Simulations of Grid-Responsive HVAC Cooling Measures via Ice/PCM storage

Bo Shen, Oak Ridge National Laboratory, USA

This study uses EnergyPlus building energy simulations to assess grid-responsive HVAC cooling measures during peak hours having high electricity prices, including: lock the high capacity of a two-speed cooling coil during grid-response hours; and use ice/PCM energy storage to drive a chilled water coil and meet the cooling load, when shut off the main electric cooling coil. The impacts on peak power reductions, energy and utility cost savings, as well as comfort levels in residential buildings of two U.S. cities, were revealed.

Grid response involves strategically shifting demand for electric power to avoid overloading the grid during peak demand. The effect of demand response is usually referred to as "peak shaving" and "valley filling".

Over the past decade, a number of control strategy and scheduling planning methods have been developed to address the demand response problem of DX (direct expansion) cooling systems. For example, cooling system energy costs can be reduced using thermal storage in building mass, or ice storge/phase change material (PCM) storage. Very few studies are available addressing how to achieve grid response by directly modulating the speed of compressor. Compared with other strategies, such as regulating the set-point temperature of smart thermostat and scheduling the heat pump to periodically start up and shut down, modulating the compressor speed does not require a balance period between building load and cooling capacity, and therefore is highly responsive.

Before implementing the grid-responsive load shifting measures, it is necessary to simulate the impact on peak power reduction, energy and utility cost savings, and comfort levels in template buildings over a wide range of climate conditions. EnergyPlus is a whole-building energy simulation engine developed by the U.S. Department of Energy. This study aims to utilize and improve EnergyPlus to simulate grid-responsive, flexible HVAC (heating, ventilation, air conditioning) cooling measures.

Energyplus grid-responsive cooling measures

Grid Signal Schedule

A grid signal can represent any variations related to the power grid. Figure 1 depicts hourly electricity prices (cents) in the summer (cooling season). This is the typical pricing pattern in the cooling season based on average prices for January 2016 through December 2019 provided by the ComEd Company, the sole electric provider in Chicago and much of Northern Illinois. The grid signal can be described using the EnergyPlus feature of Schedule: Compact.

Grid-Responsive Multi-Mode Coil Collection with Ice/PCM Storage

During a grid-responsive period, a cooling coil may be required to run at a reduced capacity than what is required by the building load. It may operate differently from its normal mode, for example, reduce the air flow ratio

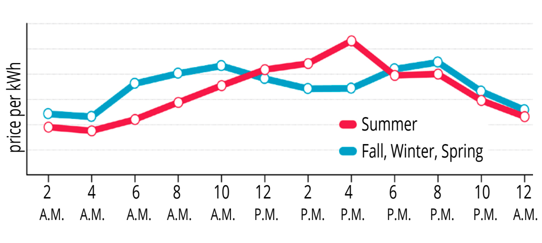

Figure 1: Grid signals (hourly electricity prices) represented by a schedule.

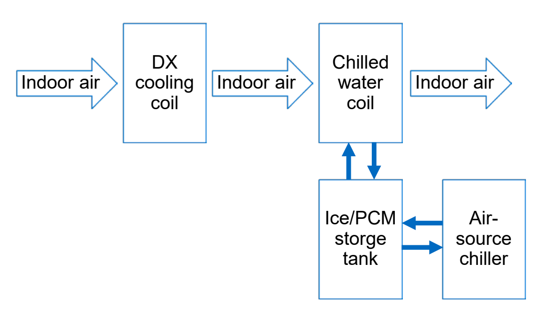

Figure 2: System configuration of a variable-speed DX cooling coil integrated with an ice/PCM energy storage, water cooling coil and an air source chiller.

relative to its delivered capacity, and thus the moisture removal may be enhanced for better comfort level. We need to incorporate multi-mode cooling coils with capacity modulation and enhanced dehumidification.

The multi-functional unit used in the simulation is based upon the EnergyPlus air-source Integrated Heat Pump (IHP). The IHP object was expanded to include a variable-speed air-source chiller, which charges an ice/PCM storage tank defined in the IHP. The configuration of integrating a DX cooling coil with supplemental chilled water coil, ice/PCM storage tank and an air-source chiller to charge the tank is given in Figure 2.

Building Energy Simulations

We selected single-family homes with slab foundations in Atlanta, Georgia (representing a typical southern climate), and Indianapolis, Indiana (representing a typical northern climate), to assess the grid-responsive cooling measures via building annual energy simulations. The single-family homes were from the EnergyPlus library of template buildings. They were built according to the IECC (International Energy Conservation Code) 2006 energy code specific to individual climate zones. The cooling set point is 23.3°C throughout the year.

To assess the grid-responsive cooling measures, we follow the grid schedule in Figure 1, and start a grid-responsive operation when the hourly electricity price is above 10 cents/kwh, which roughly covers the period from 12 pm to 6 pm in each cooling day.

