On the Feasibility of Providing Power System Spinning Reserves from Thermal Storage

Santiago Naranjo Palacio, Kevin J. Kircher and K. Max Zhang[1]
Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853

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Abstract

As power systems integrate more intermittent renewable generation, and as extreme weather events become more frequent with climate change, power systems are likely to require increasing amounts of spinning reserves in order to maintain reliable operation. While traditionally spinning reserves have been supplied by generators, demand-side resources can also provide reserves by increasing or decreasing consumption in response to system needs. As a major contributor to peak system loads, air conditioning equipment is a promising source of demand-side spinning reserves. Through building energy modeling and simulation, this paper demonstrates, for the first time, the technical feasibility of providing spinning reserves by curtailing air conditioning systems in commercial buildings, while maintaining occupant comfort by providing cooling from thermal storage. The economic benefits to the building owner are shown to be attractive, primarily due to capacity payments in the spinning reserves market. Furthermore, it is possible for a building equipped with thermal storage to participate in both frequency regulation and spinning reserves markets for more economic benefits as spinning reserves are less frequently deployed.

Keywords: Spinning Reserves, Demand-side Resources, Building Systems, Thermal Energy Storage, Ice Storage

Terminology

SR	Spinning reserve
TES	Thermal Energy Storage
NYISO	New York Independent System Operator
DA	Day-ahead
RT	Real-time

1. Introduction

Power system ancillary services are reliability products that can quickly adjust their power output in response to network contingencies such as voltage drops, line or generator failures, or rapid changes in electricity supply or demand. Currently, natural gas combustion turbines and hydroelectric generators provide most of the ancillary services. As renewable energy becomes a significant source of electricity [1], and the frequency and severity of extreme weather events continues to increase [2], concerns over the effects of renewable energy intermittency and peak electricity demand on power system reliability have grown. As a result, the ancillary services market is predicted to see increasing need for their two highest-value products: regulation capacity [3,4] and spinning reserves (SR) [5,6]. The former is deployed within seconds to

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[1] Corresponding author; Email: kz33@cornell.edu, Tel: +1-607-254-5402; Fax: +1-607-255-1222

compensate for frequency deviations, and the latter is deployed, typically, within 10-30 minutes to compensate for sudden failures of generation and transmission.

With growing electricity demand and retirement of fossil plants, supply-side resources may become scarce. As a result, the debate over the role of demand-side resources in the ancillary services market has been gaining traction in different sectors. In the U.S., some independent system operators and regional transmission organizations have started to modify requirements to allow demand-side providers to participate in the ancillary services market [7–9]. These operational changes have encouraged studies to showcase the ability of non-traditional resources to provide ancillary services [10,11]. To date, several studies have investigated the feasibility of demand-side frequency regulation services using building thermal mass, HVAC systems and electric vehicles [12–16]. Moreover, a number of demonstration projects showed that direct load control of air conditioners can provide spinning reserves [17–19], providing superior response to generators, as the curtailment of load is typically much faster than ramping thermal or hydropower plants.

While direct load control is fast and scalable, it runs the risk of inconveniencing building occupants by allowing temperatures to drift outside the range of comfort. This concern is particularly important in commercial buildings, where the productivity of occupants is far more valuable than revenues from providing SR. This project seeks to develop an alternate approach, so far unexplored in the literature, to provide cooling from thermal energy storage (TES) during SR deployments. If feasible, this approach would have the advantage of guaranteeing occupant thermal comfort during SR deployments.

TES is a mature technology that has been used for decades to shift cooling loads in buildings away from times of high electricity prices, reducing electricity costs [20] and providing valuable services to utilities [20–22]. A typical (cold) TES system consists of one chiller that directly meets load, another chiller that makes ice, and an insulated storage tank. Such systems are typically operated with heuristic schemes like chiller priority, storage priority, or constant proportion control [23]. In recent years, however, various researchers have applied model predictive control to thermal storage, with encouraging results [24,25]. We will show that this two-chiller structure for TES in commercial buildings is ideal for providing SR services.

This project has the following objectives: (1) to investigate the feasibility of providing demand-side SR through TES, (2) develop a model to simulate the operation of TES under SR deployment, and (3) explore the economic benefits to the building owner of participating in the SR market. The particular context is the New York Independent System Operator (NYISO), whose SR markets are representative of other North American systems. Because of the high market value [8,26–28], this paper focuses on 10-min SR, a category wherein resources must respond to a deployment call within 10 minutes. From here on, we will refer to these resources simply as SR.

This paper is organized as follows. Section 2 describes the NYISO SR market in detail. Section 3 discusses the physical and financial aspects of the building model. Section 4 presents the following results: (1) that SR provision through thermal storage is technically feasible; (2) that it appears economically attractive; and (3) that it can be done with no inconvenience to building occupants. The findings in this paper are valuable in facilitating the growth of TES and demand-side SR markets for an efficient and renewable power system.

