewables, buildings with ITS may also perform a load add function by ceasing routine ice discharge, or perhaps even charging in order to make use of otherwise curtailable renewable generation. For both metrics, we assume a default ITS control strategy that applies in the absence of a grid signal. This implies that our Load Shed/Add metrics will be a function of the default control; this indeed makes the metrics more useful, as they provide an additional means of evaluating a proposed ITS system in a dynamic environment. Both metrics can be measured by the change in maximum facility power draw over the duration of the event, as well as the total change in building electric energy, relative to the routine operating schedule.

Load Add/Shift Metrics

We evaluate the Load Shed and Load Add potentials in two manners. First, we assess the building over the entire simulation run period by post-processing the electric energy, cooling load, and ITS performance results for a given default ITS control strategy. Second, we apply a demand response signal within the BEM simulation and observe the building performance. This second method is vital in that it can validate the post-processing results, and that it will fully capture the rebound effects incurred by deviating from the default control sequence for the given grid event.

Post-processing assessment allows approximation of the building’s ability to shed/add load over a specified time period and for a specified duration. The fidelity of this approximation is a function of the completeness of the post-processing evaluation, with an upper-limit on accuracy set by fully re-solving the building cooling load calculations at each timestep over the analysis period. However, our goal is to assess an entire simulation run-period, thus necessitating some approximations. We apply the following steps:

1. Specify Duration of Add/Shed Event Analysis (30 min to 6 hours)
2. For every timestep:
   1. Take ITS SOC
   2. Take “Future” Cooling Load (current timestep + duration)
   3. Determine if ITS contains sufficient charge to meet cooling load
   4. Determine if ITS discharge rate is sufficient to meet cooling load
      1. If yes to both, subtract chiller electric power and energy over analysis window
      2. If no, throw a 0 value for kW and kWh Shed – Indicates smarter control logic required (special analysis)
   5. Determine if chiller capacity is sufficient to meet max cooling load
      1. If yes, calculate new average chiller power req over window and add delta (rel. default) to time window.
      2. If no, do the same anyways, but calc new ice discharge reqs.
   6. Approximate predicted ITS SOC after Shed/Add event.
3. Plot Max kW Add/Shed by Grid Event Duration
4. Quantify using histogram or statistical characterization

This post-processing analysis does not attempt to capture any rebound effects, only providing a bound on kW/kWh flex for any given timestep for grid events of specified duration.

In order to capture the rebound effects, we create an in-simulation demand response testing script. Using the EnergyPlus runtime language (ERL) we write an Energy Management System (EMS) script to provide supervisory control for the building cooling system. The code is accessible to the user as an optional method in the same OpenStudio measure we developed to apply ITS to a BEM. It allows a user to specify the following:

1. Type of Event (Add or Shed)
2. Date of Event
3. Start Time of Event
4. Duration of Event
5. Chiller Toggle – in case of insufficient ITS to meet full cooling load during storage
   1. Chiller Off – Force chiller off, regardless of facility demand and ITS SOC
   2. Chiller Backup OK – Allow chiller to turn-on during DR event to meet cooling loads unmet by ice.

This tester is especially valuable in observing the performance of other cooling system components, such as fans, pumps, and zone temperatures during a DR event. It also allows analysis of ITS rebound effects, which may impact building energy performance many hours after the termination of the DR event.

Demonstration Model

The development of this ITS measure, with its particular in-simulation control capabilities and demand response event testing script, allows a broad range of ITS analysis from BEM simulation. To demonstrate this analysis, we select a DOE Prototype Secondary School (hereafter School) building model in climate zone 2A, using a Houston, TX typical meteorological 30-year weather file. We select this model and location because it requires zone cooling over the entire year, cooling systems constitute a high portion of the total building electric load, and the model uses a central chilled water loop with an air-cooled chiller. In order to facilitate study replication, we perform no modifications to the School apart from adding ITS via the OpenStudio measure. A simulation timestep of 15 minutes is used for all models.

Four control schemes are modeled and compared using the flexibility metrics described above.

