ANL/MCS-TM-315

Next-Generation Building Energy Management Systems and Implications for Electricity Markets

Mathematics and Computer Science Division
Technical Memorandum ANL/MCS-TM-315

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Next-Generation Building Energy Management Systems and Implications for Electricity Markets

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July 2011

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Executive Summary

The U.S. national electric grid is facing significant changes due to aggressive federal and state targets to decrease emissions while improving grid efficiency and reliability. Additional challenges include supply/demand imbalances, transmission constraints, and aging infrastructure. A significant number of technologies are emerging under this environment including renewable generation, distributed storage, and energy management systems. In this paper, we claim that *predictive* energy management systems can play a significant role in achieving federal and state targets. These systems can merge sensor data and predictive statistical models, thereby allowing for a more proactive modulation of building energy usage as external weather and market signals change. A key observation is that these predictive capabilities, coupled with the fast responsiveness of air handling units and storage devices, can enable participation in several markets such as the day-ahead and real-time pricing markets, demand and reserves markets, and ancillary services markets. Participation in these markets has implications for both market prices and reliability and can help balance the integration of intermittent renewable resources. In addition, these emerging predictive energy management systems are inexpensive and easy to deploy, allowing for broad building participation in utility centric programs.

Keywords: Markets, Buildings, Energy Management, Proactive, Predictive Control, Ancillary Services, Demand Response, Real-Time Prices.

1. Motivation and Need

Emissions, reliability, supply, and infrastructure upgrade concerns are driving the current grid modernization. This is forcing a large-scale adoption of renewable energy such as wind and solar as well as the deployment of necessary modulating capabilities such as smart grid pricing, demand-response programs, and distributed storage and generation devices. Indirectly, the need for more price-responsive (elastic) demand is forcing the deployment of advanced energy management systems in residential and commercial-sized buildings. In this context, optimizing the operation of heating, ventilation, and air conditioning (HVAC) systems is critical since such systems account for 30–40% of the total energy demand in buildings [1]. To provide an order of magnitude, a typical HVAC system in a large commercial building can use as much as 14 MW of electrical power. The aggregated HVAC demand of medium to large cities can reach levels on the order of 10,000 MW. It has been estimated that commercial building HVAC systems in the US consumes as much as 4.5 quads of primary energy. [2]

Existing energy management systems (EMS) serve as interfaces for building operators to monitor sensor data and modify operational (set-point) conditions of air-handling units, thermostats, chillers, ice storage, and so on as external weather and price conditions change throughout the day in order to minimize energy costs and satisfy occupant comfort. An example is the Metasys system of Johnson Controls [3]. Current EMS systems are equipped with basic controllers that track the set-points dictated by the operator; in addition, they include basic optimization functions to minimize energy using precooling and economizer control. Currently, the human operator must make most of the economic decisions in the building while monitoring proper equipment functioning. This approach can be inefficient because weather and market conditions are highly dynamic and human operators typically have access to only limited real-time information about both building energy consumption and market prices.

A limitation of current EMS systems is that they are inherently **reactive**. In other words, they lack mechanisms to accurately quantify and anticipate the effect of weather, occupancy, building design, and market prices on the building dynamic response, energy demands and costs, and comfort conditions. This **lack of systematic knowledge** limits the participation of the building on electricity markets. For instance, buildings are normally price-takers and participate sporadically on demand response events during extreme contingencies. This situation exposes buildings to the high volatility of real-time prices and discourages investment in metering, automation, and storage technologies. In addition, the lack of systematic knowledge underestimates the value of building active and passive storage assets by utility companies, independent system operators (ISOs) and regional transmission operators.

Recently, **proactive** energy management systems have emerged as a promising alternative for building automation [4-10]. These systems use of predictive models to automatically optimize the building set-points to maximize energy revenue and maintain comfort conditions as external conditions change throughout the day. The use of predictive models enables the coordination of building thermal momentum with dynamic trends of weather, occupancy, and prices. Remarkably, HVAC power can be reduced instantaneously without affecting comfort conditions over several minutes. The use of predictive models also enables the system to **quantify and anticipate** the effect of the building internal and external conditions on energy demands and economic performance. Notably, predictive models can be constructed by using statistical and machine learning techniques that exclusively use available sensor data and minimal building topology information [11, 12]. This approach enables a high degree of modularity, low technological costs, and fast deployment times. Existing commercial vendors of this type of technology include BuildingIQ® [13].