2. Spinning Reserves (SR)

2.1 Minimum SR Requirements

The main role of SR is to ensure the reliability of the electric system in the case of a contingency, where load serving entities (LSE) need to provide a minimum number of reserves in proportion to their loads. NYISO requires that SR capacity equal or exceed the largest possible contingency [29]. This requirement increased from 600 MW in 2011 to 655 MW in 2012 [27] following an increase in the system's largest generator [27].

2.2 NYISO SR Market Operation

NYISO operates a day-ahead (DA) and a real-time (RT) market that permit the co-optimization of energy and ancillary services [8]. Using this approach, NYISO can simultaneously determine energy and reserve prices and schedule dispatch levels. SR are part of the ancillary services market and settle on both the DA and RT markets. For NYISO, as with most system operators, the market settles in the following manner. In the DA reserves market, resources can submit offers by providing their availability and amount of power they can provide. The market operator then determines which offers to accept by solving the DA security-constrained economic dispatch. During the DA market, a great majority of hours will have a non-zero settling price, as resources are committed. Offers that are not accepted in full are passed to the RT market. If during the RT, the system operator determines that more reserves are needed, it will accept offers from available resources, and will thus post non-zero settling prices in the RT SR market.

2.3 Reserve Shortage

As demand for resources to provide energy and/or SR services increase, availability of inexpensive resources to provide SR decreases, forcing the system to use more expensive resources, causing the price of SR to increase. Once the marginal cost of scheduling a reserve increases beyond the "demand curve" set by the different market operators for their reserves, currently $500/MW in NYISO, the market is unable to schedule the minimum operation reserves requirement, and a reserve shortage occurs [27]. These types of events reduce system reliability, as insufficient amount of reserves are available to support the grid in the case of a contingency.

2.4 Reserve Deployment

After all the necessary reserves are scheduled and committed, resources will be responsible to provide their services if needed. However, only a fraction of available resources are deployed during regular operation. In order to understand deployment frequency and deployment duration for the region of interest, we analyzed NYISO historical data for SR deployment between 2001-2013 [30]. Using this data, we found that reserves were deployed an average of 243 times annually with a standard deviation of 92 instances, where the maximum deployment instances occurred in 2007 at 438 instances and the minimum occurred on 2011 with 126 deployment instances, as seen on Figure 1a. Furthermore, the data analyzed showed that all deployments tend to be short as shown on Figure 1b, where the average and median historical deployment duration were 7.2 and 6.8 min, respectively, with a standard deviation 5.8 min. Here, it is important to note that there were 12, 8, and 3 instances not shown on Figure 1b, where deployment exceeded 30, 60, and 90 min, respectively.

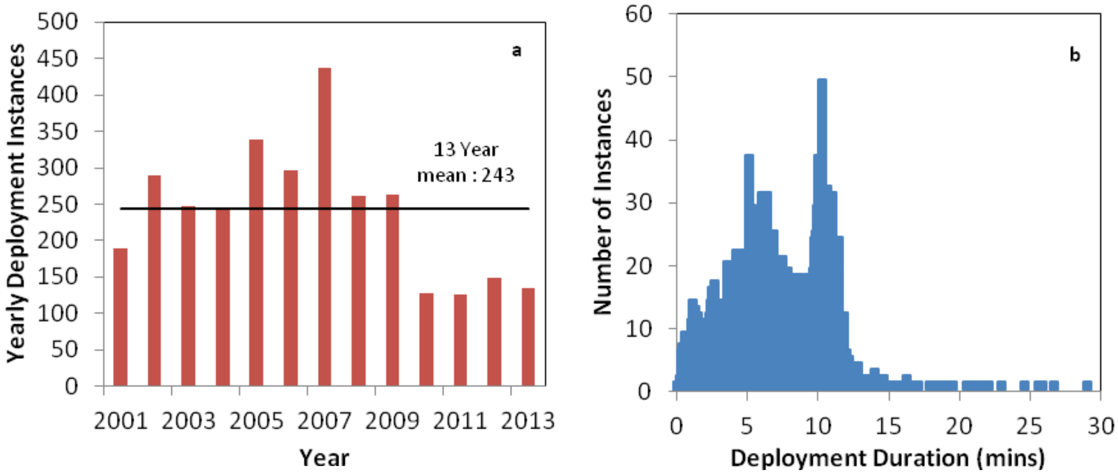

Figure 1: Historical SR deployment for 2001-2013 to show a) yearly deployment instances b) number of deployment instances based on deployment duration

Through analyzing the reserve deployment data, we discover that the likelihood of reserves scheduled on the DA or RT market to be deployed has decreased in the last four years, where four-year averages have steadily decreased since 2009 at an average rate of 16% per year. Furthermore, assuming that reserves could only be deployed once every hour, we find that reserves are on average deployed 2.77% of the available time-slots in a year. Moreover, we also find that 75% and 98% of all deployment instances experience a duration length shorter than 10 and 15 min, respectively.

