Issues Affecting Load Control in Aggregates of Commercial Buildings

Deliverable 3.5.1 (a) Draft Report

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Introduction

Overall goals of the project

The objectives of Project 3.5 are to identify opportunities to better control electrical loads in groups of buildings by aggregating load shapes and by coordinating control actions, to evaluate the potential impact of aggregated load control, and to identify needed developments in control and communication systems.

While much effort has been devoted to load management, including load shedding, in individual buildings, little reported work has focused on aggregates of buildings. Building aggregation is increasingly of interest due to the role of load aggregators in electricity-purchase contracts and the efforts at multi-building campuses to reduce electricity bills for aggregates of buildings. MIT is currently working with Drexel University to conduct exploratory research into opportunities for load management in aggregates of buildings, with emphasis on college campuses and multi-building medical facilities.

The need for load reduction in buildings in California and other states

California is experiencing a well-publicized and acute shortfall of electricity supply relative to burgeoning demand. Part of the reason for the shortfall is that many customers lack financial incentive to cut demand. Another aspect of this same lack of incentive is that two of the investor-owned electric utilities are unable to pass on wholesale prices, which have soared as a function of demand, to retail customers. In the context of control of aggregates of buildings, it is reasonable to consider the entire state as a single entity. The state government has an incentive to control load, for political reasons and because of its charge to provide useful service to state residents.

At this level, there has been no expressed need to coordinate control actions over the duration of peak load buildings, because there is a built-in temporal diversity associated with uncoordinated control actions of large numbers of building owner/operators. Accordingly, any type of effective load control measure, implemented in individual buildings, is of immediate benefit to the state. The project at hand therefore has something to offer the state if it points out and tests new methods for providing the type of information needed for effective load control. It offers something more to owners and operators of clusters of buildings served by a single revenue meter, if those control actions can be coordinated to reduce the aggregated peak that determines peaking charges.

The state is taking action. California Assembly Bill 970 has provided the California Energy Commission (CEC) with $50 million to reduce state-wide peak load. The load-reduction target for the program as a whole was to be at least 200 MW, (220 MW, with an aim of achieving a load reduction of 161 MW by June 1, 2001, per Electric Power News (2001)). The load-reduction program includes six components, as shown in Table 1 (AB970 2000).

Note from Table 1 that building controls tied to pricing and lighting and HVAC upgrades, along with wastewater and agriculture, provide demand reduction at lower cost than traffic-light upgrades, light-colored roofs, and renewable generation. The work in Project 3.5 can be classified as promoting a form of price-responsive load control.

The California Independent System Operator (CAISO) is developing demand-response programs for Summer 2001 (Fuller 2001a, 2001b). These programs include a two-tier Demand-Relief Program (DRP) and a Discretionary Load Curtailment Program (DLCP). The first-tier DLP consists of loads without back-up generators (BUGs) and the second tier consists of BUGs. Because generators are a source of local air pollution, the program stipulates that BUGs be called only after the first-tier and that they be used as a last resort prior to rolling blackouts. The program as a whole is intended to be implemented immediately prior to Stage 3 rolling blackouts, unlike current interruptible-load programs that are initiated at an ISO Stage 2 alert. Current interruptible-service customers cannot participate in the 2001 DLP. First-tier loads can be curtailed up to 24 hours per month and second-tier BUGs can be called no more than 21 hours over the summer. Payment to participating customers includes a fixed monthly capacity payment of $20,000 per MW and a performance energy payment of $500 per MWh. Requests for bids were issued in December 2000 and bids were received in February 2001. For first-tier loads, 596 MW of 1156 MW in bids have been recommended for ISO Board approval. Of the 268 MW of BUG bids, none were considered acceptable. The restrictions on BUG operation could cause this resource to be exhausted early in the summer (i.e., seven three-hour operating blocks). Further, many of the BUG bids did not include approval from local air-quality boards. The advanced metering that is central to Project 3.5 in intended to help customers better understand load-reduction opportunities and track performance at the level of an individual load.

Table 1. California Energy Commission's Load Reduction Program

Program	Allocated funds, millions $	Goal, MW	Committed funds, millions $	Estimated load reduction, MW	$/kW reduction
Energy-efficient traffic lights, using LEDs	10	10	10.0	6.0	1669
Innovative efficiency	8.6	32	8.6	48.5	177

and renewables (including renewable generation)					
Energy-smart buildings (advanced meters and software that can dim lights and raise thermostat set points automatically)	10	50	10.0	102.5	98
Light-colored roofing	9.4	30	8.0	21.4	374
Lighting and HVAC in state buildings and public universities	5.5	50	5.5	79.9	69
Energy-efficiency improvements in wastewater treatment and agriculture	5.0	20	4.4	58.0	76
Evaluation	1.5		1.0		
Totals	50.0	192	47.5	316.3	150

The DLCP is being set up to provide an energy-only payment of $250/MWh for voluntary load reduction. Participants must sign up with aggregators, who must provide a curtailable load in excess of a minimum value and who must also provide contract services, communications links, and verification mechanisms. Aggregators will receive calls for alerts and warnings and will have 60-90 minutes to firm up curtailment. Customer participation on the day of any call will be entirely discretionary. Verification would be based on interval metering for end-use loads, when available. When such metering is not available, sample measurements, historic data, process controls, data loggers, and submeters can be used. Participants must allow on-site audits and may be charged an audit fee if they are not using utility-issue interval meters. MIT's non-intrusive load monitor (NILM), part of Project 3.5, would appear to offer a useful source of low-cost information for this program, if field tests prove that it works with acceptable accuracy.