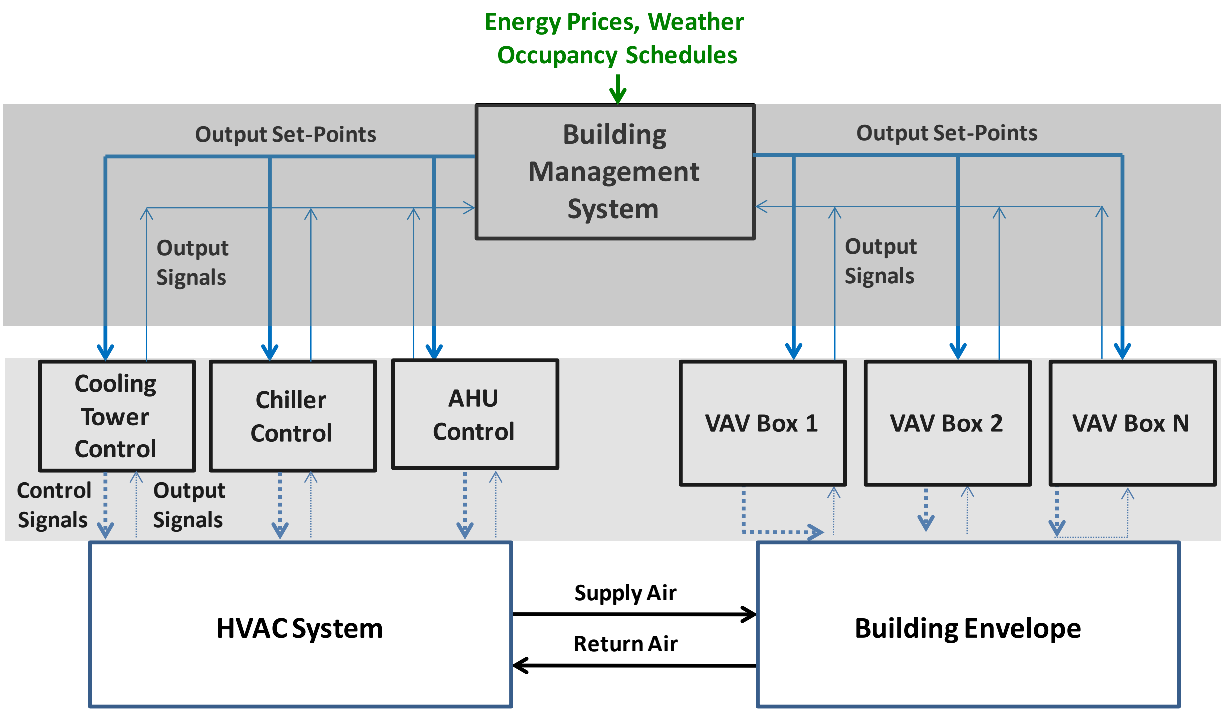

Fig. 1. Schematic representation of building management system.

2. Proactive Energy Management

A typical electric HVAC system is illustrated in Fig. 1 and 2. Ambient air at current temperature and humidity conditions is conditioned in an air-handling unit (AHU). (More complex configurations than that in Fig. 1 use chillers and ice storage to provide the cooling load to the AHU.) Humidity is modulated using a humidifier/dehumidifier that cools the mixture to remove latent energy in the air. The mixture is further cooled to remove sensible heat and achieve a predetermined cooling load. The cooling load can be achieved by finding appropriate conditions for supply temperature and air volume. The conditioned air is distributed to the building zones using air dampers. The dampers are in closed loops with thermostats that sense the zone temperature as internal conditions changes. Internal changes include heat gains due to occupants, equipment, and thermal loads resulting from external solar radiation and wind convection. The zone air is removed continuously from the zones and recycled to the AHU. This is mixed with ambient air to close the cycle. Depending on the ambient conditions, optimal combinations of ambient and recycle air can be exploited to save energy in the AHU.