3. Methods

Using some of the market principles outlined in Section 2, we build a platform to investigate how an individual building would participate in the NYISO SR market using TES and what their potential benefit of doing this would be. In this analysis, we only consider the DA SR market, as DA payments, when compared to RT payments, occur with higher frequency, providing a stable incentive. Moreover, the cost structure for demand-side resources allows them to provide cheaper SR than traditional generators. For this reason, we assume that all of the building's offered capacity is accepted in the DA SR market.

In order to estimate the potential benefit to the end-user, we study the month of July 2013, dividing it into four 5-day periods in order to see weekly performance variability for this period. Here, we describe the platform where a physical and a financial model interact to simulate operation and economic implications for a building participating in the SR market.

3.1 Simulation Platform

A simulation platform is developed on TRNSYS, a software package used to solve the transient heat flow equations associated with building thermal performance and TES operation, as well as evaluating the corresponding building electricity consumption and electricity costs. This simulating platform is composed of three main components: a physical model, a financial model, and a decision model, as shown by Figure 2. Through interaction between these three models, the simulation schedules TES operation to maximize financial benefits to the end-user. The simulation operates in the following manner. The financial model contains information on rate schedules, DA SR settling prices and wholesale electricity prices, and passes this information onto the decision model. At the same time, the physical model determines building energy consumption given scheduling constraints provided by the decision model. The decision model then determines TES scheduling to reduce the net cost to the end-user.

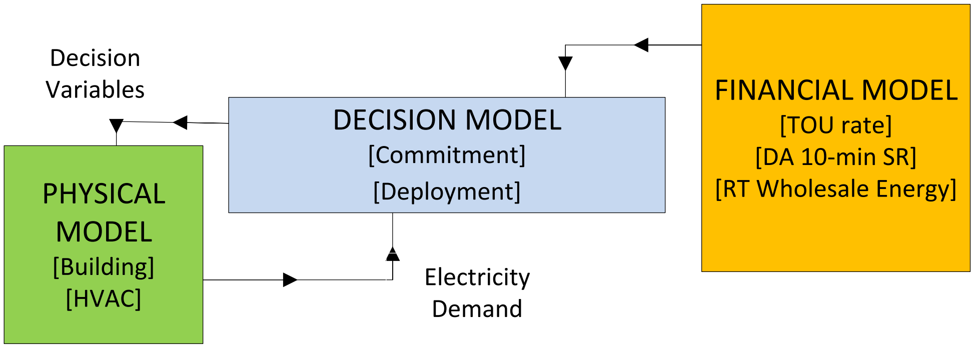

Figure 2: Components of the simulation platform

3.2 Physical Model

The physical model on the optimization platform consists of a building, an ice storage tank, and a two-chiller system. The following sections describe how each of these components was modeled.

3.2.1 Building Model

The modeled building used in this study follows the ASHRAE 90.1 Prototype Building standards [31], which reflects a typical air-conditioned new construction 3-story 153,000ft^2 (i.e., 14,214m^2) office building. A simplified building model for this ASHRAE building is available in the TESS libraries in TRNSYS [32]. This model was modified for this study in order to account for the internal gains of the building and to incorporate an HVAC system in accordance with ASHRAE standards. Moreover, as specified by ASHREA, a building occupancy schedule is incorporated to reflect diurnal variation of building use.

The model developed here simulates the cooling that the building needs in order to maintain the thermal comfort in each thermal zone, as specified by ASHRAE standards. Total electricity demand for the building is then obtained by estimating the standard *fixed load* electricity consumption profile for lighting, plug-loads, and ventilation systems [33–36], and adding them to the electricity consumption associated with cooling demand.

3.2.2 TES and SR Mechanism

To maintain occupant comfort during business hours, the cooling system must maintain an ASHREA-recommended set-point temperature of 24 °C, where a two-chiller system is used to maximize efficiency and reduce chiller size requirement [37]. As a result, the system has two separate loops shown in Figure 3: the glycol mixture loop for ice making and the water loop that provides continuous cooling load to the building, shown in green and blue, respectively. This system operates in three different modes: ice-making/charging, ice-thawing/discharging, and SR deployment.

