A DISTRIBUTED INTELLIGENT AUTOMATED DEMAND RESPONSE

BUILDING MANAGEMENT SYSTEM

1 DOE Award Number & Name of Recipient

1.1 DOE Award Number:

DE-EE0003847

1.2 Recipient:

Regents of the University of California, (UC Berkeley campus), with Lawrence Berkeley National Lab and Siemens Corp as sub-awardees.

2 Project Title and Principal Investigators

2.1 Project Title:

A DISTRIBUTED INTELLIGENT AUTOMATED DEMAND RESPONSE BUILDING MANAGEMENT SYSTEM

2.2 Task Title:

"Task 5: Demand Response Algorithm Development"

2.3 Date of Report:

20 April 2011

2.4 Principal Investigators:

Professor David Auslander, Department of Mechanical Engineering, U.C. Berkeley (UCB)
Professor David Culler, Department of Electrical Engineering, U.C. Berkeley (UCB)
Professor Paul K. Wright, Director, Center for Information Technology Research in the Interest of Society (CITRIS) and the Department of Mechanical Engineering, U.C. Berkeley (UCB)
Dr. Yan Lu, Siemens Corporate Research Inc (SCR)
Mary Ann Piette, Lawrence Berkeley National Laboratory (LBNL)

2.5 Key personnel:

Thomas Gruenewald, Siemens Corporate Research Inc (SCR)
Prasad Mukka, Siemens Corporate Research Inc (SCR)
SilaKiliccote, Lawrence Berkeley National Laboratory (LBNL)
Dr. Therese Peffer, Project Manager, U.C. Berkeley and CIEE (UCB)

2.6 Authors:

Daniel Arnold, Graduate Student Researcher, UC Berkeley, Mechanical Engineering
Kevin Ding, Graduate Student Researcher, UC Berkeley, Mechanical Engineering
Tyler Jones, Graduate Student Researcher, UC Berkeley, Mechanical Engineering
Dr. Yan Lu, Siemens
Nathan Murthy, Student Researcher, UC Berkeley, Applied Mathematics
Michael Sankur, Graduate Student Researcher, UC Berkeley, Mechanical Engineering
Jay Taneja, Graduate Student Researcher, UC Berkeley, Computer Science
Jason Trager, Graduate Student Researcher, UC Berkeley, Mechanical Engineering
Rongxin Yin, Graduate Student Researcher, Lawrence Berkeley National Laboratory
Siyuan Zhou, Siemens

Table of Contents

3 Executive Summary

The Distributed Intelligent Automated Demand Response (DIADR) project endeavors to develop an energy management system with intelligent optimization and control algorithms to achieve 30% peak load reduction while still maintaining the building as a healthy, productive, and comfortable environment for the building occupants. The selected building site is Sutardja Dai Hall at UC Berkeley. Two earlier reports outlined the System Architecture and the Building Management System integration with the OpenADR protocol that administers the demand response signals. This report describes the development of central and distributed load control algorithms.

The report begins with a discussion of establishing an energy baseline, with which to compare any energy savings. The next section describes the algorithms that manage central loads, such as Heating, Ventilation, and Air Conditioning (HVAC) systems as well as lighting systems. Many factors, such as weather and occupancy patterns and a model of the building enter into the algorithms; the architecture is multi-agent and distributed rather than central and top-down, requiring a negotiation protocol. The following section outlines the development of the distributed load algorithms. This process started with an innovative plugload audit of the building to automate the process of logging and accessing information about each appliance in the building. Fundamental to the distributed load management was the development of a commercial gateway. Multiple gateways can be distributed throughout the building, each controlling a number of plugload devices typical of an office, such as computers, printers, task lamps, portable heaters or fans, and refrigerators. A user interface was instrumental to the gateway to engage occupants and provide choice of appliance curtailment during DR events. Laptop/computer power management and printer management are outlined in detail. The control architecture is discussed in the next section, including discussion of agent-based control. Finally, an Energy-Plus model was developed for the algorithm simulation; the details are in the Appendix.

This research will add to the body of demand response research by pushing the boundaries of typical DR goals. While typical DR goals for commercial buildings is on the order of 10%, this project plans to triple that energy reduction by expanding the role of control to distributed nodes. Reliance upon centralized pre-programmed controllers to take action based on a demand response signal can result in a loss in the system responsiveness to the dynamic changes of energy price, occupancy patterns, load requirements as well as weather conditions. The distributed approach embeds as much autonomy as possible in local sections of the network to enable distributed optimization and control functions.

The techniques involved in this work mostly rely on software; this implies that applying this process to other buildings is relatively inexpensive. Intelligent algorithms rely on distributed sensors (hardware) to provide information. However, a goal of this project is to optimize economic feasibility, by balancing information points with cost to provide the best control strategies with the fewest sensing points.

Demand Response in general aims to reduce peak electricity consumption, which can benefit the public by slowing the pace of creating new power plants and reducing air pollution created by older peaking power plants. This project not only deepens a building's demand response, but also actively engages occupants in order to maintain a productive work environment.

4 Comparison of Project Accomplishments and Project Goals

The Demand Response Algorithm Development (Task 5) includes six subtasks: DR optimization and control architecture design, central load management optimization algorithm development, distributed load management (Agent-based) development, DR optimization with onsite DG, simulation-based demonstration of DR optimization and control, and documentation (this report). All subtasks but one were accomplished according to plan. Regarding subtask 4, since the building selected for this project did not currently have any distributed generation (DG), we decided to focus on energy storage instead. The simulation of the DR algorithms will be demonstrated to DOE on April 27, 2011.

Tyler Jones of UC Berkeley developed a program using MATLAB to determine a baseline value to be used for centralized control. Yan Lu and others at Siemens Corporate Research developed centralized load management optimization algorithms, which include the HVAC system and many of the lighting controls of Sutardja Dai Hall. Michael Sankur and other students from UC Berkeley created an agent-based distributed load management system (Commercial Energy Gateway), with which plug loads in the building will be controlled directly. Jason Trager and other students from UC Berkeley conducted a plugload audit of Sutardja Dai Hall in support of the algorithm development. In addition, a user-interface for the gateway collects local parameters for the HVAC system and lighting control and submits them to the central control system for further strategy implementation. Jay Taneja and Nathan Murthy of UC Berkeley developed strategies for curtailing plug load such as desktops, laptops, and printers during Demand Response events. Kevin Ding and Nathan Murthy of UC Berkeley developed a User Interface for the Gateway. Siemens introduced the UC Berkeley team to JADE as the control architecture for the interaction between the central load management system and distributed load management system, setting up the protocol for communication between the two acting agents. SilaKiliccote and Rongxin Yin of Lawrence Berkeley National Laboratory developed an Energy Plus model of Sutardja Dai Hall for use on the Distributed Intelligent Automated Demand Response Project. The Energy Plus model is being used to simulate the building HVAC, plug load, and lighting parameters to estimate the distributed load by control zone. The model will be used to estimate and predict the building energy consumption and temperature for various HVAC and lighting control scenarios in the interest of optimizing demand response control strategies.

5 Project Summary

5.1 Introduction

Sutardja Dai Hall is a 141,000 square foot building on the UC Berkeley campus that houses the Center for Information Technology Research in the Interest of Society (CITRIS). Much of the building occupancy is dedicated to offices, with a few classrooms, an auditorium, café and a nanofabrication lab that is not included in the project’s energy reduction goals. The whole building demand load is approximately 940kW.

The diagram below describes the basic system architecture: a demand response signal is sent by the Demand Response Automated Service (DRAS) and is received by the Siemens Smart Energy Box (SEB) installed in Sutardja Dai Hall at UC Berkeley. The SEB then generates a load shedding goalsent to the Building Automation System for the HVAC system, the WattStopper lighting system, and to the distributed load gateways that control appliances.

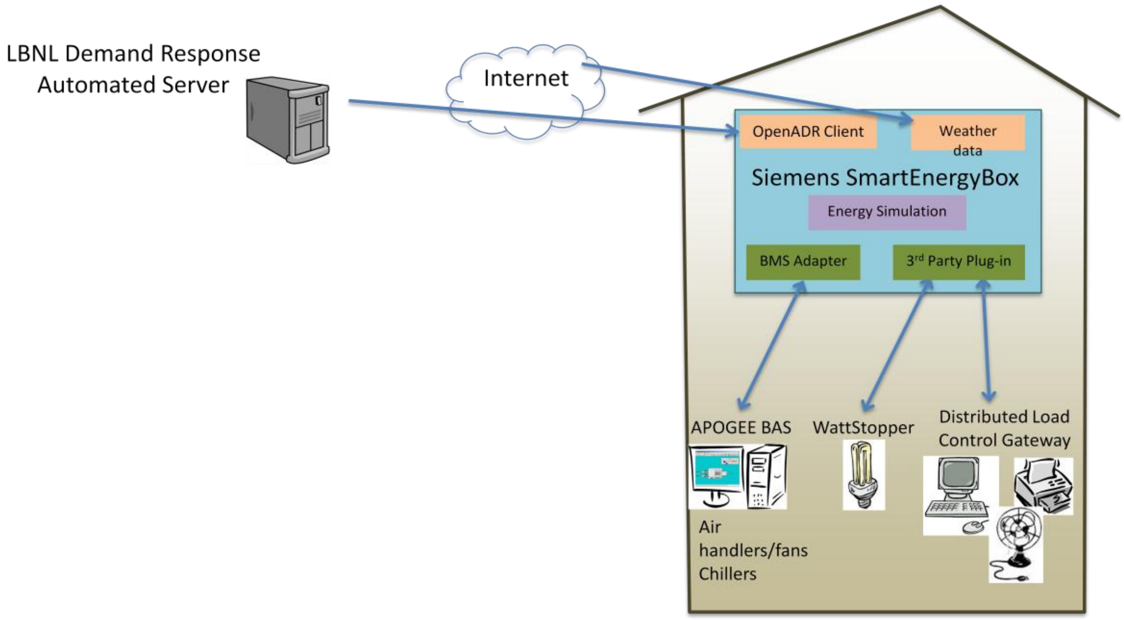

Figure 1: Overall DIADR control management system.