1. Partial Storage 08-21, Chiller downsized to 60%, 70% Capacity Limiter, Chiller upstream
2. Partial Storage 08-21, Chiller downsized to 60%, 68% Capacity Limiter, Chiller up
3. Partial Storage 08-21, Chiller downsized to 70%, 65% Capacity Limiter, Chiller up
4. Full Storage 09-18, No Downsize (charge 21-07)
5. Partial Storage, 08-21, Chiller downstream, 70%, no limiter, 4 deg F across chiller during day

ITS parameters held constant for all configurations:

* 08-21 Discharge
* 23-07 Charge \*Except Full Storage
* 25F Charge Temp
* 44F Loop Temp
* 2000 Ton hours \* Except Full Storage

Successful implementations of ITS may be easily checked by examining chiller evaporator cooling rate, ITS cooling charge and discharge rates, ITS state of charge, and unmet cooling hours. Detailed assessment of the results will inform further analysis, which is now easily accomplished through parametric application of the measure.

For the detailed load flexibility analysis, we select configuration C60L70.

Results

Part 1: Assessing School performance with ITS relative to Baseline DOE Prototype

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Model | EUI [kBtu/ft2] | Peak Demand [kW] | Chiller Electricity [MWh] | Chiller Average COP [-] | **Annual Runtime** | Min ITS SOC |
| Baseline | 49.49 | 989 | 963 | 2.55 | 5945 | N/A |
| Full | 50.10 | 797 | 980 | 2.71 | 4346 | 12.3% |
| Partial 1 | 49.26 | 795 | 942 | 2.76 | 6286 | 14.3% |
| Partial 2 | 49.60 | 801 | 963 | 2.68 | 5794 | 11.4% |
| Partial 3 | 48.85 | 771 | 921 | 2.78 | 6028 | 5.6% |
| Partial 4 | 48.81 | 764 | 918 | 2.79 | 6029 | 1.5% |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model | Chiller Capacity [tons] | Limited Capacity [tons] | Storage Capacity [ton-hours] | Charge Window | Discharge Window\* |
| Baseline | 578 | N/A | N/A | N/A | N/A |
| Full | 578 | N/A | 3200 | 2100-0700 | 0900-1800 |
| Partial 1 | 405 | N/A | 2000 | 2300-0700 | 0800-2100 |
| Partial 2 | 405 | 263 | 2000 | 2300-0700 | 0800-2100 |
| Partial 3 | 347 | 243 | 2000 | 2300-0700 | 0800-2100 |
| Partial 4 | 347 | 246 | 2000 | 2300-0800 | 0800-2100 |

\* Weekdays Only

Plot: September Average Day

Plot: Load Duration Curves

Part 2: Assessing School performance for Load Shed Flex:

Summary Table: Full-Storage Shed Flex

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | All Hours (Annual) | | Occupied Hours Only | |
| Event Duration [hours] | Average Shed [kW] | Full Flex Availability | Average Shed [kW] | Full Flex Availability |
| 0.5 | 133 | 65% | 123 | 71% |
| 1 | 130 | 62% | 118 | 71% |
| 2 | 132 | 59% | 116 | 68% |
| 3 | 132 | 57% | 115 | 65% |
| 4 | 128 | 55% | 113 | 62% |
| 5 | 120 | 51% | 107 | 57% |
| 6 | 110 | 47% | 99 | 50% |

Occupied hours defined as 08:00 – 21:00 weekdays throughout the year. An event is considered to have occurred during occupied hours if it starts during that window, regardless of when the event terminates.

Plot: Example Week or Day Shed Bounds

Plot: Histogram

Part 3: Assessing School performance for DR Event

Summary Table: Compare DR Event to Predictions

Plot: Example DR Event (short)

Plot Example DR Event (long, w/chiller modes)

Conclusions

* Benefits of in-simulation ice modeling
* Measure to permit rapid evaluation of different configs and controls
* Post-processing to predict add/shed kW
* In-simulation testing to evaluate add/shed kW

Future Work

* True Demand-Limiting Control (useful after equip selection)
* More-realistic in-simulation control (chiller delta-t fixed while upstream, varied daily)
* More assessment of flexibility provided by ITS, metric to characterize system as an eval tool for GEB