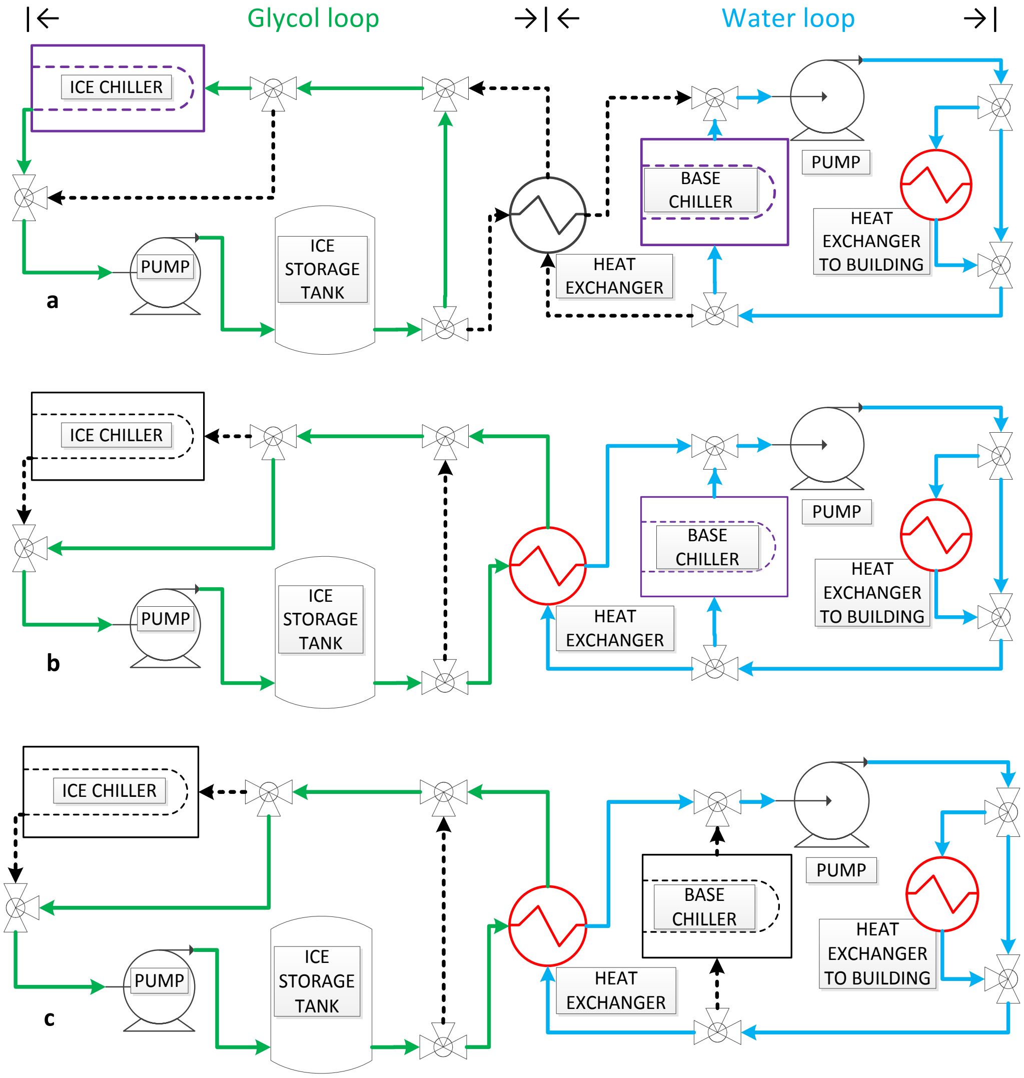

Figure 3: Schematic representing TES system operation during a) the ice-making mode b) the ice-thawing mode and c) the SR deployment mode. Operating components are shown in color, while non-operating and always-on components are shown in black

The ice-making mode, shown in Figure 3a, consists of both the glycol and the water loop running independently of each other. The glycol loop is used to transfer cooling from the *ice chiller* to the ice storage tank, thus making ice, while the water loop is used to provide direct cooling needs to the building. This mode is exclusively used during times when the *base load chiller* can provide all of the cooling needs of the building, which, given cooling demand patterns, happens only during the night and early morning.

The ice-thawing mode, shown in Figure 3b, operates when the glycol loop is connected to the water loop via a heat exchanger in order to supplement the cooling load. As the heat transfer between the water and glycol loop takes place, the amount of ice available in the storage tank decreases. The discharging mode takes place at times when the *base load chiller* alone cannot provide all of the cooling needs of the building. During these times, the *base load chiller* runs at full capacity; providing 30% to 40% of the peak cooling load. This mode is used during late morning to early evenings, where cooling demand is highest.

SR deployment is a mode of operation that can be used in order to respond to deployment calls, as shown in Figure 3c. This mode functions by turning off the *base load chiller* and providing the entire cooling load through the ice storage tank, thus significantly reducing power demand and complying with SR commitment.