Limit high capacity of modulating cooling coil with/without enhanced dehumidification

A two-speed DX cooling coil in each home was auto-sized to match the building design cooling load at the high speed. The low speed has approximately 75% capacity of the high speed. In the two cities, we conducted annual simulations, comparing three scenarios: 1) the DX cooling coil to match the building load as needed, without a grid response (baseline); 2) turn on a grid responsive control to only run the compressor low speed with its normal air flow rate, during the specified grid-responsive hours (modulating with normal flow); 3) use a grid responsive control with enhanced dehumidification, i.e. running the compressor at a low speed with 50% reduced indoor air flow rate (enhanced dehumidification). Figures 3 and 4 below illustrate a controlled zone temperature and relative humidity during a peak cooling day in Atlanta. After locking the top capacity, neither the operation at the low speed with normal air flow nor with enhanced dehumidification can meet the zone sensible load, which resulted in lost control of the zone temperature. The option with enhanced dehumidification resulted in the highest impact on the temperature because of its smaller capacity. On the other hand, this option controlled the indoor relative humidity below 40%.

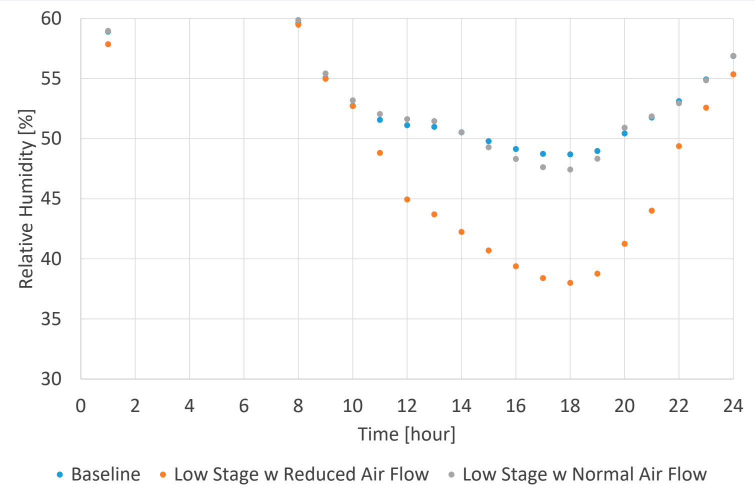

Figure 3: Controlled zone temperature during a peak cooling day.

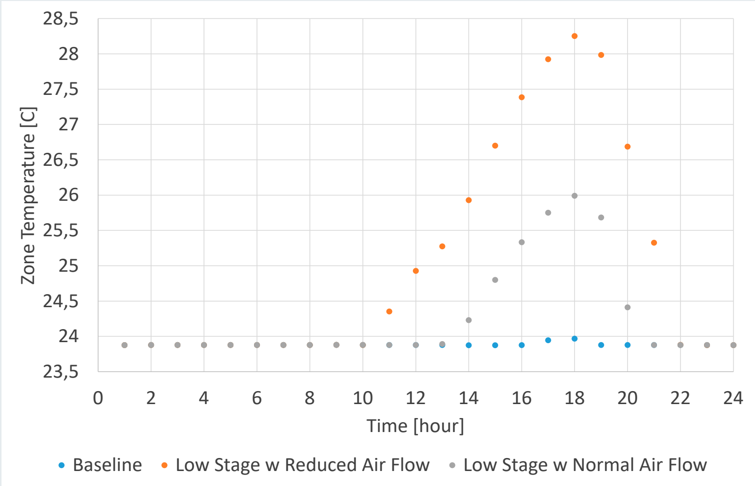

Figure 4: Controlled zone relative humidity during a peak cooling day.

Table 1: Cooling seasonal energy simulations in Atlanta, with locking high speed during grid-responsive hours.

Atlanta	Cooling Delivery	Electricity consumption	Seasonal COP	Price	Un-comfort hours	Peak Power Reduction
Unit	kwh	kwh	W/W	USD	> 27°C, 50% RH	%
Baseline	11069.8	2423.0	4.57	251.1	0	0
Modulating w Normal flow	10957.1	2381.1	4.60	246.1	0	26%
Enhanced dehumidification	11187.2	2691.2	4.16	281.9	0	28%

Table 2: Cooling seasonal energy simulations in Indianapolis, with locking high speed during grid-responsive hours.

Indianapolis	Cooling Delivery	Electricity consumption	Seasonal COP	Price	Un-comfort hours	Peak Power Reduction
Unit	kwh	kwh	W/W	USD	> 27°C, 50% RH	%
Baseline	8351.5	1797.5	4.66	191.7	0.0	0%
Modulating w Normal flow	8205.3	1741.8	4.72	184.7	6.0	27%
Enhanced dehumidification	8346.4	1954.5	4.28	209.0	12.0	28%

Table 1 shows the annual energy simulation results from Atlanta. The total cooling energy delivered is identical among the three scenarios. Generally, a cooling coil is sized to match the building's maximum cooling load at the peak ambient temperature in the climate zone. Therefore, the low-speed operation (75% capacity) is still able to satisfy the building load on most occasions except a small range around the highest ambient temperature. During the grid-responsive hours, the zone temperature increases due to top capacity locking. After the grid-responsive period, the DX cooling unit recovered the zone air and envelope to the original setting temperature. Consequently, the grid responses did not reduce the total cooling demand noticeably. Due to the reduced indoor air flow rate, the enhanced dehumidification causes lower seasonal cooling COP, i.e., 4.16 versus 4.57 of the baseline. As a result, the enhanced dehumidification leads to more seasonal electricity consumption and higher electricity costs. Limiting the top cooling capacity did not reduce the electricity cost, but resulted in a 26–28% peak power reduction. Both the modulating with normal flow and enhanced dehumidification maintained the zone temperature below 27°C and relative humidity below 50%, i.e., with minor impact on the comfort level.