Proactive energy management systems use weather forecasts and predictive dynamic models of the building zones to anticipate and exploit weather and internal condition trends to minimize the cooling load in the AHU. A key principle is that the building has sufficient momentum or thermal mass to withhold the conditioned air internally over extended periods of time without affecting comfort conditions. This basic synchronization principle is key in saving energy and in shifting cooling demands throughout the day [14]. In Fig. 3 we present the base and optimized power profiles for an AHU operating at Argonne National Laboratory using BuildingIQ technology [7]. We note that 20–30% electricity savings can be realized during off-peak and peak times even under strict comfort conditions. As shown in [7], the peak demand can be further decreased by relaxing comfort conditions at critical times. Proactive systems perform comfort relaxation in optimal ways by exploiting the building momentum to minimize occupancy dissatisfaction.

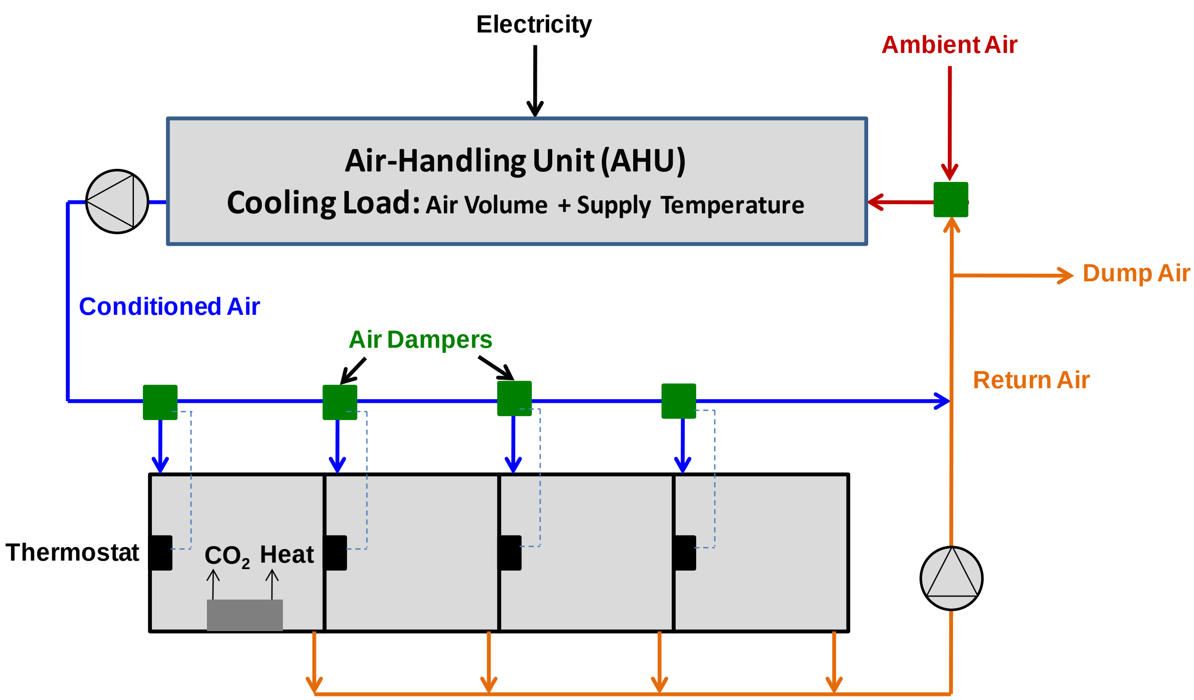

Fig. 2. Schematic representation of HVAC building system.

Two key technological advances make possible the development of proactive energy management systems. The first is the availability of **statistical and machine learning** techniques [11, 12] that enable the creation of low-cost and adaptive building models using available sensor data and minimal building topological information. The second enablers are numerical weather prediction (NWP) capabilities that have enabled increasingly accurate forecasting capabilities. In Fig. 4 we present a five-day-ahead weather forecast obtained with the NWP model WRF, developed by several federal agencies, including the National Oceanic and Atmospheric Administration [15]. This system is currently in operational mode in the

Mathematics and Computer Science Division at Argonne National Laboratory and has been used extensively to estimate economic benefits of weather forecasting in power grid and building operations [6]. Note the remarkable predictive capabilities of the NWP model for the ambient temperature, the most critical variable affecting AHU electricity demand.