3.2.3 Chillers

The two chillers mentioned above, i.e., the base load chiller and the ice chiller, are both modeled as air-source chillers. The *former* uses water as a refrigerant and operates at a temperature of 3°C with a rated COP of 3.6. The *latter* uses glycol as a refrigerant, and operates at a temperature of -6.67°C, and has a rated COP of 2.8. Performance data for both chillers were obtained from chiller data sheets for a TRANE chillers [38]. The *base load chiller* and *ice chiller* are sized at 75 and 75 tons (of refrigeration), drawing 72 and 93 kW_e, respectively.

3.2.4 Ice Storage Tank

The ICEPIT ice storage tank developed by Hornberger [39] was used for the TRNSYS implementation of the TES. The parameters for the ICEPIT were obtained following the ICEPIT validation presented by Christophe and Philippe [40].

3.3 Financial Model

The financial model is used to provide the platform with the different financial information needed to operate. This part of the model contains the TOU electricity rate, the DA SR prices, as well as the wholesale RT electricity prices.

3.3.1 Time-of-Use Rate

A 3-tiered TOU rate [41] was used as shown in Figure 4 where the on-peak price is $0.23/kWh, the medium-peak price is $0.19/kWh and the off-peak price is $0.063/kWh. Moreover, we consider a demand charge of $22.34/kW-month. However, comparing simulation results to a SR deployment case, we found that demand charges do not change when compared to typical TES operation. Consequently, from here on, we will only discuss energy prices.

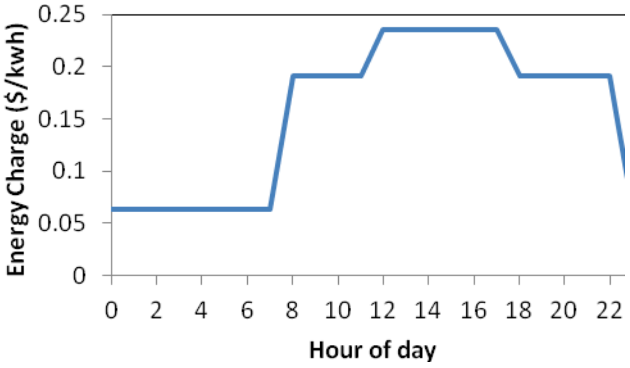

Figure 4: Daily 3-tiered TOU pricing used

3.3.2 Energy Cost

Let $P \in \mathbb{R}^{24\times 7}$ be a matrix containing the average power consumption P_{ij}(kW) during the i^{th}hour of the j^{th}day for a 5-weekday period. The formulation used to obtain electricity cost g_e ($), is shown in Eq. (1):

$$g_e(P) = \sum_{j=1}^{5}\sum_{i=1}^{24} c_{ij}P_{ij}\Delta t \tag{1}$$

where c_{ij} ($/kWh) represents the energy charge during hour *i* of day *j*.

3.3.3 SR Commitment

Given the load cooling demand during off-peak hours for the type of building described here, it is a challenge to find the best strategy to place offers during times where capacity payments are low and SR deployments happen regularly. For this reason, we limit the periods when SR can be provided to on-peak times when the *base load chiller* is operating at full capacity.

In order to successfully place offers on the SR market, the building operator predicts the amount of power the building can curtail by turning the *base load chiller* off and offers this in the DA SR market. For our purposes, we assume the building manager can easily and accurately predict cooling demand in a 5-day horizon, and places offers accordingly.

For the case described here, the building manager sends weekly capacity offers, B_{ij} (kW-hr), by using the formulation described by Eq. (2):

$$B_{ij}(P) = \prod_{j=1}^{5}\prod_{i=1}^{24} z_{ij}b_{ij} \tag{2}$$

where b_{ij}(kW-hr) represent the amount of power the building can provide as reserves for a one-hour period, and z_{ij} is the availability offer represented by a binary function of the form

$12 \leq i \leq 19 \qquad z_{ij} = 1$

$else \qquad\qquad z_{ij} = 0$

where 12-19 represent the hours when the base-load chiller is operating at full capacity and thus capable of providing a significant amount of SR.

3.3.4 SR Capacity Payment

We assume that the building behaves as a price-taker and that their offer will be accepted at the closing price for the market. So for any of the offers accepted to provide SRs, the payment made to the building manager, $p_{DA}(P)$ (\$), is determined using the closing market price for the DA SR, D_{ij} (\$/kW-hr) as shown in Eq. (3).

$$p_{DA}(P) = \sum_{j=1}^{5} \sum_{i=1}^{24} D_{ij} B_{ij} \tag{3}$$

Moreover, because demand-side resources are relatively cheap and to simplify the problem, we will assume that all offers will be accepted.