Siemens met with the facilities manager to determine which elements of the building could be subject to demand response control and which were not allowed. (The building houses an energy-intensive nanofabrication laboratory that is not included in the energy reduction goals of the project, but shares chilled water with the whole building). Initial control strategies include: expand the allowable building zone setpoints(minimum to 69F and maximum to 78F), precooling to 69F before occupied, can change duct static pressure and supply air speed, and can turn off some air handling units, supply fans, and exhaust fans. For lighting, some overhead lighting can be dimmed (stepped dimming). UC Berkeley conducted a plugload audit of the building to determine gateway controllable loads, such as computers, monitors, printers, coffee/tea pots, task lamps, and portable heaters and fans.

5.2 Baseline Development

In order to determine an appropriate goal for DR load shed, a proper baseline load for a normal day must be demonstrated and defined as a reference for gauging how effective the control strategies are with the project goals of 30% load shed during a DR event. UC Berkeley has worked on a program to predict a baseline for Sutardja Dai Hall for a day in which a DR event is to occur. This baseline can be used for feedback control as a reference to engage further DR strategies in cases where the commercial DR goal is not met.

The baseline prediction program uses a series of inputs including Outside Dry Bulb temperatures, power data from the past ten days, power data from the morning of at 10 AM and 11 AM, as well as power data from a year ago and HVAC data if available.

The baseline prediction program first draws data from the sMAP[1] server, a server developed by students at UC Berkeley containing weather and energy data from numerous sites on campus. On the day of a DR event, the program will be run after 11 AM to generate a baseline load profile for the day. The program generates a discrete profile with a sampling time of 5 minutesdue to the limit of the Siemens BMS Apogee points set to 5 minutes for the data. The program is based on a LBNL's Best Method that uses data from the morning of the DR event to create a first correction factor for the DR Day. Data from the ten previous days is also accessed with the hottest 3 days selected for use. The submeterdata from 10 AM until 6 PM of the hottest three days is averaged for each time step.

A correction factor was created using the actual loads at 10 AM and 11 AM of the morning of the DR event. The correction factor is described as:

$$c(d) = \frac{pl(d, h = 10) + pl(d, h = 11)}{al(d, h = 10) + al(d, h = 11)}$$

Where:

al(d,h) – the actual load for the day and the hour

pl(d,h) –the average of the 3 highest actual loads at this hour over the 10 previous days.

The baseline prediction was tested for 5 days. Figure 2 shows two of the days tested in which data was available to run the program with sufficient data.

[1] [1]Simple Monitoring and Actuation Profile (sMAP) defines a data schema and API to allow multiple disparate interfaces to communicate data. Details regarding the sMap server can be found at http://www.openbms.org/smap/plot

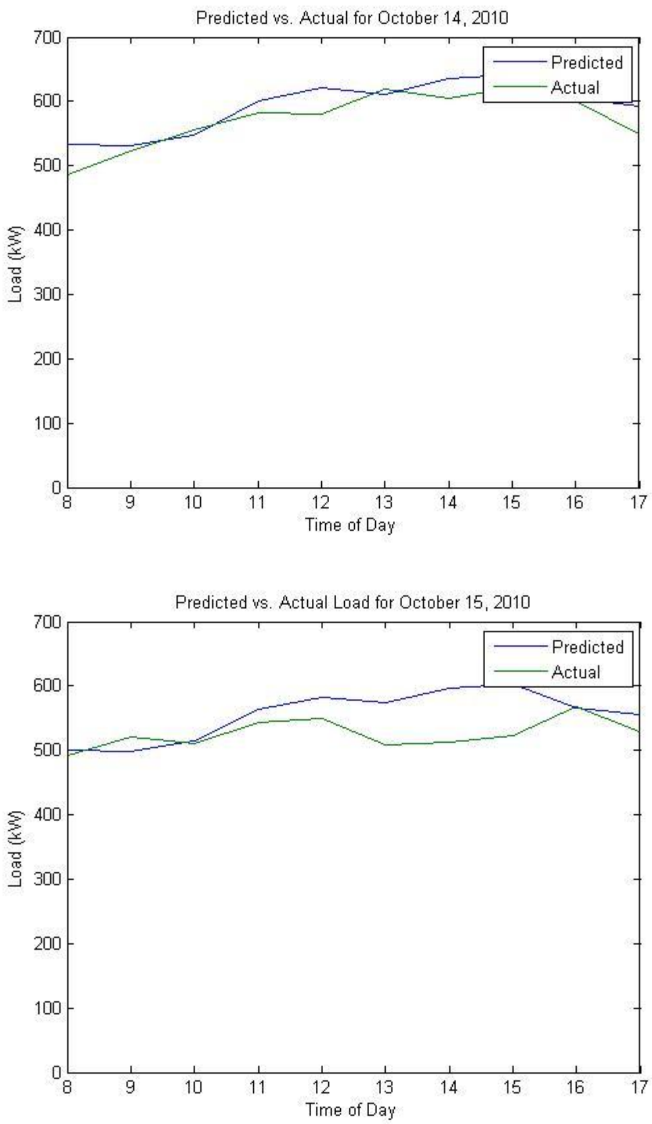

Figure 2: Baseline Prediction tested for October 14 and 15, 2010[2]

The prediction requires increased robustness of accuracy with respect to weather fluctuation. There may be problems if the prior ten days have been cold and the DR day is the first day that is classified as a DR day. This calls for the use of a second correction factor using data from the past year with a correction factor accounting for HVAC efficiency, as well as occupancy. Both of these parameters are not currently dynamically measurable due to current limitations with submetering and actuation. However, a static occupancy estimation can be used based on total building employee numbers for various time periods. This assumes that with significantly larger numbers of employees assigned to a work station, there is a strong correlation with the number of people that are expected to be at work on

[2] Note: Dates for testing were limited due to submetering implementation. Many of the days that could be tested as DR days lacked the data.

any given day. Employment numbers from previous years were gathered and used to create a second correction factor. The HVAC parameters currently are not accessible due to the lack of equipment to measure HVAC process flows in the building. The program factored occupancy manually for these calculations until more data is available.

The second correction factor is dependent on the HVAC efficiency parameters, which can be calculated with parameters of the mass flow rate of the chilled water, and the inlet and outlet temperatures of the chilled water, as well as the actual power measured for the compressor in compression chiller. The equations guiding these calculations are shown below.

$$Netrefrigerationcapacity(TR) = \frac{mc_P(T_{in}-T_{out})}{3024}$$

Where:

m : mass flow rate of chilled water, kg/hr

C_p : Specific heat, kcal/kg °C

T_{in} : Chilled water temperature at evaporator inlet, °C

T_{out}: Chilled water temperature at evaporator outlet, °C

$$kW/ton\ rating = \frac{Measuredcompressorpower(kW)}{Netrefrigerationcapacity\ (TR)}$$

$$COP = \frac{3.516}{kW/ton}$$

The COP from last year is compared to the COP this year based on measurements and the ratio is used as the correction factor.

$$c(COP) = \frac{COP_{TY}}{COP_{LY}}$$

This correction factor will be very crucial in developing a baseline for DR events. It will be implemented once the submetering is available.

There is also possibility for occupancy data to be collected. These methods have not yet been decided on but once implemented can provide information to increase the accuracy of the baseline profile model. A test using the static occupancy data for a given day proved to provide small improvements in the accuracy of the prediction.