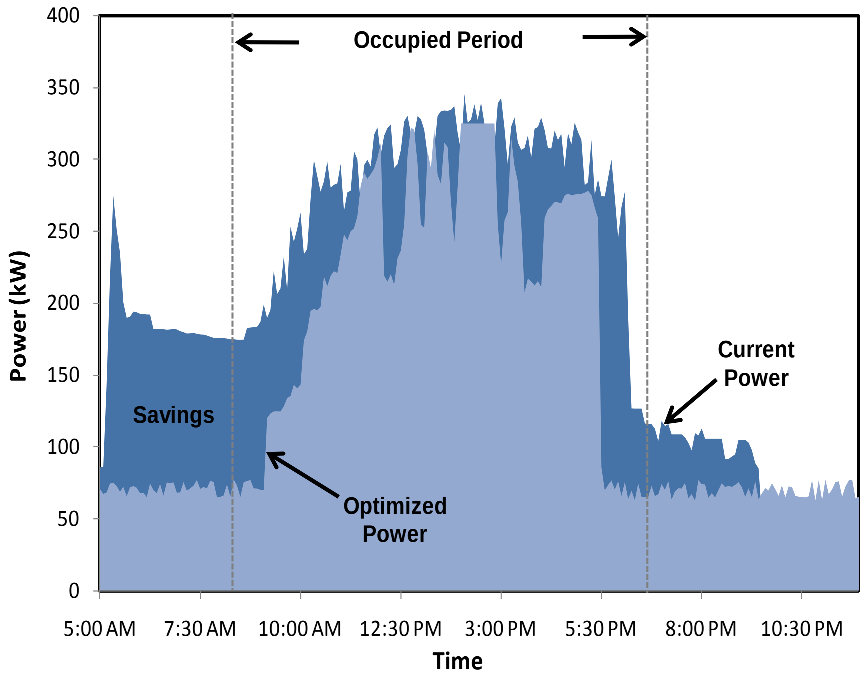

Fig. 3. Base and optimized power profiles using proactive energy management system of BuildingIQ at Argonne National Laboratory.

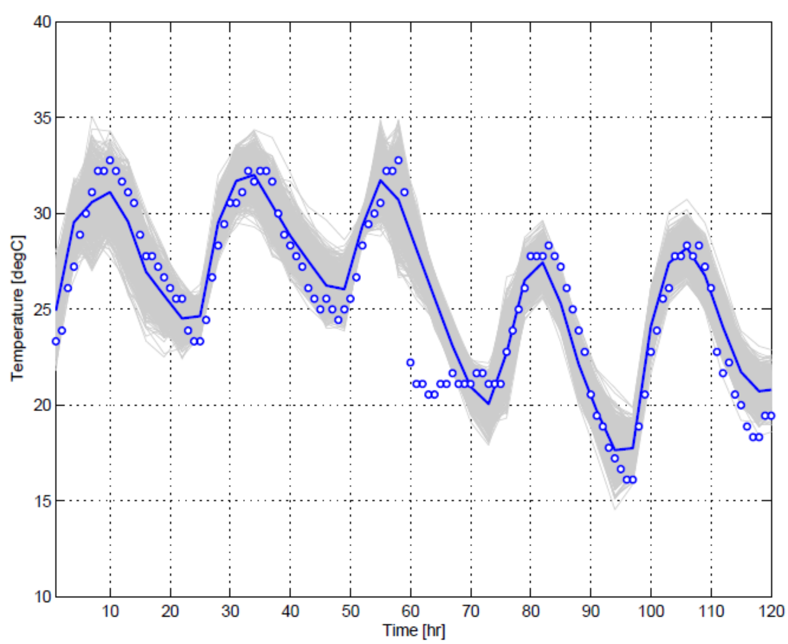

Fig. 4. Five-day-ahead forecast, uncertainty envelope and sensor measurements. Forecast generated with the WRF system at Argonne National Laboratory.

3. Electricity Markets

It has been recently found that real-time prices alone might not provide sufficient financial incentives because of perceived risk (i.e., they are difficult to predict) and because they can lead to highly volatile operations and poor operational efficiency (e.g., equipment wearing). In addition, demand response programs are currently run sporadically [16]. Proactive energy management systems, however, can enable building participation in several other markets provided by ISOs [17]. This capability provides incentives to invest in advanced energy management technology.

