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Evaluation of distributed building thermal energy storage in conjunction with wind and solar electric power generation

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A B S T R A C T

Energy storage is often seen as necessary for the electric utility systems with large amounts of solar or wind power generation to compensate for the inability to schedule these facilities to match power demand. This study looks at the potential to use building thermal energy storage as a load shifting technology rather than traditional electric energy storage. Analyses are conducted using hourly electric load, temperature, wind speed, and solar radiation data for a 5-state central U.S. region in conjunction with simple computer simulations and economic models to evaluate the economic benefit of distributed building thermal energy storage (TES). The value of the TES is investigated as wind and solar power generation penetration increases. In addition, building side and smart grid enabled utility side storage management strategies are explored and compared. For a relative point of comparison, batteries are simulated and compared to TES. It is found that cooling TES value remains approximately constant as wind penetration increases, but generally decreases with increasing solar penetration. It is also clearly shown that the storage management strategy is vitally important to the economic value of TES; utility side operating methods perform with at least 75% greater value as compared to building side management strategies. In addition, TES compares fairly well against batteries, obtaining nearly 90% of the battery value in the base case; this result is significant considering TES can only impact building thermal loads, whereas batteries can impact any electrical load. Surprisingly, the value of energy storage does not increase substantially with increased wind and solar penetration and in some cases it decreases. This result is true for both TES and batteries and suggests that the tie between load shifting energy storage and renewable electric power generation may not be nearly as strong as typically thought.

1. Introduction

Utilities generate power exactly as it is needed by consumers, which creates a set of challenges and inefficiencies. Maintaining constant, reliable, on demand, high quality power for a varying demand requires a generation profile that can be ramped up and down quickly and efficiently. Increasing levels of non-schedulable renewable generation sources increases the variation of the demand on the schedulable facilities and makes reliable power generation more difficult. Larger amounts of energy storage are generally seen as a requirement for substantial penetration of wind and solar electric energy generation due to the intermittent, non-schedulable nature of these generation sources. Common approaches used or envisioned include pumped hydro, compressed air, and batteries. All of these technologies are based on the concept of using the storage to generate electric power and managing this storage as part of the electric utility system to allow it to economically meet electric demand on a continuous basis. In this study, we looked at the potential for using building thermal energy storage (TES) for this same purpose. Rather than using stored energy to provide schedulable electric power generation, building TES can have essentially the same impact on the electric utility system by decreasing system load at times of peak demand or when wind or solar generation is not available.

Since building TES systems are normally part of the building heating and cooling system, they are typically managed by the building owner or operator and their value is derived from reduced heating and cooling capacity requirements and from taking advantage of time of day electricity pricing where it is available. With the development of the smart grid, it is possible to take a completely different approach to using building TES. If detailed electric system information and TES system information can be exchanged through the smart grid, building TES can be operated as part of the electric utility system, increasing its positive impact on the system.

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The purpose of this study was to examine the potential for building TES to serve as an effective energy storage system for an electric utility system. Additionally, the ability of building TES to aid in the large scale penetration of wind and solar electric power generation was explored. Like wind and solar electric power generation, building TES is dependent upon environmental conditions and daily cycles in these conditions. Thus, a framework in which these variable parameters and their interaction with TES storage and wind and solar electric power generation could be realistically included was a requirement for the study.

1.1. Background information

Energy storage systems can be evaluated by their ability to offset renewable energy's variation, thus enabling greater penetration of the energy source [1]. Blarke et al. [2] have shown that TES can be used to increase the allowable penetration of renewables. To date, the most widely used energy storage technology is pumped hydro, which is expected to continue to grow [3]. Where feasible, pumped hydro storage is valuable because it enables greater penetration of renewable sources and can convert non-schedulable capacity to schedulable capacity [4]. However, it suffers from geographic limitations and is not generally applicable to a system.

On the other hand, TES (either cooling or heating) is applicable across most regions. In addition, TES compares well to other general storage systems, specifically batteries, due to cost, lifetime, stable capacity, and cycle efficiency [2]. It is generally established that TES can reduce consumer energy costs if time of day tariffs are used, however, studies find that consumer side energy consumption remains mostly constant [2,5]. While consumer side energy consumption remains roughly constant, it is important to consider the whole energy system; base-load energy generation is generally more efficient than peak generation, hence the utility could see a reduction in energy cost with energy storage even if there is no net effect on total energy use.