3.3.5 RT Deployment Payment

Whenever the grid-operator deploys a SR resource that has been committed on the DA (or RT) market, the grid-operator must make a payment, $p_{RT}(P)$ (\$), to the resource for the amount of energy provided (curtailed) based on the wholesale energy price as described by Eq. (4):

$$p_{RT}(P) = \sum_{j=1}^{5} \sum_{i=1}^{24} R_{ij} C_{ij} \tag{4}$$

where C_{ij} (kW-hr) is the amount of load deployed, curtailed, by the demand-side resource in accordance to their DA offer and R_{ij} (\$/kW-hr) is the RT wholesale energy spot-price.

3.3.6 Net Cost

The net cost to the end-user, $J_B(P)$ (\$), is then calculated by subtracting capacity and deployment payments from energy costs as shown by Eq. (5):

$$J_B(P) = g_B(P) - p_{DA}(P) - p_{RT}(P) \tag{5}$$

where the net cost to an end-user that does not participate in the SR market is represented by the energy costs alone.

3.3.7 RT Deployment

Table 1: SR Deployment for weekdays July 2013

	Deployment Duration (min)				
	Monday	Tuesday	Wednesday	Thursday	Friday
Week 1	N/A	N/A	7.5	N/A	15

Week 2	N/A	N/A	15	15	N/A
Week 3	21	21	7.5	7.5	N/A
Week 4	N/A	15	7.5	N/A	N/A

To test the platform presented here, we used historical NYISO SR deployment data (as discussed on section 2.4) for the month of July in 2013 [30] as shown on Table 1, for reference. In this table days with a SR deployment are marked by the duration of the event, where the actual duration is rounded up to match the simulation time steps.

3.3.8 TES Operation Scheduling

TES operation is scheduled in the following manner. The ice-chiller operates on a fixed schedule, turning on at 11:00 PM and turning back off at 8:00 AM. The base load chiller remains on at all times, with the exception of times when SR are deployed. Whenever there is a SR deployment signal, the decision platform turns the base load chiller off. The base load chiller remains off until another signal is sent to end the deployment event.

4. Results

In order to show that demand-side resources can provide SR services, we discuss the operation and financial effects of responding to a SR deployment call.