Implementation of the DLCP through aggregators is an important and perhaps first case where aggregators are controlling load of independent customers and not simply amassing load for block purchases. It is the kind of case that an ASHRAE research project, to be described later, did not uncover. However, it appears that the load control in each facility will be entirely independent of what others are doing. Payments are on the basis of energy savings and not reduction in coincident peak load.

Some have argued that the financial crisis facing Southern California Edison and PG&E is due in part to the structure of the California Power Exchange, in which offers to provide electricity are ranked in merit order by cost and the most expensive power needed to meet system demand sets the market clearing price that is paid to all suppliers. A hypothetical alternative is that each successful supplier would be paid the individual bid price. The California Power Exchange commissioned a blue-ribbon panel to examine the merits of both approaches (Kahn *et al*. 2001). The panel noted that the current system encourages suppliers to bid at their marginal cost, anticipating that the difference between that cost and the market-clearing price would provide revenue to pay for capital investments and provide a profit. Paying at the bid price, the panel argued, would cause suppliers to bid at a higher price, as close as possible to the market-clearing price. While the panel did not advocate a shift to paying generators at bid prices, it did note the role of demand control in alleviating California's supply problems. Specifically, they note that demand responsiveness is needed in the short term to reduce the inelasticity in demand that contributes to the price spikes in the Power Exchange's power market. Further, demand responsiveness in the long term will contribute to more efficient use of electricity. Demand responsiveness, in the view of the panel, is achieved via two approaches: providing a financial incentive to consumers to cede control of their electrical loads and permit them to be curtailed; or providing consumers with varying prices that show the same sort of sharp spikes as the wholesale market. The financial benefits of load control would appear to justify the cost of metering necessary to verify responsiveness. The work to be performed as Project 3.5 is intended to promote demand reduction under appropriate price signals.

Electric-system reliability problems in 1998-2000 were not confined to California. The American Council for an Energy-Efficient Economy (ACEEE) recently published a report that recommends the programs shown in Table 2 to reduce peak demand as a lower-cost alternative to supply-side remedies to shortages (Nadel *et al*. 2001). Criteria for the programs included large load reduction, use of proven technologies, and reliance on successful program designs for implementation. These measures are forecast to reduce national peak demand in 2010 by about 64 GW, offsetting 40 percent of the growth in peak load predicted over the next decade.

Table 2. ACEEE Recommended Programs to Reduce Peak Electrical Loads.

Program	Percentage peak reduction
New and replacement residential cooling systems	45
Residential cooling system tune-up and repair	11
Commercial and industrial HVAC equipment	6
Commercial building retro-commissioning and maintenance	15
Commercial and industrial lighting retrofit acceleration	15
Commercial and industrial lighting design enhancement	8

Electricity Rates

It is worthwhile to briefly consider the electricity rates under which building load control takes place. Rates may include charges for both energy and peak power, as well as a fixed charge. Both energy and demand charges may vary with time of day or seasonally. Both may also vary with consumption, in ascending (price increases with energy usage or demand) or descending blocks. Demand charges may be set by the peak load recorded during a twelve-month sliding window. Energy charges may vary hourly, in what is known as a real-time-pricing (RTP) rate. RTP energy prices account for the marginal cost of producing, transmitting and distributing electricity. Capital costs, for generation and transmission and distribution systems, are added to the basic rate in the form of fixed charges or an hourly adder or multiplier. Some RTP rates start with a customer baseline (CBL), which a usage profile recorded under a previous rate. A customer whose load profile does not change under the RTP rate will pay the same as under the old rate. This guarantees the same revenue stream to the utility. Changes in load lead to hourly changes in cost at a marginal rate; in some rate structures, an increase in load is priced differently from a decrease.

One interruptible rate of interest for this project is Southern California Edison's I-6 rate. This rate is intended to give Edison a source of demand reduction when system capacity is strained. Participating customers receive a reduction in energy and demand charges during non-interruption hours, as shown in Table 3. The demand charge is substantial: the normal time-related demand charge of $17.95/kW for customers with 2-40 kV service is reduced to $8.60/kW. Service is still available during interruption periods but power is priced at $9.01/kWh, more than 100 times the normal energy charge. Customers choose the firm-service level that sets the threshold for both lower prices on energy and demand and the penalty charges. A low firm-service level provides a large savings during non-interruption hours but a large penalty for usage during interruptions.