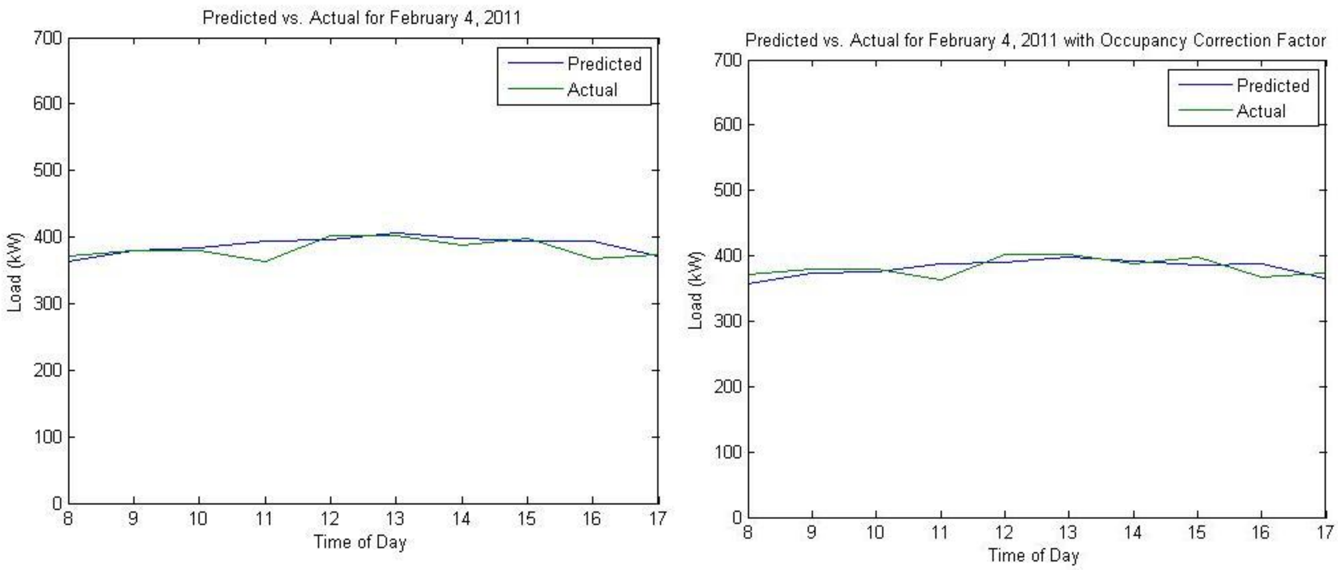

Figure 3: Comparison of Prediction without and with Occupancy Correction Factor

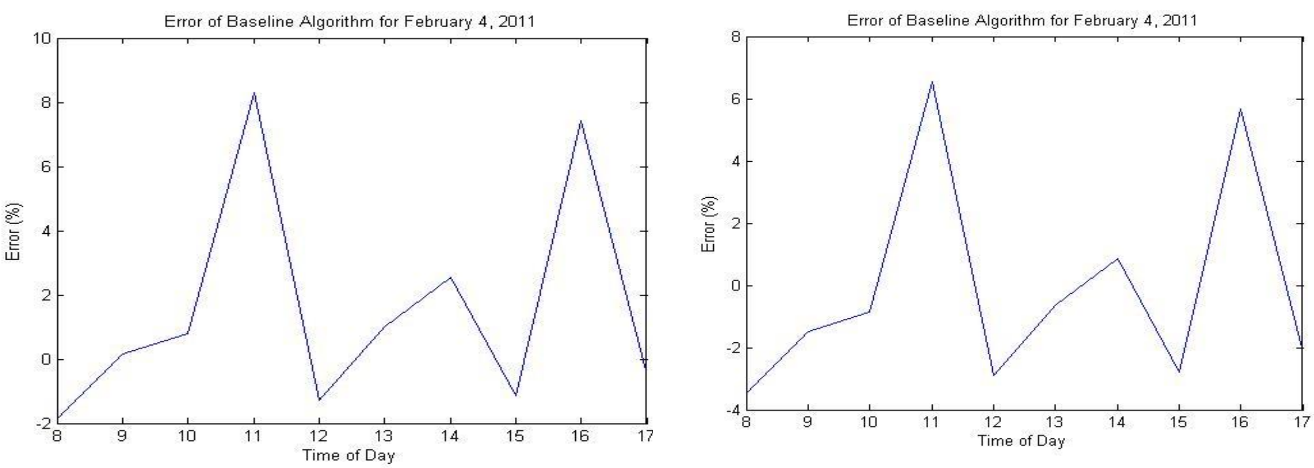

Figure 4: Error of Prediction without and with Occupancy Correction Factor

Further development of the baseline will be possible with the future installation of submetering equipment in Sutardja Dai Hall, including HVAC submetering dealing with flows as well as improved occupancy data.

5.3 Central Load Management Framework

Siemens Corporate Research (SCR)has worked on the control architecture for DIADR system, defining the distributed Demand Response (DR) control framework based on multi-agent and market-based control approach.

For centralized DR control, only one top-tier DR Manager works as the decision maker to control building load shedding/shift/shaping and the local DR Manager only needs to execute the commands from the central DR Manager. To generate control commands in response to the DR event centrally, all of the local system (HVAC, lighting, distributed zone/offices) observations and states have to be fed to the central DR Manager. As the local status changes from zone to zone, the central DR Manager must reconfigure the DR strategy.

Figure 5 shows the architecture of centralized DR management, where there is a central DR Manager making a decision on the load shaping strategy to respond to DR events. The central DR Manager sends direct control commands to each subsystem and distributed load controller, which implement the desired strategy for each load in the building. The control commands include but are not limited to set points for individual zone temperature, Air Handling Unit (AHU) supply air pressure, fan speed and dimmable light settings, as well as on/off switching of distributed loads, power generation and energy storage. To make a reasonable and optimal decision, defined as achievingmaximal **demand reduction,**while still maintaining the building as a healthy, productive, and comfortable environment for the building occupants, the central manager should keep all the static and dynamic information about the sub-systems and local distributed load control systems. The static information is stored in a global database and the dynamic data is updated in the Run-time Data Repository. The static information includes the whole building information model, as well as the operation schedules. The dynamic data reflects the real-time subsystem and local control system states, temporary occupancy changes, space mission changes and meter data. In addition, a user interface is also included for the building operator to change the DR configurations. Online connection to weather service is needed by the central manager to create DR strategy based on load prediction. Usually, the larger loads will be assigned more load shedding during the peak period.

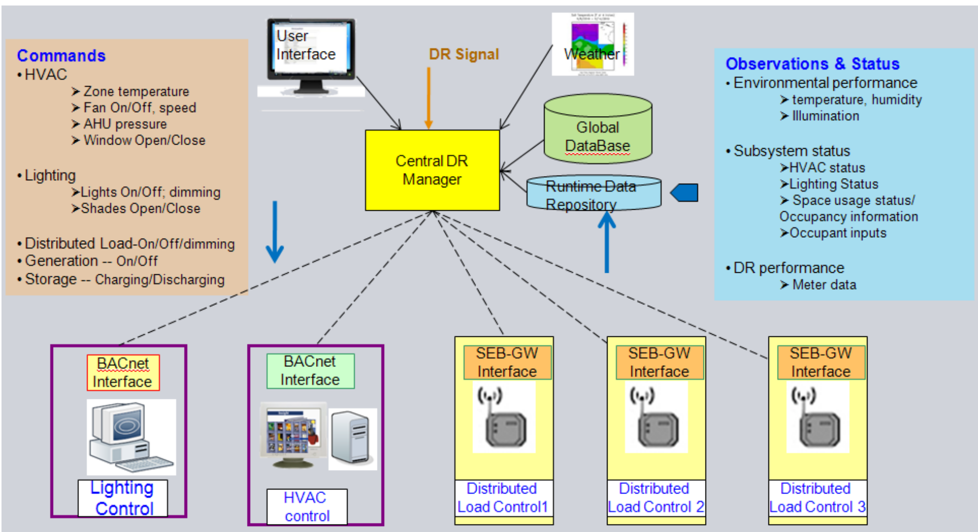

Figure 5: Centralized DR control architecture.

For centralized DR control, the subsystems and local controllers are completely passive, acting as an executor without intelligence. The centralized control is not flexible and robust. Whenever there is a real-time event happening, either from User Interface or from subsystems, the central manager has to reconfigure the whole system again, which could takes several minutes and makes fast DR impossible.

On the contrary, if distributed DR is implemented, the task of decision-making is distributed to local control and gateways. The top-tier DR Manager only needs to pass DR signals or generate goals to pass on to the second/third tier DR Managers. For example, agents could react to DR events using market mechanisms by bidding either for energy service or load shedding if an economic incentive is given. The controlling agent can be hosted at the subsystem level as well as in the central device (e.g. for HVAC and lighting control, the Smart Energy Box (SEB) can host agents for HVAC load and light load DR control). The agent can sense, derive, plan and execute autonomously. This architecture also allows local agent aggregation to respond to a local event without making overall system configuration.

A multi-agent architecture has been proposed for distributed demand response. Each building control subsystem, local distributed load controller, distributed generation and energy storage is represented by an agent, including HVAC agents (HVACA), the lighting control agent (LCA), the Gateway agent (GA), distributed generation agent (DGA), energy storage agent (ESA). In addition, there is an SEB Agent (SA) which acts as a task agent which also receives DR signals. The SEB generates the load shedding/shifting/shaping goals after receiving DR signals. The load agents(HVACA, LCA, GA), the energy generation agents (DGAs) and energy storage agents (ESAs)perform load shedding/shifting/shaping to achieve the DR goal. Figure 6 shows the potential control architecture for distributed DR management.