4.1 Chiller Operation

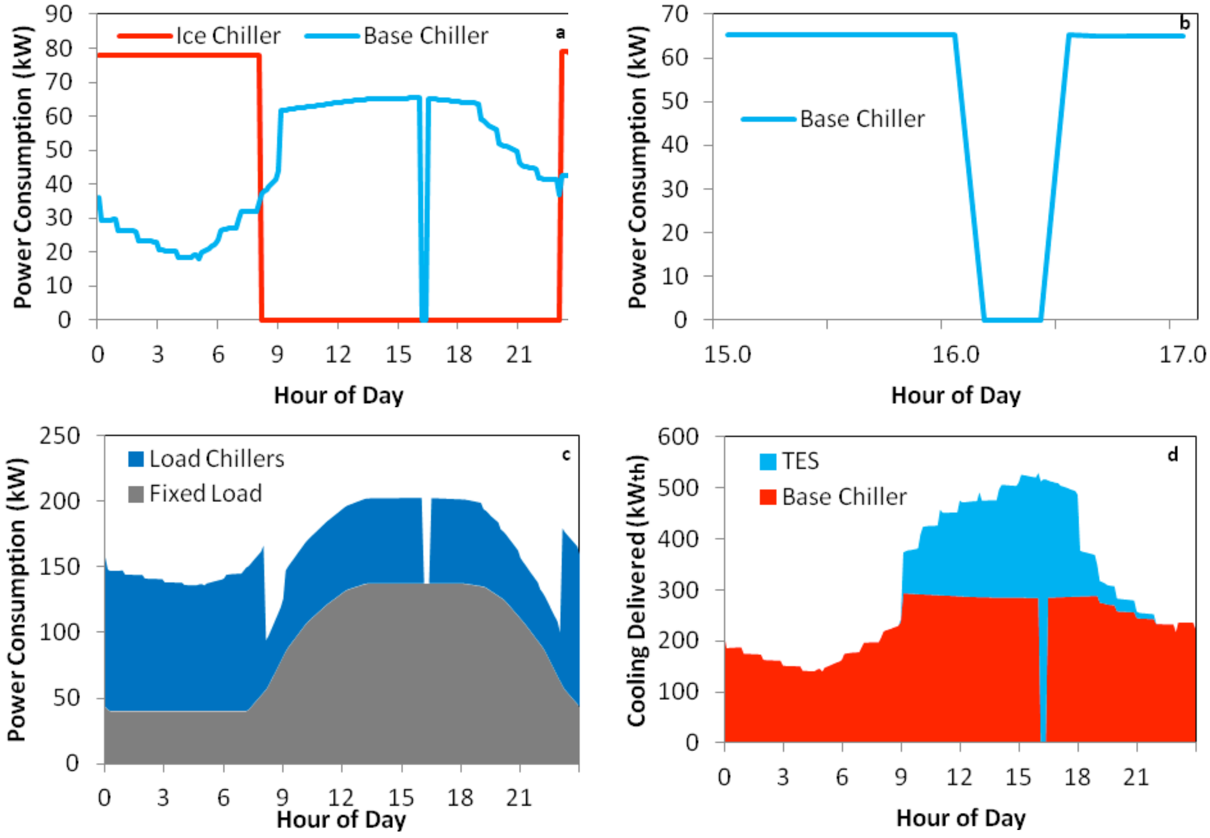

Figure 5: Daily profiles for Wednesday July 17th, 2013 for a) ice and base-load chiller power consumption b) base-load chiller reaction c) total building power consumption d) thermal load delivered by the base-load chiller and the TES

To demonstrate the implications of providing SR on chiller operation, we present chiller operation for one sample day, Wednesday, July 17th. Chiller operation varies slightly from operation under a typical TES strategy as shown in **Error! Reference source not found.**a, where the *ice chiller* is only turned on at night in order to take advantage of off-peak prices, while the *base load chiller* operates throughout the day and is turned off only to respond to a SR deployment. **Error! Reference source not found.**b shows a close-up of the SR event and power consumption before, during, and after the deployment call, with a 7.5 min reaction time for the chiller to turn on/off. **Error! Reference source not found.**c shows the total daily building power consumption. Here, we see that chiller load is quite high during the night, when both chillers are in operation. Finally, **Error! Reference source not found.**d shows how the TES provides cooling demand during peak hours of the day, increasing cooling output during the SR call in order to meet the cooling deficit from turning the *base load chiller* off. These results show that, if properly operated, a building with TES could be capable of providing SR services.

4.2 Financial Implications

In order to assess the financial benefit that demand-side resources with TES could obtain, we compared each of the weeks being studied with results where the building does not participate in the SR market. The results comparing the end-user cost when participating in the SR market, *Net Cost with SR*, with the corresponding benchmark scenarios, *Net Cost w/o SR,* are shown in **Error! Reference source not found.**a. Here, we see that participating in the SR market could reduce the approximately $400/week energy cost to the end-user by an average of roughly $30/week, thanks to capacity and deployment payments made by the utility provider, as well as some energy savings during the deployment event. Moreover, **Error! Reference source not found.**b shows the payments made to the end-user by committing and deploying SR, where capacity payments significantly outweighed deployment payments, with the exception of the third week, when four out of the five days experienced deployment events. Also, the cost reduction through energy savings is minimal, as the only change to energy consumption stems from the short curtailment periods. Finally, the savings obtained through capacity and deployment payments, as well as the energy savings, are divided by the weekly net cost without SR to represent the percentage savings that operating under such a system would bring to the building operator as shown in **Error! Reference source not found.**c. Here, we see that just from the capacity payment, the building operator would incur >4% savings on their electricity bill with those reductions increasing up to 10% in weeks with numerous deployment events. These results show that the financial incentives of providing SR services are quite attractive even under a scenario with few deployment events.

It is interesting to compare these results to a study of demand-side frequency regulation in a similar office building [16], where frequency regulation is provided by increasing or decreasing power drawn from the electric system with respect to a baseline, and the revenue is obtained by multiplying the change in power drawn by the regulation price and factors accounting for response velocity and how well the regulation dispatch is followed. Pavlak *et al.* show higher revenues from providing frequency regulation [16], which is a higher value service with more frequent dispatches, compared to the SR revenues presented in this paper. It should be noted that providing SR does not prevent a building operator from providing frequency regulation. A building with appropriate control infrastructure could provide both forms of ancillary services.