Table 3. Southern California Edison's I-6 Interruptible Rate (SCE 2001).

Tariff component	I-6 charges per meter per month for 2-40 kV service above the firm-service level		TOU-8 charges per meter per month for 2-40 kV service	
	summer	winter	summer	winter
Customer charge, $			299	299
Facilities-related demand, $/kW			6.60	6.60
Time-related billing demand (added to facilities-related demand for TOU-8), on-peak $/kW	8.60	0	17.95	N/A
Mid-peak billing demand	1.30	0	2.70	0
Off-peak billing demand	0	0	0	0
On-peak energy charge, $/kWh	0.07674	N/A	0.09422	N/A
Mid-peak energy charge	0.05022	0.06096	0.05847	0.07071
Off-peak energy charge	0.03244	0.03327	0.03758	0.03874
Penalty charge for consumption above firm-service level during interruption periods, $/kWh	9.01	9.01		

The I-6 rate provides a load-aggregation option to customers with multiple service accounts on the I-6 rate or other Edison interruptible-load tariff. In response to a notice of interruption, the customer may use the aggregate interruptible load to meet the load-interruption obligation. The customer may select which service accounts will be interrupted, rather than using the account to which notice of interruption was given. This option requires installation of Edison meters to record and transmit load information. The option provides an incentive for a form of aggregated-building load control, whereby load reduction at one site is used as a credit for another account. Sites do not need to be on the same service meter. However, if Edison issues interruption signals to all blocks of customers on interruptible-service rates, the load-aggregation option is effectively nullified, because penalty charges will be levied for all accounts.

Benefits of economically correct electricity rates

There is ample evidence that customers respond to changing hourly prices, particularly very high prices. Georgia Power's RTP program serves customers with an aggregated demand of 5,000 MW; these customers have reduced load 400-750 MW on moderate- to high-priced days. A subset of very responsive customers reduced load by 60% when prices exceeded $1.00/kWh (Braithwait and O'Sheasy 2000). Georgia Power's O'Sheasy has said that "it's amazing how ingenious people become when it affects their bottom line" and noted that measures have included a shift of industrial production to take advantage of lower electricity prices on weekends (DJ 2001).

Dynamic pricing can and has been implemented in a number of ways: pure hourly rates, or spot prices, spot prices or "super peak" prices that are limited to a small number of critical hours per year, and a variety of interruptible-load programs (Eatkin and Faruqui 2000, Braithwait 2000). More widespread use of rates such as these is considered to be an appropriate mechanism for ameliorating the power crisis in California. As a further benefit, even modest reduction in load can substantially reduce spot prices, by a ratio as much as 10:1 (Braithwait and Faruqui 2001). Today, interruptible load programs have been implemented not only in California but also by the PJM Interconnection, the New England ISO, and such utilities as Portland General Electric, GPU Energy, and Wisconsin Electric (Braithwait and Faruqui 2001).

Current load-aggregation efforts

ASHRAE has sponsored a steady stream of research projects that focus on building dynamics and control at a supervisory (rather than local-loop) level. Projects have included optimal control of chilled-water plants based on on-line model identification and optimal control of thermostat set points in a single building to minimize operating cost. In an ongoing research project, 1146-RP, ASHRAE has shifted its attention to aggregates of buildings, with the goal of identifying load-and cost-control opportunities that would exist for groups of buildings. The specific objectives of this project are

1) To identify situations and conditions under which aggregating individual building loads is attractive for managing total, multi-building load;
2) To identify and evaluate operating and control strategies for use in individual buildings that will reduce energy costs at the aggregated level by taking advantage of the diversity of demand among buildings; and
3) To develop specific recommendations as to
    i) What engineering developments are needed for accurate prediction of utility prices and building loads
    ii) What types of loads in buildings can be aggregated (i.e., classification of individual loads in a manner suitable for load management)
    iii) What load analysis tools are available
    iv) What control strategies can be used
    v) What types of communication and controls systems should be considered (BEMS, internet)

vi) What education needs to be provided to building owners, facilities operators, and Energy Service Companies (ESCOs).

The first phase of this project included a survey of load-aggregation ventures, which revealed that the considerable amount of activity in this area was primarily focused on building portfolios of customers and not on time-of-use load control. Aggregators appeared to show little interest in a customer's ability to shift load at the time of assembling a portfolio, even though such flexibility could provide a basis for contracting for cheaper power from a supplier. While many aggregators offer energy-management services, such services appear to be focused on individual buildings. Table 4 summarizes the review of load aggregation efforts conducted as part of 1146-RP.

As Table 4 suggests, load management for large consumers is becoming more tightly and automatically linked to energy prices, via Internet technologies. For example, AES New Energy recently the development of an internet-based service for selected customers in New York and New Jersey (Power Markets Week 2000). Based on spot-market prices, AES New Energy will be able to automatically start up generators and implement pre-determined DSM strategies. Reduced load can then be immediately re-sold at the spot-market price. AES claims that the new system will enable it to reduce supply-side costs for its customers.