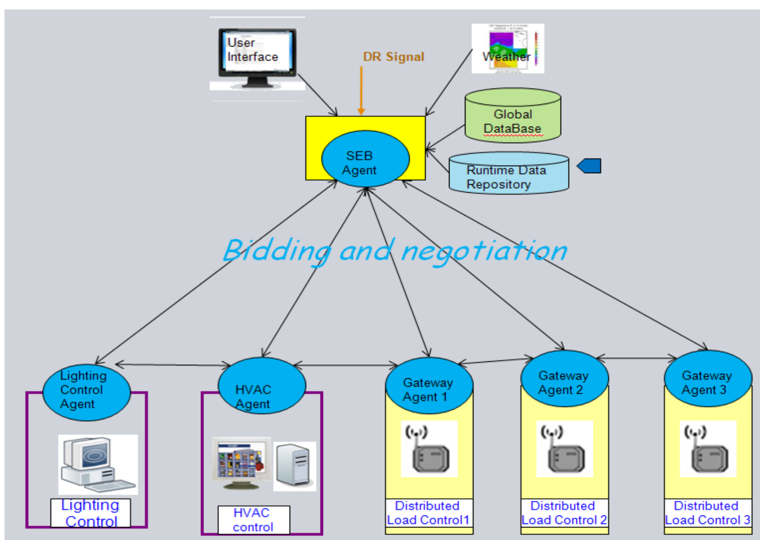

Figure 6: Distributed DR control architecture

In order for the agents to find a feasible global DR strategy, the agents must cooperate and coordinate their local actions. The most widely used cooperation and coordination method is the Contract-Net Protocol (CNP). The CNP is a high level protocol for achieving efficient cooperation,and is based on a market-like protocol. The CNP has been extensively used for inter-agent cooperation in dynamic resource management; it also was standardized by many international organizations and implemented based on multiple open-source agent platforms. The FIPA Contract Net Interaction Protocol (IP) is one of such protocols, which defines a minor modification of the original contract net IP pattern in that it adds rejection and confirmation communicative acts.

Using Contract Net can be advantageous when compared with other coordination strategies for the following reasons outlined below.

1. Tasks are assigned (contracts awarded) dynamically, resulting in the better deals for the parties (agents) involved.
2. Agents can enter and leave the system at will.
3. The tasks will be naturally balanced among all the agents since agents that already have contract(s) don't have to bid on new ones. If an agent is already using all its resources, it will be unable to bid on new contracts until the current ones are completed.
4. A reliable strategy for distributed applications with agents that can recover from failures (to be discussed more in the following paragraphs).

5.3.1 FIPA Contract Net Protocol

In the contract net IP, one agent (the Initiator) takes the role of a manager that wishes to have some task performed by one or more other agents (the Participants) and further wishes to optimize a function that characterizes the task. This characteristic is commonly expressed as the price, in some domain specific way, but could also be the soonest time to completion, fair distribution of tasks, etc. For a given task, any number of the Participants may respond with a proposal; the rest must refuse. Negotiations then continue with the Participants with proposals. In FIPA Contract Net Protocol we basically have two different actors, an Initiator and a Responder (Participant in the picture). The Initiator asks for m proposals from different Responders by sending a call for proposal (known as CFP). The CFP specifies the task the Initiator wants the Responder to achieve as well as any kind of conditions the Initiator is placing upon the execution of the task. Within these conditions, we define a deadline for Responders. Once the deadline passes, the Initiator will evaluate two kinds of responders, the ones who will PROPOSE and the ones who will REFUSE.

Within the Responders who will PROPOSE, the Initiator will selects agents to perform the task: one, several or no agents may be chosen. The Initiator will send an ACCEPT-PROPOSAL message to selected agents, and a REJECT-PROPOSAL message to others. Once the task is performed by the Responder, it will send an INFORM-done- result message to let the Initiator know that the task was successfully performed or a FAILURE message if the message was unsuccessfully performed. Figure 7 shows the typical FIPA bidding-negotiation sequence.

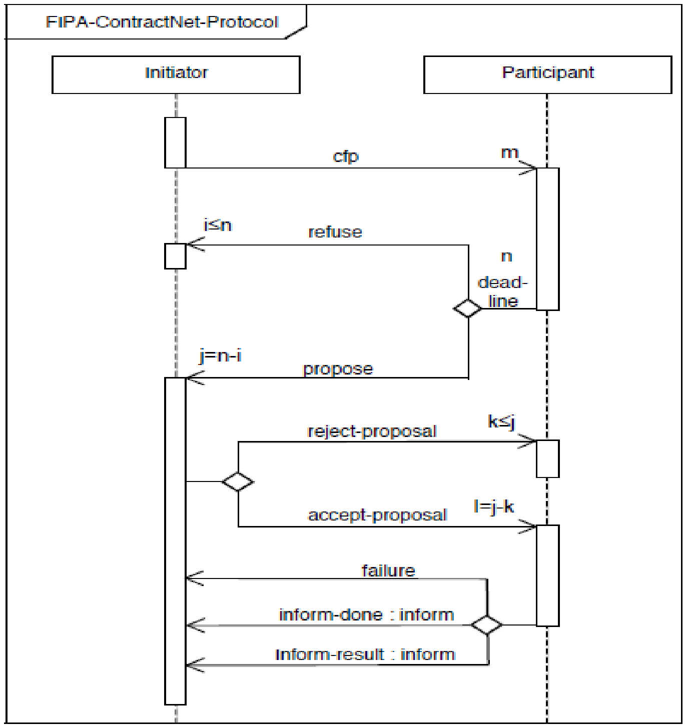

Figure 7: FIPA Contract Net Protocol

5.3.2 Scenario1: Receiving a Goal-- the negotiation protocol developed for cooperative optimization

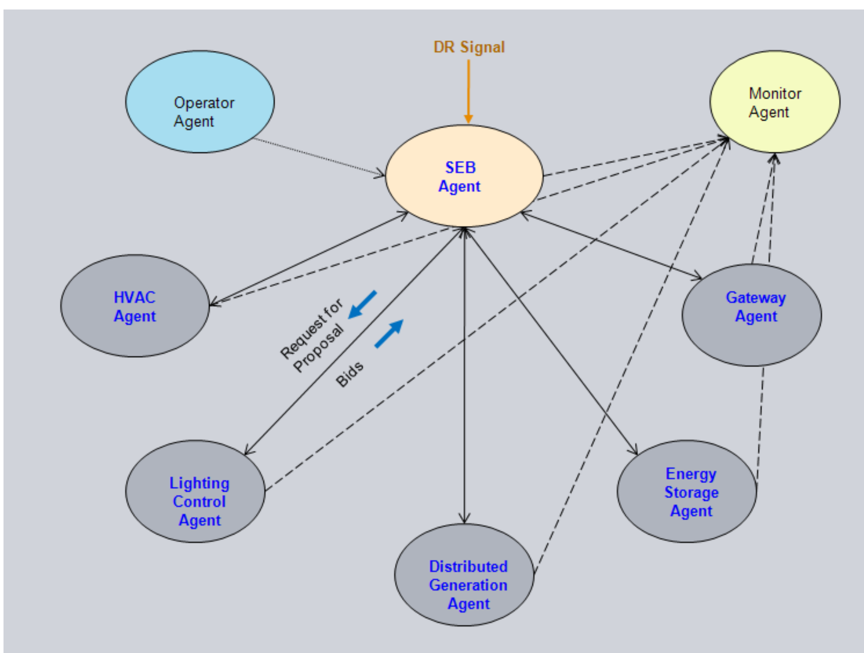

Figure 8: SEB Agent as buyer, Load Control Agent as seller

Upon receiving the DR signal, the SEB Agent (SA) analyzes the announcement and generates a load shedding goal for the requested DR period. Negotiation starts with identifying the load, generation and storage agents to generate the schedule for load shedding. The SEB Agent sends the DR-announcement message to the load/generation/storage to request the shedding of energy usage. The DR-announcement message describes the following information:

Sender: SEB Agent,

Receiver: HVAC Agent, Lighting Control Agent, Gateway Agent, Distributed Generation Agent and Energy Storage Agent

Type: Load shedding task announcement,

Task specification: the load shedding requested by the BDRA with the description of duration of the DR event, maximal cost and penalty for de-commitment.

Bid-reception deadline: the time by which HVAC Agent, Lighting Control Agent, Gateway Agent, Distributed Generation Agent and Energy Storage Agent must respond with a bid.

The bidding process starts after the HVAC Agent, Lighting Control Agent, Gateway Agent, Distributed Generation Agent and Energy Storage Agent receive the load shedding task announcement. A bid represents an offer to execute the task specified in the DR-announcement concerning the production of the load-shedding required by SA. Each HVAC Agent, Lighting Control Agent, Gateway Agent, Distributed Generation Agent and Energy Storage Agent will inspect the DR-announcement message and will decide whether or not it should respond with a bid, considering its own operation schedule and status of the equipment. To respond, it will develop its locally optimized scheduling and sends an LS (Load Shedding)-bid message to the BDRA. The LS-bid message describes the following information:

Sender: HVAC Agent, Lighting Control Agent, Gateway Agent, Distributed Generation Agent and Energy Storage Agent,

Receiver: SEB Agent,

Type: bid,

Bid specification: the load shedding to produce with the proposed production time

Bid-acceptance deadline: the time by which the SEB Agent must respond with a contract.