- **Day-Ahead Demand and Reserve Market:** Buildings can submit price-responsive demand and reserve bids for different times of the day. These bids can be constructed by exploiting storage and demand shifting and shedding capabilities of the HVAC system. The ISO uses bids from generators and consumers to clear the market and set day-ahead prices and demand schedules for the consumers, including the buildings. This type of structure is widely used by large industrial consumers such as steel, semiconductor, and cement plants. In the day-ahead market, prices tend to be low and stable since the market includes generation from low-cost bulk plants such as coal and nuclear. EMS systems can anticipate their demand using weather forecasts and predictive models to submit bids. In addition, they can allocate some level of reserves in the form of ice storage or demand shedding capacity. This forward market can enable buildings to lock their prices and be less exposed to real-time price volatility. In particular, buildings can make better use of their fast HVAC ramping capabilities as well as lighting devices to track the day-ahead cleared demand profile. This approach is economically more efficient for the building than paying for high real-time prices. Additionally, the customer can utilize price responsive demand bids to optimize their day-ahead consumption schedule to further minimize cost and maximize revenue potential for real-time market curtailments.
- **Real-Time Market:** Buildings can submit price-response demand bids that the ISO uses to schedule dispatch every 3 to 5 minutes. This market balances real-time deviations in demand and renewable supply from the day-ahead forecasts and manages contingencies. Ice storage devices and fast HVAC demand shedding (ramping capacity) are highly valuable assets that are competitive with natural gas peaking plants. Additionally, the customer can maximize the revenue potential for day-ahead market positions by submitting offers to receive payment to forgo day-ahead scheduled consumption if energy prices rise.
- **Ancillary Services Market:** Buildings can allocate their storage and shedding capacity to provide regulation services for the ISO. Such high-value services can provide revenue streams back to customers to help offset energy payments.

As can be seen, there exist several operational tasks and markets for which building assets can be exploited. The potential revenue provides significant incentives to building owners for investments. In addition, predictive energy management systems can help reduce building exposure to the high volatility of real-time prices and can incentivize investments in energy efficiency, automation, and storage technologies. Also, the creation of systematic knowledge can help accurately value building active and passive storage assets by utility companies and independent system operators. The ability of buildings to provide ancillary market services can also aids in the integration of intermittent renewable resources and increase the resources that system operators can rely on to keep the frequency of the electricity grid stable.

4. Research Needs

Several directions of research can be explored to accelerate widespread deployment of proactive energy management systems and quantify the impact on markets and operations.

- **Development of bidding strategies for building systems.** It is necessary to develop optimization formulations to quantify the value of different the building assets in the most efficient way to provide reserve and ancillary services capacity.
- **Assess market benefits at grid level.** A wide-area study is needed to analyze the impact of building demand elasticity and reserves on market efficiency and renewable integration. For instance, it is necessary to quantify effects on emissions, locational marginal prices, ancillary service prices, and reductions in transmission and generation investments.
- **Reassess suitable electricity markets for buildings.** Markets might not be designed to incentivize sufficient deployment of advanced automation technologies. For instance, current smart grid programs that request building response during sporadic events might not provide enough incentive to building owners. Building assets are competitive with scarce natural gas resources. In some cases, buildings might even be able to respond more quickly than existing grid assets. With recent FERC rulings, the market should enable building owners to realize these benefits.
- **Demonstration studies.** More implementations are needed to mitigate perceived risk and to identify technical bottlenecks that can lead to further exploitation of building resources. In addition, demonstration enables the collection of valuable performance data that can point technological bottlenecks. Also, data collection enables the disaggregation of loads; this can be used to identify additional valuable building assets.
- **Multibuilding energy management:** Distributed energy management algorithms are needed that can coordinate multiple buildings in large sites such as federal facilities and university and corporate campuses. On-site coordination is needed for more efficient market participation, to minimize energy losses and to coordinate with central utility plants that generate chilled water and steam. Similar initiatives are currently pursued as part of micro-grid programs [18].

Acknowledgments

This work was supported by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357. Financial support from the Building Technologies Program, Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy is also acknowledged.

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