Table 4. Sample Load Aggregation Ventures. (Adapted and extended from "Building Operation and Dynamics within an Aggregated Load Phase 1 Report," ASHRAE 1146-RP, Drexel University and Tabors Caramanis & Associates, January 2001.)

Organization	**Owner**	**Services**	**Contracts**
Cinergy Business Solutions	Cinergy	Design and engineering, energy use analysis, and energy supply ideas	Business associations • NH Retail Association
PG&E Energy Services	PG&E Corporation	Supply electricity, identify energy-efficiency projects, provide financing	Commercial loads with multiple locations: • Marriott hotels and resorts in California • Massachusetts High Technology Council load-aggregation program • Equity Office Properties Trust – 15 office buildings and parking facilities in San Francisco, San Diego, and Orange County • Burger King franchises in CA – 450 restaurants • Portfolio also includes McDonald's and Carl's Jr. restaurants; Blockbuster video and music stores; Rite-Aid and Save-on drugstores; Safeway, Vons and Lucky supermarkets; Neiman Marcus, IBM, Mitsubishi Silicon America and

			NEC America; Smucker's, Pepsi Cola General Bottlers and others.
Excelon	PECO Energy	Fuel, plant, and energy management services; distributed infrastructure planning, construction and maintenance; energy-efficiency evaluation and implementation; energy procurement and brokering; consolidated energy billing and reporting; commercial and industrial energy supply	Commercial and industrial: • Wampler Foods • Princeton • Vision Quest • USX • Massachusetts HEFA (Health and Education Facilities), an aggregator of loads and finance provider for energy-efficiency projects)
Onsite Energy Corp.		Billing analysis, demand-side management, direct-access planning and cogeneration services	• Business Associations of Food Wholesalers/Distributors (e.g., National Frozen Food Association, California League of Food Processors) • NJ Coalition of Automotive Retailers (NJCAR)
Wheeled Electric Power	Independent, located in Uniondale, NY		• Small businesses: several thousand retail customers buying electricity and natural gas. • Participant in retail electricity pilot programs in New Hampshire, Massachusetts, and New York, for which most customers are residential or small-commercial consumers
New Energy (formerly New Energy Ventures)	AES	Shared-savings programs, internet link between trading desk and major customers to start on-site generators or curtail load	Large commercial users: • California Retailers Association • Catholic Health Care West (San Francisco hospital) • Association of California Water Agencies • Northern California Grocers Association
Allegheny Energy Supply		Volume pricing	Large commercial and industrial users: • NJ Chemical Industry Council • Pennsylvania State University • Brandywine Realty Trust • Pennsylvania municipalities
Sempra Energy Solutions	Sempra Energy (formerly San Diego Electric and Gas and S. California Gas)	Uses Web Encharge, an internet-based product to manage energy information and billing. Information is updated daily. Also offers energy-cost savings)(up to 5% in one case) and bill consolidation	Retail chains with multiple locations across broad geographic locations: • Union Bank of California-252 locations in California, Oregon and Washington • Advance Auto Parts-700 stores in 37 states • Penske Truck Leasing-120 locations in Midwest • City of San Diego-2400 facilities, including Qualcomm

			Stadium and the San Diego Convention Center
EnerShop	Wholly-owned subsidiary of Central and Southwest Corporation	Uses EnerACT, a two-way communication system for optimizing energy operations that collects facility information over the internet. Engineers analyze information and advise clients on energy-savings opportunities. Also offers energy-aggregation services.	• La Quinta Motor Inns-19 facilities in Texas and California • Building Owners and Management Association (BOMA) of Dallas

The next phases of 1146-RP include development of procedures that might later evolve into tools that could be used by aggregators to quantify the benefits of load-curtailment actions and to optimize them in the sense of accounting for both demand reduction and changes in thermal comfort. In lieu of classifying load profiles in the absence of control measures, itself a useful method for targeting buildings where load curtailment could have the most benefit (Hull and Reddy 1990), this work will use simulation to determine how load shapes change under control actions. A related effort will be done as part of the revised scope of work for Project 3.5, to be discussed later in this report.

Current load-control efforts in Los Angeles County buildings

MIT researchers have twice visited buildings operated or occupied and operated by the Internal Services Division (ISD) of Los Angeles County. As noted in the Deliverable 2.2.2a report, the subject buildings include the ISD headquarters and the Edmund Edelman Children's Court. ISD staff has obtained permission to work in these buildings and have obtained preliminary acceptance of an MIT request to also work in a nearby building occupied by Los Angeles County sheriffs. These buildings are on the I-6 rate.