After receiving the bids before the bid-reception deadline, the SEB Agent evaluates the LS-bids and selects the best bid based on the cost.

Contracting starts after the SEB Agent accepts/rejects the bids. SEB Agent can respond before the bid-acceptance deadline with the following alternatives:

• Accept the bid and send the award message to the appropriate load/generation/storage agents.

• Accept the load shedding in the bid and renegotiates the production of load shedding with increased maximal cost. The SEB Agent restarts a re-negotiation session with a new announcement message, which specifies the part of load shedding with higher cost and an additional allowance of lower penalty. The renegotiation process iterates cyclically until the SEB Agent states that the solution matches the requirements of its schedule within acceptable tolerances.

A failure to send a contract message before the bid-accept deadline means the SEB Agent is rejecting the bid.

5.3.3 Scenario2: Dynamic Response --in the presence of real-time events/ decommitting.

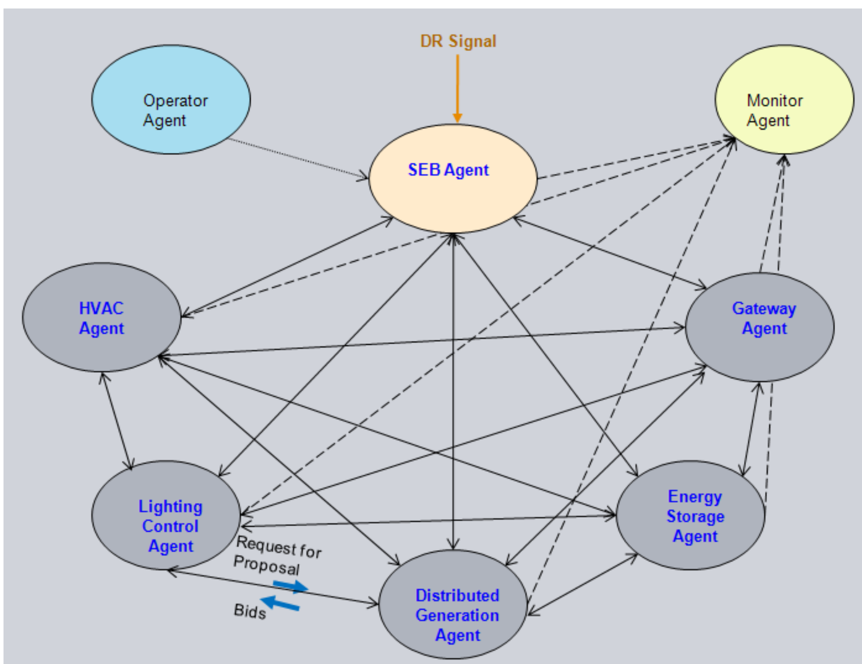

Figure 9: Load Control Agent as seller and buyer.

The task agent and the SEB Agent negotiate the operations of the task with the resourceagents (HVAC Agent, Lighting Control Agent, Gateway Agent, Distributed Generation Agent and Energy Storage Agent) using the CNP. When a resource agent, for example, the Lighting Control Agent, detects a light-sensitive use case such as for a lab experiment, it can senda fault message to the SEB Agentthat has contracted its operations. The SEB Agent will renegotiate the operations with other resource agents capableof performing the operations. Other resource agents can make decisions based on their status to respond for a bid or not. Hence, not every resource will be impacted.

A more flexible reconfiguration can happen if we treat each agent as both task and resource agents. When the Lighting Control Agent finds it cannot commit the task, it can send a CFP (call for proposal) to its peer agent and request for load shedding. In the same way, the LCFnegotiates using the CNP with the peer agents in its database that can cover the load shedding task. InFigure 9 shown above, it turns to distributed generation for task rescheduling.

5.4 Distributed Load Management

Management of distributed loadsis a major goal for the DIADR project and has been led by the UC Berkeley team.The first step was conducting a plugload audit of the building to determine how many and what type of appliances were in the building, as well as how much power each consumed. To implement the individual strategies for control required a gateway; the Commercial Energy Gateway (CEG) was developed for this project to communicate with the Smart Energy Box and negotiate control of devices. Each device, whether smart or “dumb” will have power characteristics that are accessible to the Gateway and allow the Gateway to make intelligent decisions as to how the devices in the given sphere of influence are to be controlled.The power is measured instantaneously on all devices and their states are relayed back to the Gateway, either independently or with the use of a switchable power strip (SPS). The Gateway, after gathering the states of all machines, the user preferences, and receiving the shed goal from SEB, categorizes and orders the control tasks to be submitted for implementation in the office spacebased on the preferences set by the user and the possible savings that can be harnessed. Finally, UC Berkeley has explored individual strategies for computers with energy storage capabilities such as laptops and desktops connected to uninterruptable power supply (UPS) devices, and printers.

5.4.1 Plugload Audit of Sutardja Dai Hall

Plugload auditing of Sutardja Dai Hall has been completed as an assessment of the static base load of the building. The next step is to understand the dynamic behavior of distributed loads in the building through limited but increasing sensor deployment.

The Rapid Auditing Protocol (RAP) allows researchers to energy audit the building in a continuous fashion, and will lead to effective demand response through improved user involvement and awareness of energy usage throughout the building. The protocol involves the following steps:

- Record Device Information:
    - Power usage
    - Local coordinates (relative to room origin [west,north]
    - Device power draw or amperage rating
    - Device make and model number
    - Device type (place in taxonomy)
    - Extra information

- Scan device QR code (unique for each device)
- Take picture of device
- Enter device in database

This energy auditing protocol can place each device into the database in approximately one minute, and is very useful for assessing the energy usage of the building on a room by room, floor by floor basis.

Figure 10: Example of unique QR Codes Used for Rapid Auditing Protocol

The current auditing procedure involves the use of an Android smart phone application to conduct the audit and database entry in one combined system. In order to enter an object into the database, an auditor enters the room, locates the South-West corner, and begins to document devices in the room using certain assumptions[3].

This information is fed into a datastore capable of publishing data to a report. A MATLAB code developed by UC Berkeley is used to produce a static power usage map of any room. An example of the data in a Power Usage Colormap is shown for room 464 in Sutardja Dai Hall in Figure 11. This power map will eventually be animated using data provided by the Simple Measurement and Actuation Profile (sMAP). The sMAP server pulls data at various time intervals from live feeds on campus and stores them in a database that can be accessed for the Power Map as well as other applications within the project. This active animation allows for the integration of time and space into the feedback of power use in the building. It is through these mechanisms that human users may acquire an interest in and actively participate in the feedback loop of energy conservation. Figure11 below show the energy map of the room while a refrigerator is running, and when it is not. Axes are measurements in feet.

[3] The assumptions for the Rapid Auditing Protocol are listed in Section 7 Appendix Table

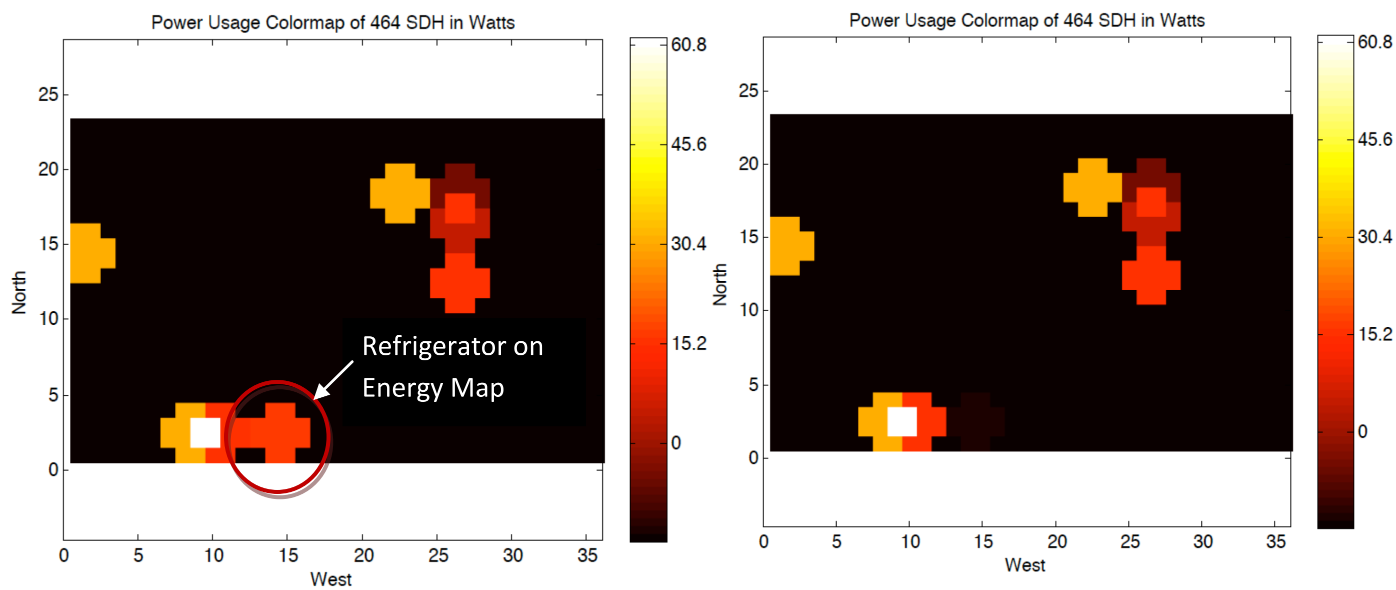

Figure 11:Energy plan of room showing refrigerator currently running (Left) and off (Right).