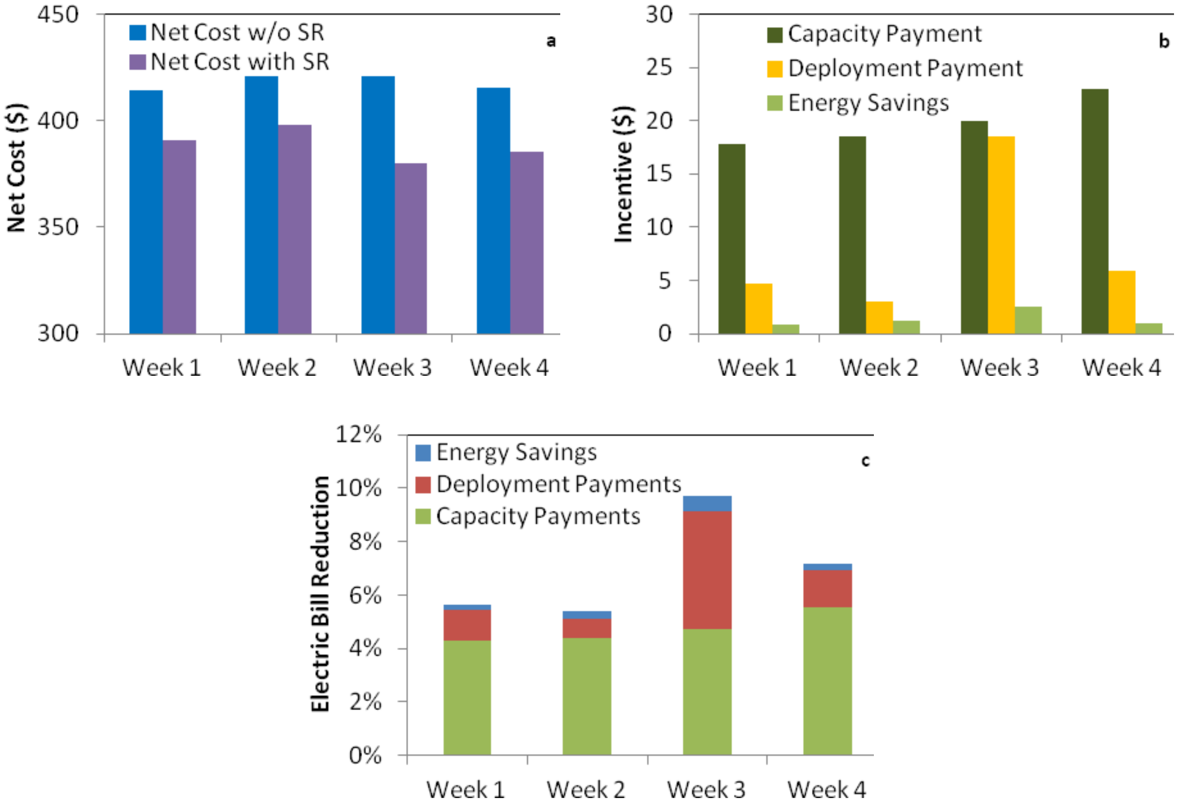

Figure 6: a) Weekly comparison between the net cost to the end-user with and without providing SR, b) weekly monetary incentive from energy savings, capacity payments, and deployment payments, and c) weekly percentage savings stemming from energy savings, capacity payments and deployment payments

4.3 Discussion

After analyzing the benefits that building operators could obtain from participating in the SR market, it is important to discuss some practical considerations in employing TES on the ancillary services market, as well as to discuss the impact that such a move could have on the grid.

To successfully provide SR from TES, the following system aspects need to be considered. In order to respond to deployment calls, the TES should have an automated control system capable of controlling chiller operation without human input. Without such a system, constant human supervision would be required to maintain optimal operation, reducing or eliminating financial benefits. Moreover, current technology allows the base-chiller to rapidly respond to a deployment call and come back online rapidly after the call has ended. However, because chillers are rarely operated in this manner, further studies are needed to estimate the resulting wear and tear of turning the chiller on/off on a regular basis. In addition, the tank size of the TES needs to be slightly oversized when compared to a traditional system, in order to provide the additional cooling requirement during deployment events. For the simulations presented here, only a 5% increase in storage capacity was needed to provide reliable service during deployment calls. Finally, the glycol loop pumps and the glycol-water loop heat exchanger have to be sized properly to provide all of the building's cooling load during SR deployment times, leading to an increase in the capital cost of such an installation.

Demand-side resources can play a significant role in the ancillary services market by providing large amounts of SR at a low marginal cost. In the case of TES, technological development and various incentives have made it economically viable for many medium and large commercial buildings to install TES in order to reduce their energy consumption. Those buildings are ideal to provide SR as outlined in this paper. By allowing buildings with TES to curtail all of their cooling load for a brief period, a small number of resources could be used to provide a significant amount of SR.

5. Conclusion

This paper has, for the first time, assessed the technical and economic feasibility of providing spinning reserves through the use of thermal energy storage. The operations of NYISO's SR market were discussed, including the history of low deployment frequency and brief deployment durations. A simulation platform, consisting of mutually interacting physical and economic models, was then developed. Using this platform, we determined a TES schedule capable of responding to SR deployments, and explored the corresponding financial implications. Simulations showed that it is technically feasible for TES to provide SR with minimal changes to conventional operation and without sacrificing occupant thermal comfort. Capacity payments contributed the most to end-user savings, reducing the ~$400 weekly electricity bill by $16-25 (4-6%). Reductions in energy consumption during SR deployments contributed much less ($1-3 per week), highlighting the importance of capacity offers. Finally, we determined that by providing SR, demand-side resources could expect savings ranging from 5% to 10% of their electricity expenditures during summer weeks. For more economic benefits, building operators can choose to participate in both frequency regulation and spinning reserves markets, considering spinning reserves are much less frequently deployed than frequency regulation.

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