Two intertwined issues face ISD: whether to stay on the rate and how to respond to it. In prior years, customers have been given an annual option to continue with the rate for the next year or leave it. Such decisions have been made in the context of available response mechanisms and estimates of the frequency of interruption. At the moment, there is a moratorium on leaving the program, but energy penalties are not being collected. As of January 2001, when the Lead Investigator visited ISD headquarters, the Director of ISD had asked that building load be cut substantially during interruption periods. In that building, a facilities engineer, who is physically based in another part of Los Angeles and serves a number of buildings, has reduced chiller power by increasing the discharge-air set point in the constant-volume, dual-duct system. ISD staff is considering a lighting retrofit that will enable lights throughout the building to be dimmed. Little is now done in the children's court, which has a variable-air-volume (VAV) system.

I-6 buildings feature a power meter that shows the consumption for the entire building and provides visual feedback about the magnitude of power reductions during I-6 periods. There are two problems with this approach. First, the information is only available locally, to a person standing in front of the meter. Second, it requires that person to estimate or remember the power level before any control actions were taken and it only shows the aggregated impact of all control actions. No information is provided about individual actions. While individual measures could in principle be staggered, there is an overwhelmingly large cost penalty to doing so. ISD staff has expressed strong interest in learning the impact of individual measures. Further, staff would like to have a first-cut breakdown of major loads, to help identify targets for further control action. Accordingly, there is considerable interest in what the NILM could offer.

It is worth noting that this interest in not primarily centered on control of aggregates of buildings, the focus of the project. ISD staff look at buildings individually, due to current control options and the structure of the I-6 rate. But the targeted buildings still provide a useful test bed, for several reasons. ISD staff members are supportive, in large part because of the cost of service during interruption periods. Further, ISD headquarters and the sheriff's office are on the same revenue meter. Coordinated control actions that would reduce aggregated peak loads would save the $8.60/kW demand charge noted in Table 3 in addition to the much large energy penalty charge of $9.01 for each kWh used during an interruption period.

Assessment of Aggregated-Building Load Management Issues (as included in Scope of Work for Deliverable 3.5.1a)

The scope of work for Project 3.5, Deliverable 3.5.1a, includes an investigation of five issues: engineering, implementation, customer motivation, legal issues, and requirements for load-cooperative agreements. These will now be addressed.

Engineering aspects of aggregated-building load management

Norford *et al*. (1996, 1998) investigated four strategies that a building operator could consider in order to respond to real-time prices:

1. Thermostat control
2. Thermal storage systems
3. On-site generation of electricity
4. Control of lights

Thermostat control. Building dynamics constrain load control based on thermostat adjustment in individual buildings. Consider, for example, an effort to pre-cool an office building in early-morning hours, while electricity rates are low. In principle, the thermostat is set to the lower limit of thermally comfortable conditions. Temperatures are then maintained at this lower level until rates hit peak levels, at which point the thermostat setting is raised. Electrical power demanded by air conditioners or chillers, cooling towers, chilled-water and condenser-water pumps, and ventilation fans is reduced.

In the simplest case, the chiller and associated pumps are turned off completely until indoor temperatures reach the upper bound of thermal acceptability, at which point this equipment is again turned on, to maintain the upper bound set point until the end of the peak period. Such a simple approach usually fails to reduce demand charges during peak periods, because the indoor temperature rises to the upper limit before the peak period is over and the chillers must be turned on again. However, this approach is in large part satisfactory for a building under the I-6 rate, because the largest expense is the energy surcharge.

Optimal or near-optimal control strategies (Anderson and Brandemuehl 1992, Braun 1990, Daryanian 1989, Keeney and Braun 1996, Norford *et al.* 1998, Rabl and Norford 1991, Reddy *et al.* 1991, Ruud *et al.* 1990) for temperature control and use of thermal mass for pre-cooling in a single building account for both the electricity rate and the thermal dynamics of the building. A supervisory controller with such an algorithm would control the temperature set point during peak charge periods (whether under a time-of-use rate or a real-time rate) such that electricity charges were minimized. This means that the chillers are running at part load during peak periods.

Norford *et al.* (1996) systematically examined hourly loads and real-time prices, in order to determine what hours were best suited for cooling a building. Minimum and maximum allowable indoor temperatures were constraints. Cooling at night, when rates are usually low, was penalized by the increase in heat flow across the building envelope, expressed as a dimensionless cool-storage efficiency, $\eta_{storage}$:

$$R_{z,h} = R_{t,z,h}\ \eta_{conv}\ \eta_{storage} \qquad (R > 0, \text{ i.e., charging})$$
$$R_{z,h} = R_{t,z,h}\ \eta_{conv} \qquad (R < 0, \text{ i.e., discharging})$$

where

$R_{z,h}$ = zone response in kW for hour h
$R_{t,z,h}$ = zone response in tons for hour h
η_{conv} = conventional cooling (e.g., chiller) efficiency, kW/ton

The storage efficiency approximates losses due to heat flow through the building envelope. If the building is pre-cooled with a unit of energy, some of that energy is lost by the time when it is needed. Norford *et al.* (1996) used a default value of 0.8.