Figure 12 shows the refrigerator duty cycle that is being monitored over a 6 hour period using sMAP. During the peaks on the graph, the refrigerator is on and will show up on the Energy map. When the refrigerator is off, it will change color on the Energy map. This energy map may be developed for large scale use in which building occupants can understand their energy use better and may offer a social solution to problems of unnecessary energy use.

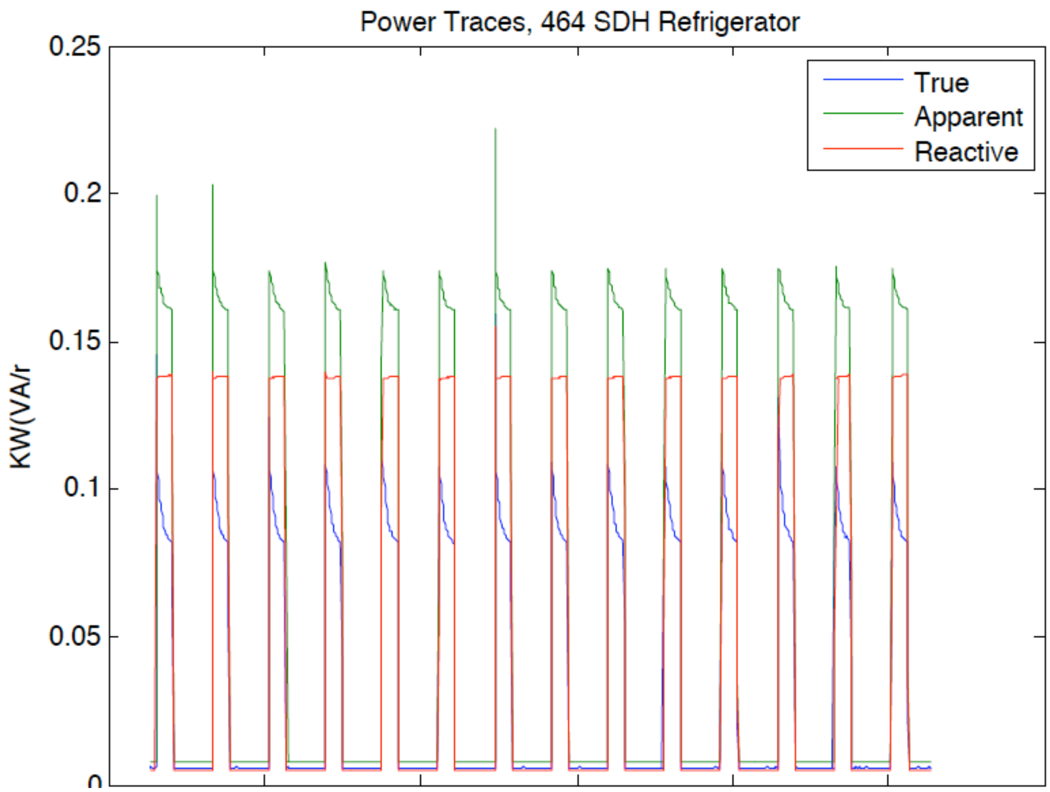

Figure 12: Time plot of refrigerator duty cycles.

The plugloaddata is shown below in Figure 13, a total of 730 devices with total faceplate power draw of 65.8 kilowatts. Note that nearly 60% of the appliances are computers and printers, which draw less than 50% of the load. On the other hand, while there are relatively few electric tea kettles and coffee makers, these draw lots of power. The water heaters also have high power consumption.

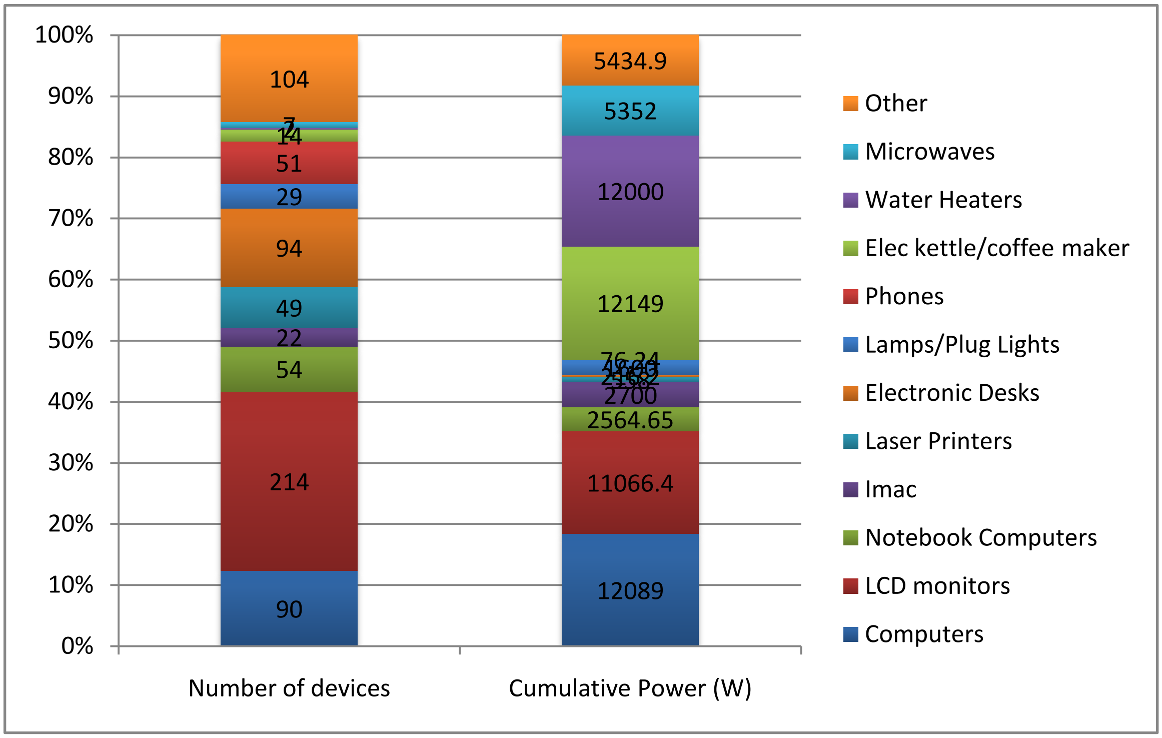

Figure 13: Device count and power breakdown for Sutardja Dai Hall

5.4.2 Commercial Energy Gateway (CEG) in Distributed Demand Response

5.4.2.1 Introduction

The Commercial Energy Gateway[4] (CEG) is a communication and control software package, developed to be an open-source and open-standard architecture for use in commercial applications. The essential functionality of the CEG originates from the Energy Information Gateway (EIG or Gateway for short) originally developed for residences and converted for commercial applications. The primary purpose of the EIG is to empower users to manage their energy usage more effectively. In a commercial setting such as for the commercial demand response, this amounts to establishing communication and control between appliances in the CEG's sphere of influence and communicating energy and control information to the user in a practical manner. The sphere of influence may include lighting, smart appliances that can be controlled directly as well as "dumb" appliances, which can be controlled through the use of load switches or switchable power strips (SPS) that can be directly controlled by the Commercial Energy Gateway. Central to the operation and success of this project is enabling widespread connectivity over several communications media (e.g. WiFi, ZigBee, Zwave, LAN, etc), which make up the current marketplace of smart communicating energy products. The Gateway also relies on a Web User Interface (UI) that is in the process of being developed.

[4] Additional technical Information for the Commercial Energy Gateway can be found in Section 6.3.1 of the Task 5 report

5.4.2.2 *Functionality of the CEG*

The CEG is designed as a communication and control system that aggregates appliance and device power consumption data and presents it to the building management system for automated control based on a set of goals determined for a given DR event period. It is also designed to automatically exert control on appliances and devices within its sphere of influence during a DR event. Currently this is done on a priority based model, in which appliances/devices with low priority settings are turned off or their power use is altered before ones with higher priority settings. The CEG goes through its list of connected and controllable appliances and devices exerting control when needed to meet a goal of power reduction. The user is still allowed supervisory control over the EIG operation during these events. For example, suppose a user is running intense computation when a DR event starts. The user can override control of their computer to continue the computation instead of having the CEG set the computer to a standby or sleep mode.

There are two types of appliances, dumb or legacy appliances and smart appliances. For the sake of simplicity, appliances will refer to actual appliances, such as any electrical power load such as a lamp, fan or computer. Dumb appliances are what the majority of household and commercial spaces currently employ. These do not monitor their power usage and do not have connectivity capability. Therefore external monitoring and control is needed.