Building TES is potentially well suited for distributed applications for a number of reasons. First, heating and cooling demand account for a significant portion of energy use [6]. If the heating and cooling loads can be effectively controlled, the daily generation profile can be substantially modified. Second, building TES circumvents the traditional energy storage conversion losses by converting directly to the end-use energy type at the end-use location. Depending on the local circumstances, energy losses in the storage process may be partially or totally offset by allowing air-conditioning equipment to operate during times when the ambient environment is more conducive to efficient operation.

While the benefits to building TES are important, a number of drawbacks exist. First, predictions of building demand for several days are needed, and if not accurate, the storage management system could make less than optimum use of the storage medium, resulting in a reduction in reliability and/or a lack of sufficient cooling/heating capacity. Second, the cost to the consumer to install a thermal storage system is generally greater than a typical on-demand system. However, it has been found that TES can be economical in cases where time of day tariffs are used [7,8] and in some scenarios, the initial TES investment is less expensive than traditional systems [9]. Lastly, improper management of the storage system could result in negative effects on the electrical grid.

2. Methods and concepts

There are no universal answers to the questions posed in this study. The suitability and economics of building TES for the purpose of electric utility energy storage will depend on countless factors in a given situation. The approach taken was to make a realistic assessment using real data and representative models for key factors. It is believed this approach provides a realistic assessment but conclusions drawn from it are not intended to be generally applicable. A year of hourly data, within a defined geographic region, were used. Five key factors were included in the assessment.

- A real electric utility system hourly load profile for the region for the year.
- Wind and solar generation models based on hourly weather data for the year reflecting weather diversity over the region.
- Realistic models of building heating and cooling energy requirements based on hourly weather data for the year reflecting weather diversity in the region.
- Storage system operation algorithms based on the hourly electric utility system load profile and local weather and building energy requirements.
- An economic assessment framework that reflects the impact of storage operation and wind and solar electric power generation on the hourly load profile for the year and the resulting impact on the required amount and mix on generation capacity and the cost of its operation.

There are clearly many other factors such as transmission losses, spinning reserve requirements, plant availability, etc. that will ultimately impact the economics and utilization of storage but it is believed the above factors capture the primary components and provide sufficient challenge without the added complexity of the secondary factors. By using actual load data for a specific region, the results should provide realistic assessments. However, care should be used in generalizing the results to other regions. The numerous simplifying assumptions, which are described in the following sections, should also be kept in mind when drawing general conclusions.

2.1. Wind power generation, solar power generation, and utility load data

Hourly electric load, temperature, wind speed, and solar radiation data were obtained for 10 locations, centered about the state of Kansas in the United States, from publicly available databases for 2009 [10–13]. The data were retrieved during the summer of 2010 at the outset of this study. The 2009 year was chosen simply for the completeness and availability of the data. However, some datasets had missing readings and reasonable assumptions were made to account for the loss of data. For a more detailed description, see the detailed report by Powell and Jones [14]; this section summarizes the specifics that are addressed therein.

The wind speed and solar radiation data are used to model non-dispatchable renewable power sources, specifically wind power and solar power. Wind power generation is modeled by considering a single wind turbine at each location and then scaling the results to the desired capacity. Throughout this study, renewable power generation is stated as a percentage of the peak demand on the system before any storage or renewable generation is incorporated. The wind turbines are equally placed at each of the 10 locations in the study. This distribution differs from reality, which would have more optimum placement but should not degrade the results of this study because a relative comparison is being made. A representative 1.5 MW wind turbine power curve was used to model the power output of the wind turbines at each location (Fig. 1).

A similar method is used for modeling solar power generation. Solar panels were equally distributed across all 10 locations and the same capacity percentage convention as with wind is used. A simplified solar power generation model is used that assumes a linear relation between incident radiation intensity and solar power generation. Panel saturation is set at 1000 W/m^2.