The space-temperature control analysis was performed for each user-defined zone in a building, for each of three use-specified periods during the day, for both weekdays and weekends. The strategy was one of the following:

- Space temperature is unchanged.
- Space temperature is allowed to swing minimally (default 1 ^{o}F) on days when prices are above the threshold.
- Space temperature is allowed to swing moderately (default 2 ^{o}F) on days when prices are above the threshold.

- Space temperature is allowed to float on days when prices are above the threshold.

The algorithm, termed a first-order approximation to an optimal solution, was simple to implement in simulation for a single building:

1. For each zone, take a given day type (for which the RTP price type is at or above the threshold), 24 hours of data.
2. For each hour, calculate the cost per ton of direct cooling and shifted cooling using chiller and building mass storage efficiencies and RTP prices.
3. If the storage price for the least expensive hour is not less than the conventional price for the most expensive hour, using building mass to shift load for the day is not feasible.
4. Search for candidate discharge hours. If found, take the most expensive.
5. Search for candidate charge hours. If found, take the least expensive.
6. Classify each hour of the day as "inside" (after the charge hour and before the discharge hour) or "outside" (before the charge or after the discharge hour).
7. For the inside and outside sequences, find the maximum possible load shift, given the constraints of temperature control limits, available excess chiller capacity, and chiller use. Take the higher of the two, and shift load from the discharge hour to the charge hour. Adjust temperatures, conventional cooling use, and excess capacity variables.
8. Repeat from step 5 until all charge candidates are exhausted.
9. Repeat from step 4 until all discharge periods are exhausted.
10. Calculate the response in tons and kWh/h. Negative response is a decrease in energy use.
11. Repeat for the next day type.

Optimal control strategies and simplified approximations include a model for the thermal dynamics of the building, parameters of which must be learned on-line or supplied as estimates made from review of building plans or from experience. In Daryanian (1989), for example, the model was a simple one-node thermal capacitance with two thermal resistances. The thermal parameters were estimated with a least-squares procedure from repeated measurements of the outdoor and indoor air temperatures and the heat (or cool) input. In many cases, these control strategies also require a model of plant performance as a function of load and environmental conditions.

In principle, these models could be extended to apply to groups of buildings. Thermostat set points and chiller loads in individual buildings would be manipulated to minimize the cost of operating the HVAC plants in all the buildings. The third task of this project will explore such an approach.

Thermal storage systems. Load reduction can include measures other than thermostat control. Unlike space-temperature control, control of TES requires no variation of indoor temperature. A near-optimal control algorithm, as presented in Norford *et al*. (1996, 1998), follows the same logic as that for space-temperature control, given above. The thermal-storage tank is charged at hours when prices are low and discharged when prices are high. The algorithm must account for the capacity of the tank and the charge and discharge rates as well as the efficiency of chillers when producing chilled water for direct cooling and when producing a low-temperature glycol solution suitable for making ice. Daryanian *et al*. (1994) and Daryanian and Norford (1994) reported a three-year experiment to implement an RTP-based controller in an office building in New York State. The customer's cost of service was reduced about 5% compared to time-of-use control. Compared to no-storage operation, costs were reduced 22%. Simulations showed that savings relative to time-of-use control would have increased from 5 to 13% if the storage tank were larger.

Others have developed more detailed and accurate algorithms for optimally controlling TES in a single building (Drees and Braun 1996, Henze *et al*. 1997a and1997b, Henze and Krarti 1998 and 1999). In principle, thermal-storage systems in multiple buildings could be controlled to minimize aggregate costs. However, Project 3.5 will not emphasize thermal-storage systems (TES) because they are not in widespread use and are not used in the buildings identified in Deliverable 2.2.2a.

On-site generation. Use of on-site generation typically produces the largest load reduction as a result of a single control action. Generators installed to serve emergency loads when there is no power from the grid need appropriate paralleling equipment to meet part of a building's load while the grid serves the remainder. It is relatively simple to schedule a generator when there is a pure RTP rate with hourly prices: the generator is used when its operating and maintenance cost is lower than the hourly price. Scheduling is more difficult when there is a demand charge, under an RTP or time-of-use rate (Shanbhag 1998).

Generators have been used in load-coop programs, where a utility favors groups of buildings with lower rates in exchange for an aggregated load reduction when prompted, subject to an upper limit on the number of load-reduction events. Load-coop programs such as this are very much the sort of aggregated-building load control effort that Project 3.5 seeks to support, with more-informative metering. However, use of on-site generation will very likely not be part of Project 3.5, unless use of the generator in the LA County Children's Court becomes a load-reduction system. The thrust of Project 3.5 centers on demand reduction rather than local supply, and air-quality regulations continue to be a sufficiently major concern to make the California ISO consider generators as a last-resort approach to avoiding blackouts.