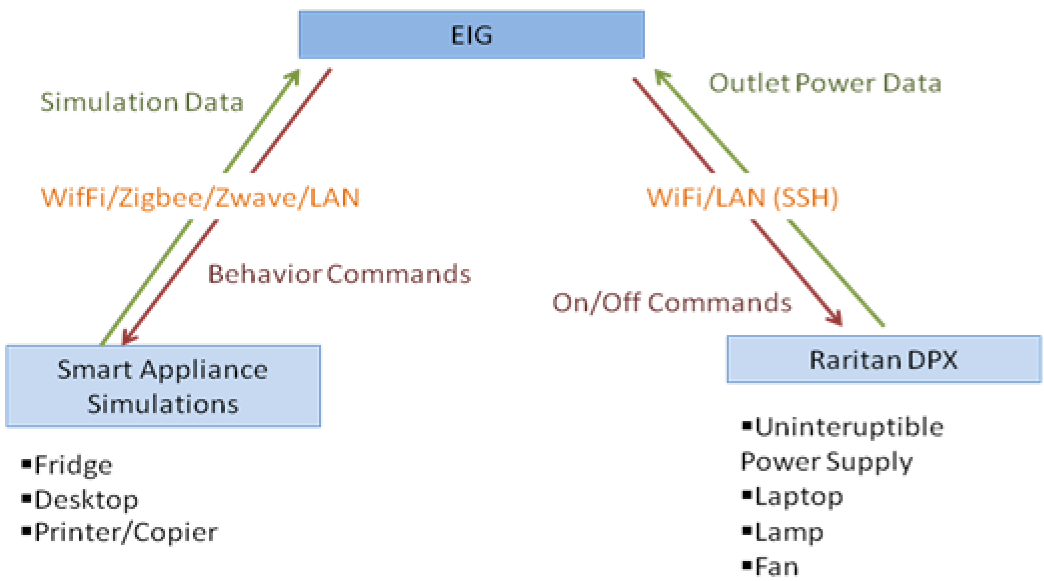

Figure 14: Current EIG configuration for testing

What is envisioned is that dumb appliances will have a switch and sensor package between its plug and the wall socket that reports its load data and can turn the appliance on and off. Within the DIADR project, two packages are in use: Raritan Dominion PX switchable power strips (SPS) and ACME meters, produced at UC Berkeley. The SPS is an Ethernet enabled power strip that houses eight controllable outlets. For example a dumb appliance is plugged into an outlet on the SPS. When the EIG is running it regularly polls the SPS for outlet power use data. When a DR event occurs, the EIG selects the appropriate appliances to turn off and send a command to the SPS to cut power to the appropriate outlet.

In the future smart appliances will become more ubiquitous. These are appliances that can have connectivity capability, can monitor and control their own power use, and are envisioned to have more power states than on and off. The EIG looks to the future and proposes an open standard for communication and control of smart appliances, by using a widely used language, XML, to send and receive control and data respectively. Students at UC Berkeley are also developing computer simulations of smart appliances that can run on a variety of platforms to demonstrate the versatility of the EIG's open-standard. These smart appliance simulations are also used in simulating DR events and their projects.

The CEG is designed to enable the communication of multiple CEGs and a building management system working in conjunction to reduce power use in a large commercial building. The EIG is built on the concept of open-standard connectivity so that it can connect to any appliance that can utilize XML. This connectivity will help multiple EIGs communicate and jointly develop a strategy to meet a power reduction goal during a DR event.

5.4.2.3 A Lab Plan for Distributed Load DR Control Demonstration

Figure 15 shows an SCR lab demonstration plan for distributed load control using the same gateway as previously described. The red lines indicate the connections with AC power, the blue solid lines represent wired connections, the blue dash lines represents wireless connections, and the blue dash dot lines indicate the connection can be either wired or wireless. The plug load appliances are divided into four groups: task lights, portable heaters and humidifiers, printers and other smart appliances, and the office kitchen appliances. The sensors will provide environmental status so that Gateway can decide which appliance to control based on the related factors. The different group of appliances will also have corresponding priorities.

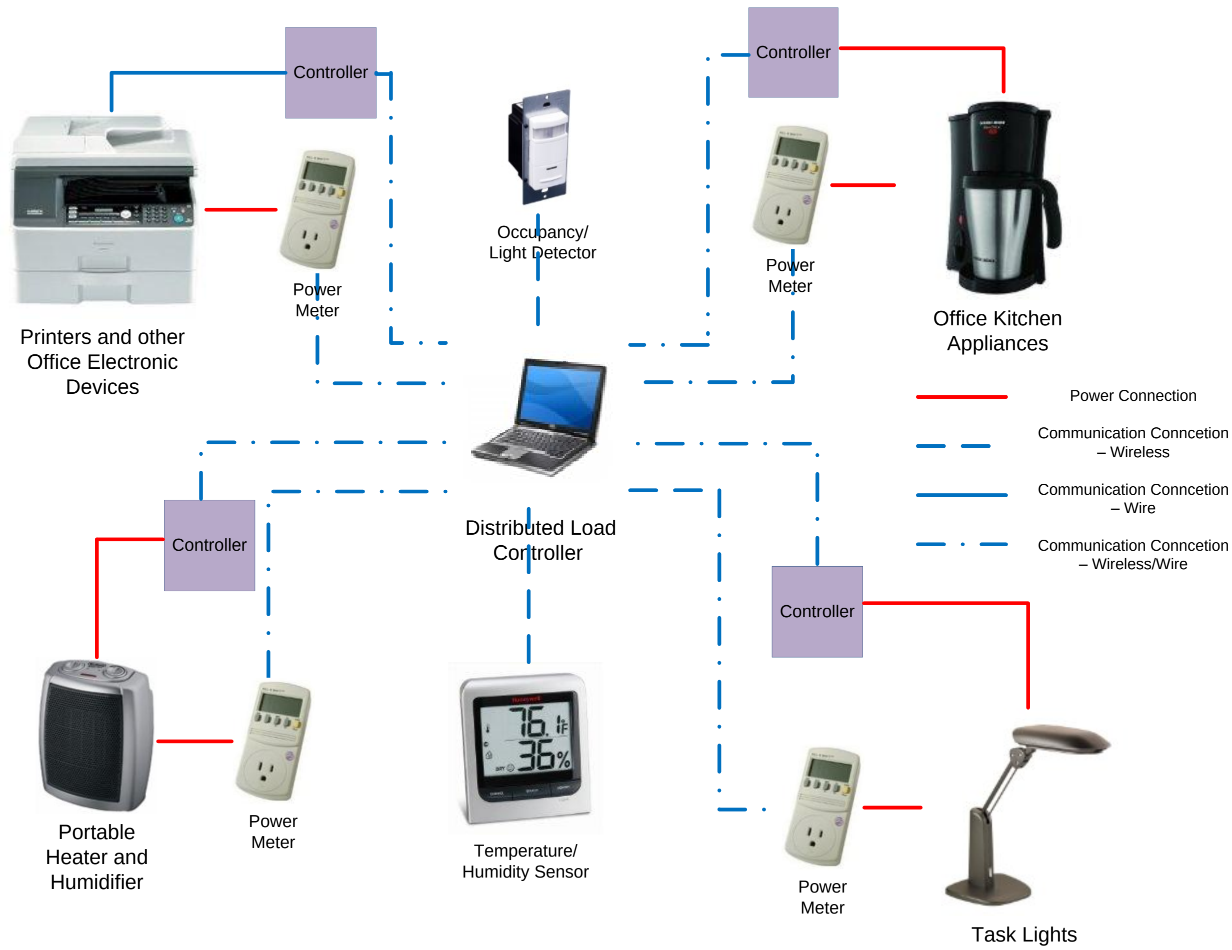

Figure 15: Local DR control scenario

Figure 15 shows the logical plan instead of the physical relationship. For example, the Power Meter might be physically inside a controller, or all sensors can be in a same box. The physical picture is subject to change with the specific devices to use.

5.4.3 Distributed Control Algorithm

The Gateway functions as the main actor and makes decisions for distributed control. The Gateway has access to the current power data and to environment parameters. The Gateway also has user preferences that can be entered using a Web User Interface. The Commercial Energy Gateway houses the specified algorithms for laptops/desktops, printers and other devices. It will measure their power instantaneously and then prioritize the tasks for implementation during a DR event. Objects that have the potential to shed the most load and have no restrictions are listed first as possible solutions. The Gateway will then make suggestions to the SEB for further confirmation. Once the suggestion is accepted, the Gateway will implement the change. The distributed algorithm relies heavily on the user input from the User Interface which will be discussed in the next section.