Table 2 shows the annual energy simulation results from Indianapolis. The trends are the same as Atlanta, except with more uncomfortable hours with the indoor air temperatures >27°C and relative humidity >50%.

Ice/PCM Storage

When coupled with an ice/PCM storage as shown in Figure 2, the compressor is turned off during grid-responsive hours, while running the air flow rate corresponding to the high (nominal) compressor speed. The storage tank drives the chilled water coil to provide supplemental cooling. The water coil supply air temperature is controlled at 13.0°C.

The air-source chiller was auto-sized together with the DX cooling coil to maintain a constant ratio between the rated capacities. When the solid ice/PCM fraction is below 90%, it calls the chiller to start charging until the fraction reaches above 99%. The chiller is only allowed to run when the electricity price is below 10 cents, i.e., during non-grid-responsive hours.

To simplify the analyses, it is assumed that the ice storage tank has a constant exit temperature of -0.5°C to the chiller during charging, and 7.2°C to the water coil during discharging. The PCM storage tank has an exit temperature of 4.5°C to the chiller during charging and 10.0°C to the water coil during discharging. The PCM has an onset phase change temperature of 5°C and termination temperature of 6°C. The heat transfer UAs (U = overall heat transfer coefficient, A = heat transfer area) are auto-sized to satisfy the temperature settings.

Table 3 presents cooling energy simulation results when coupled with ice storage and PCM storage in Atlanta. During the grid-responsive hours, the ice/PCM cooling storage drove the water coil to meet the zone load. The total cooling energy delivered and total electricity consumption contains the energy from both the DX cooling coil and the air source chiller during non-grid-responsive hours. It can be seen that the chiller delivered capacity to the storage tank, amounting to 70% of the total cooling energy delivered, because the grid-responsive periods involve the major cooling load. Although the energy consumptions of ice and PCM storages are higher than the baseline, their seasonal electricity price are lower, since the charging operations use low-cost electricity in off-peak hours. The electricity consumption and cost of the PCM storage is lower than the ice storage because the PCM storage corresponds to higher coolant charging temperature, which elevates the chiller COP.

Table 3: Cooling seasonal energy simulations in Atlanta, coupled with ice/PCM energy storage.

	Total Cooling Delivery	Total Electricity consumption	Total Seasonal COP	Price	Chiller Delivery	Chiller Electricity Consumption	Chiller COP
	kwh	kwh	W/W	USD	kwh	kwh	W/W
Baseline	11069.8	2423.0	4.57	251.1	0	0	0
Ice Storage	11004.1	2830.0	3.90	191.9	7842.0	2189.3	3.6
PCM Storage	10806.7	2523.6	4.28	175.0	7634.2	1881.8	4.1

Table 4: Cooling seasonal energy simulations in Indianapolis, coupled with ice/PCM energy storage.

	Total Cooling Delivery	Total Electricity consumption	Total Seasonal COP	Price	Chiller Delivery	Chiller Electricity Consumption	Chiller COP
	kwh	kwh	W/W	USD	kwh	kwh	W/W
Baseline	8351.6	1797.6	4.66	191.7	0	0	0
Ice Storage	8526.6	2156.2	3.96	150.1	6313.6	1715.8	3.7
PCM Storage	8374.9	1921.9	4.37	137.1	6155.5	1481.1	4.2

Table 4 presents cooling energy simulation results when coupled with ice storage and PCM storage in Indianapolis. It indicates the same trends as for Atlanta.

Conclusions

The EnergyPlus building energy simulations imply that locking the high capacity of a modulating, cooling coil, from 100% to 75% during the grid-response hours, can effectively reduce the peak power consumption up to 28%. The strategy impairs the comfort level only to a minor extent. Enhanced dehumidification at the low speed is able to reduce the indoor relative humidity at the expense of lower cooling efficiency. Ice/PCM storages coupled with a DX cooling coil are able to eliminate nearly all the peak power consumption, excluding the indoor fan power. They result in lower electricity bills due to mainly using low-cost electricity during off-peak hours.

References

[1] ComEd Company, typical pricing pattern in cooling season based on average prices for January 2016 through December 2019, https://hourlypricing.comed.com/live-prices/

[2] U.S. Department of Energy, EnergyPlus, https://energyplus.net/

BO SHEN
Oak Ridge National Laboratory
United States of America
shenb@ornl.gov
https://doi.org/10.23697/z1jv-1x76