Curtailment of HVAC loads and lighting. Supervisory control of HVAC plants involves the automated selection of set points that serve as reference inputs to local-loop controllers. Optimal control of thermostat set points, as described above, is one type of supervisory control of the building as a whole, which can usefully be distinguished from supervisory control of set points internal to the HVAC system. The thermostat set points are used as the reference inputs to controllers that regulate the amount of cooling that flows into rooms. HVAC set points include supply-air temperature, supply-air static pressure, chilled-water temperature, and condenser-water temperature for those chillers that are water cooled. There is a rich literature on this subject, as typified by Brandemuehl and Bradford (1999) and as summarized in an excellent review in Chapter 40, Supervisory Control Strategies and Optimization, of the 1999 ASHRAE HVAC Applications Handbook (ASHRAE 1999).

Typically, supervisory control strategies that adjust HVAC set points are intended to minimize the energy (electricity, gas oil) required to deliver a certain service (heating or cooling). The amount of service is taken as a constraint. These strategies are not load-control measures. The objective function is energy usage and inputs to the optimization include loads but not prices. In short, a supervisory controller would select the same set of set points whether prices were high or low. In contrast, load-curtailment strategies seek to adjust HVAC set points, or turn equipment off, in order to reduce load in ways that unavoidably reduce service.

Gabel (1998) and Flood *et al*. (1994) described the implementation of an RTP-based automatic control system in a large New York City hotel. As shown in Table 5, fans and lights were controlled. The total controlled load of 1.2 MW as 20 percent of the building peak electrical load of 6 MW. The predominant control action was on/off control for individual loads as a function of individual price thresholds. For two air handlers with variable-speed drives (VSDs), the control was a reduction in motor speed by 20 percent.

Table 5. Automatic Load Reduction in Response to Real-Time Prices in a New York Hotel (Flood et al. (1994).

Controlled equipment	**Load (kW)**	**RTP control strategy**	**RTP trigger ($/kWh)**
Atrium circulating fans	410	On/off for one or both fans as a function of RTP trigger price	0.06
Air-handling fans	125	On/off as a function of RTP trigger price	0.06
Theater air-handling fans	70	On/off as a function of RTP trigger price	1.00
Elevator air-handling fans	25	On/off as a function of RTP trigger price	0.40
Outdoor advertising sign	100	On/off as a function of RTP trigger price	0.40
Exterior lighting	105	On/off as a function of RTP trigger price	0.06
Ballroom lighting	30	On/off as a function of RTP trigger price	1.00
VSDs on eighth and ninth floors, supply and return fans	20	Reset 20% lower if RTP trigger is exceeded	0.20
Miscellaneous motor loads	330	On/off as a function of RTP trigger price	0.06
Total	1215		

Energy reductions during high-priced hours totaled 2.5 GWh in 1994. As shown in Table 6, the largest savings, 73 percent of the total, was from turning off or slowing down air-handling fans. Reduced cooling provided to the building - i.e., a reduction in service – accounted for 16 percent of the savings and exhaust fans eight percent. Lights produced a very small savings because few lighting circuits were controlled, due to the expense of re-wiring.

Table 6. Reduction in Annual Energy Use Due to RTP Control in a New York Hotel.

System	Electrical-energy reduction in 1994, GWh	Percentage reduction
Air-handling fans	1.87	73
Chillers	0.42	16
Exhaust fans	0.21	8
Lighting	0.03	1
Miscellaneous loads	0.02	1
Total	2.55	100

Flood *et al*. (1994) proposed a somewhat richer set of control actions for another hotel, as shown in Table 7. Of note is pre-cooling, discussed above, optimal control of a thermal-storage system, and modulation of motor speeds for fans and pumps.

Table 7. Proposed RTP Control for a San Francisco Hotel (Flood et al. (1994).

Controlled equipment	**Load (kW)**	**RTP control strategy**
Air-handling fans (VSDs)	275	Modulate set point as a function of RTP price level
Pump motors and exhaust fans (VSDs)	140	Modulate set point as a function of RTP price level
Lighting (on/off)	30	On/off as a function of RTP trigger price
Lighting dimmers	20	Modulate set point as a function of RTP price level
Ballroom and meeting room HVAC systems	200	Pre-cool as a function of RTP price level and occupancy
Office ventilation fans	20	Reset CO2 set point as a function of RTP price level
Thermal cool storage	95	Optimize the charging and discharging schedule based on the predicted cooling load and RTP price level
Miscellaneous motor loads	100-200	On/off as a function of RTP trigger price
Kitchen equipment	20	Optimize scheduling and coordination of various kitchen operations as a function of RTP price level
Total	900-1,000	

Norford *et al*. (1998) based reduction in lighting levels on the output of an expert system that queried the facility manager about space type, service level when occupied, occupancy status of the space, whether control was manual or automatic, the use of dimming or on/off switching control, and the presence of usable daylight. For example, illuminance level and lighting power might be reduced in a hotel corridor, where occupants pass through the space quickly and the tasks are not critical, but would remain at normal levels in an executive conference room occupied in early evening when daylight is not available.

Implementation issues

What are the barriers to implementation of load-reduction strategies in single buildings or aggregates of buildings? During the January meeting of the Project Advisory Committee (PAC), a PAC member expressed the view that building energy management systems

(BEMS) can control temperatures to reduce load. The Lead Investigator for this project believes this not to be the case. Optimal temperature control algorithms have been tested in simulation and in laboratories, but little work has been done in real buildings. One ongoing ASHRAE research project designed to provide a field test has been hampered by changes in ownership of the targeted test building.

In single buildings, therefore, a key implementation barrier appears to be lack of supervisory control algorithms in commercially available BEMS software. Even were such algorithms available in the produce line of one or more controls manufacturers, it would be necessary for the owner or operator of a candidate test building to implement the algorithm. This is a significant barrier. If the BEMS in a targeted building is not part of the product line that includes the optimal control algorithms, it is not likely that it would be replaced. Even if the BEMS in the target building were made by a company that could provide an optimal control algorithm, the control could require additional upgrades, such as centrally adjustable temperature set points throughout the building.

Work with aggregates of buildings would tend to exacerbate this problem, but it also offers a way forward. If aggregated-building load control is to be implemented as a high-level supervisory control system, in which an optimizer accounts for the dynamics of several buildings, it would be relatively straightforward to test in simulation but very difficult to implement, because the problems in individual buildings would be compounded for the aggregate. On the other hand, if aggregated-building control can be implemented as a coordinated series of actions that are easily implemented manually or automatically, such as turning off chillers at different times in different buildings, then there is some hope for near-term load reduction.

Another perspective on implementation comes from financial incentives currently in place in California to encourage load reduction during peak periods. These incentives, whether in the form of the energy penalty in an interruptible-service rate or payments from state agencies for reduced energy usage, address energy usage and not peak power. The aggregate effect of individual actions to reduce energy use will certainly be a reduction in system-level power. And customers may realize demand-charge savings for reducing peak power. But to the extent that incentives focus on energy, the aggregated-building load control problem from the perspective of an owner of multiple buildings or an aggregator becomes one of ranking and implementing energy-reduction measures in individual buildings. Implementation does not require coordinated control actions, but does require a review of all sites in aggregate to determine the most cost-effective energy-reduction opportunities.

Customer motivation

As Kahn et al. (2001) noted, customers need to be motivated to control peak loads, either through payments in exchange for allowing a service provider to automatically curtail load or run an on-site generator or through communication of marginal prices that show sharp increases when system demand nearly matches available supply. Such motivations have now been provided to the owners and operators of many commercial buildings in

California. The test sites to be used for Project 3.5 are on Southern California Edison's I-6 rate that, until very recently, has provided ample motivation through its energy penalty charge. While penalty charges are not being collected at the moment, it is anticipated that financial incentives for load reduction will continue to be an option for those who operate the test-site buildings.

Legal issues

The scope of work for Deliverable 3.5.1 included an assessment of legal issues and requirements for effective load-cooperative programs. Legal issues, meaning regulations that affect use of load-control technologies, have been mentioned earlier in this report and include:

- Permitting of back-up generators
- Regulator-approved rates that provide incentive for load control
- State programs that provide payment for load reduction
- Metering, measurement and verification requirements

For aggregates of buildings, the issues also include rates that allow credit for load reduction in buildings that are not part of a load-interruption block and regulations that affect bringing multiple meters under a single account.

The Lead Investigator's assessment is that laws and regulations in California, as typified by Assembly Bill 970, are in general supportive of state-wide load reduction. Rates with what economists would consider proper signals are not in universal use. CEC commissioners (Rosenfeld, as quoted in DJ 2001) and others have noted that real-time rates should be more widely implemented. The economic crisis currently faced by consumers and two investor-owned electric utilities is causing some changes, as in the implementation of the I-6 rate. Overall, however, laws and regulations would not appear to hamper the experimental work planned for Project 3.5 nor unduly constrain the use of the results of this project in other buildings.

Requirements for Effective Load-Cooperative Agreements

The intent of this sub-task was to enumerate what is required for building owners and operators to work together to reduce load. Again, this issue has been addressed in part in earlier parts of this report. In short, the requirements are

- financial incentives;
- information about loads and load-control opportunities; and
- the means to reduce load.

These same requirements apply to a single building, of course. For aggregates, the financial incentives and demand for interaction apply at a level higher than an individual building. For example, in a traditional load-cooperative program, a utility gives a group of commercial building owners a financial incentive for reducing aggregated load. All share in the incentive and all bear a collective responsibility to reduce load when asked. The Discretionary Load Control Program under consideration by the CAISO provides an incentive for a form of cooperative action, in that load-curtailment coordination and measurement is the responsibility of a load aggregator.

Conclusions

Based on the findings reported above, the Lead Investigator proposes to modify the scope of work and accelerate the schedule for the demonstration portion of Project 3.5. The Lead Investigator proposes to delete Deliverables 3.5.1b and 3.5.2a as unnecessary in California at this time. Further, it is proposed to shift the emphasis of Deliverables 3.5.3a and 3.5.4a and to place more emphasis on field studies. The details of the proposed changes are described in a separate letter.

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