5.4.4 Web User Interface

Providing an easily accessible, user-friendly and intuitive interface for client access to the Energy Gateway has been a crucial piece of the project. The user interface can be used by occupants of the building to enter his or her personal appliances within his or her own control, such as computers, coffee makers, and/or task lamps. The occupant could then prioritize these devices with respect to DR curtailment. For example, the user could choose to dim or turn off the task lamp and not use the coffee maker during a demand response event, but always have the computer functional; these preferences would be used by the gateway in deciding which loads to switch off during a DR event. The user could also indicate preferences for heating, cooling, ventilation, and lighting levels, which would be relayed to the Smart Energy Box. The interface would allow the occupant to override prior set priorities to provide greater flexibility. The following will provide a brief and comprehensive guide into the architecture of the website, some insights into the decisions that were made, problems faced and solutions used to achieve our goal in providing the UI.

5.4.4.1 Architecture

The interface originally began as a very simple webpage written in HTML, designed with CSS and filled with static fields and variables serving as placeholders in an empty mold. For simplicity, the visuals were designed with three main components in mind: the configuration page, operation page and event page. The configuration page was built to serve to allow the user to add appliances and select curtailment priorities during DR events. A user can navigate through the configuration page to change appliance priorities and energy states with respect to the current DR event. The pages below represent Engineering screens with all the possible data; the user screen for the lay person will be simpler with just basic information.

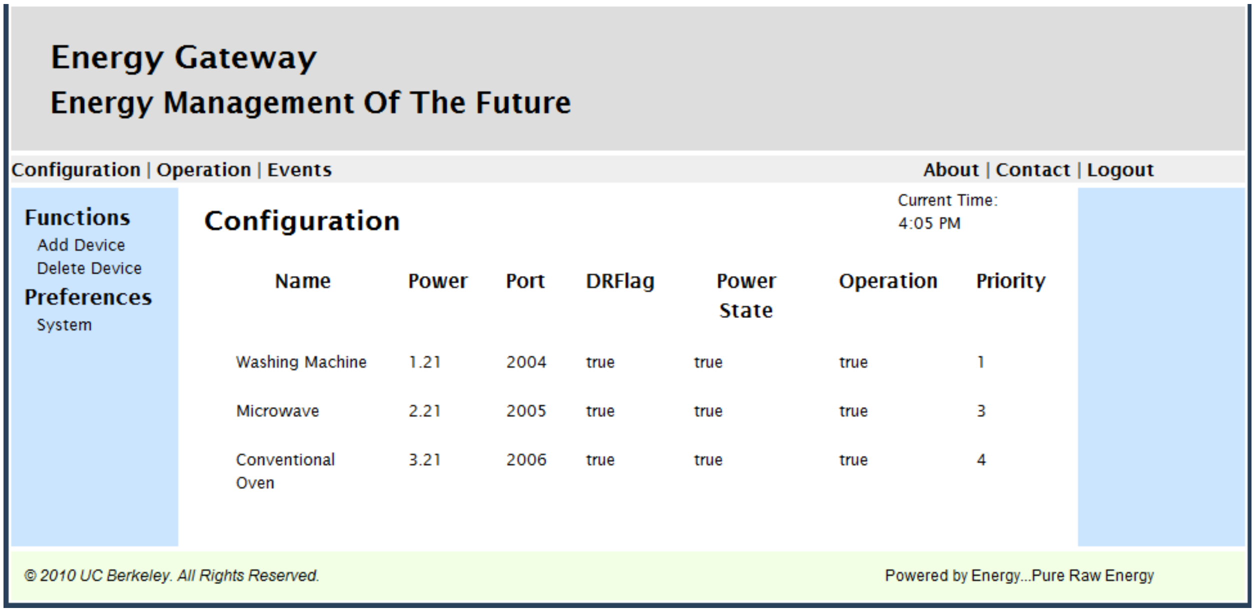

Figure 16: Configuration Page

On the operation page, the occupant would find out about current appliance state and energy consumption.

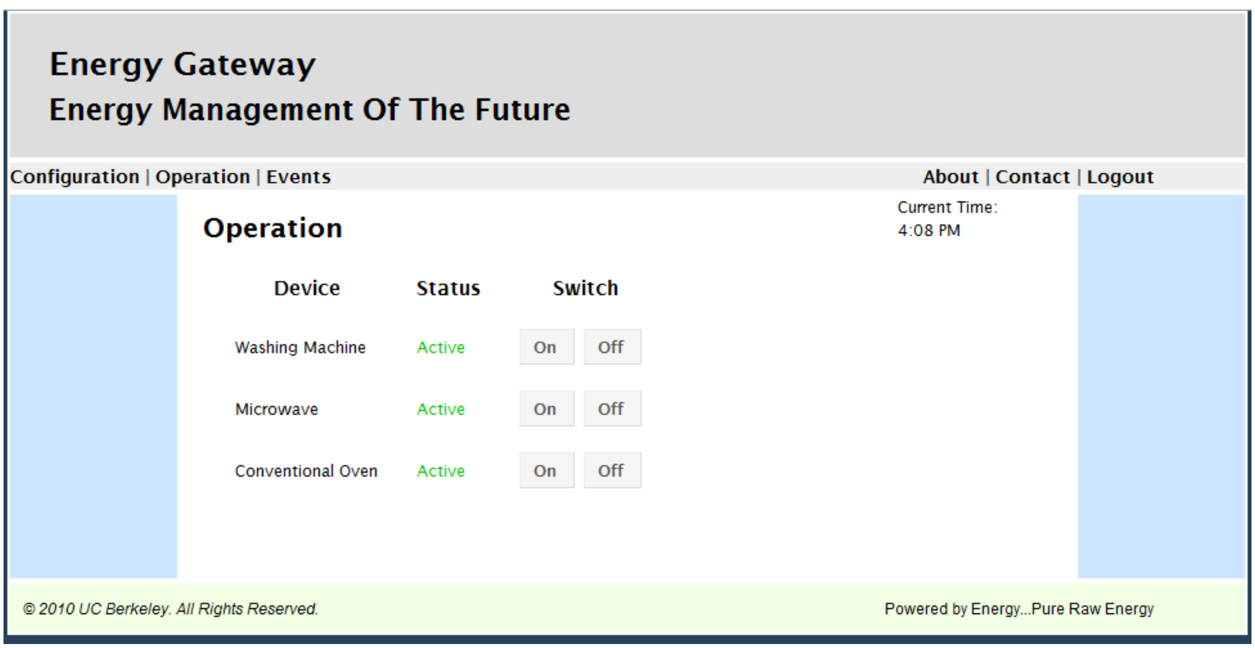

Figure 17: Operation Page

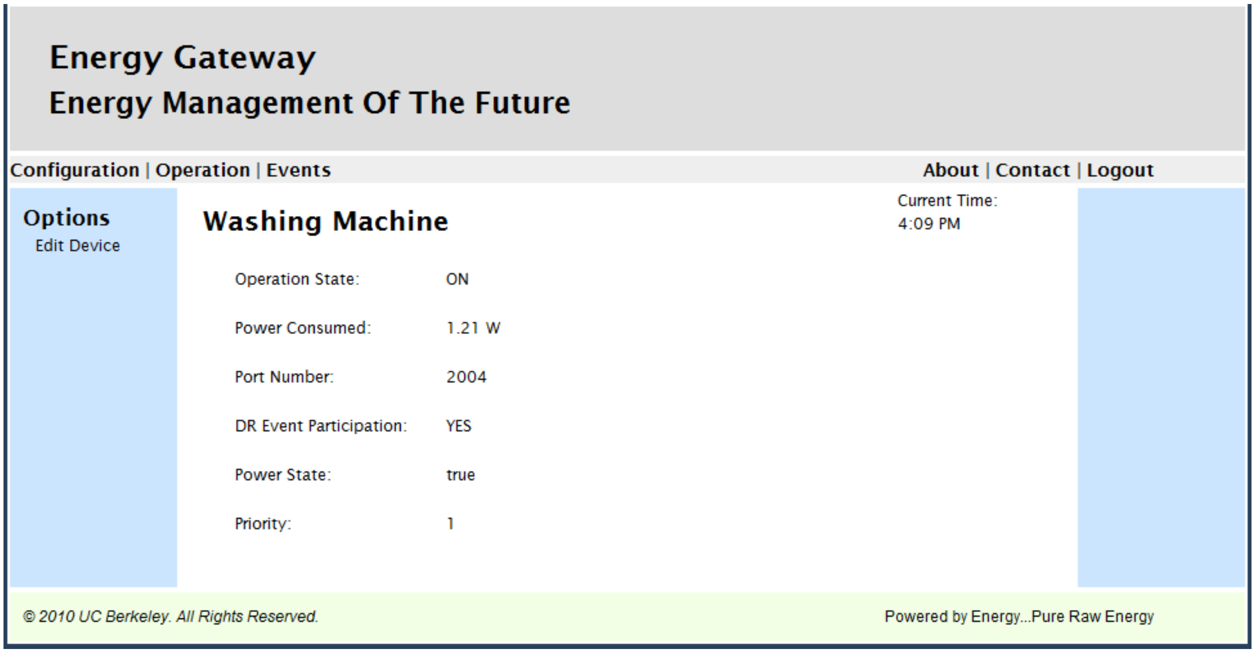

Figure 18:Operation Page: After selecting one of the devices for in-depth examination

The Events tab provides the occupant information about the actual DR events, such as a timeline of past, current and future DR events along with their durations and severity levels.

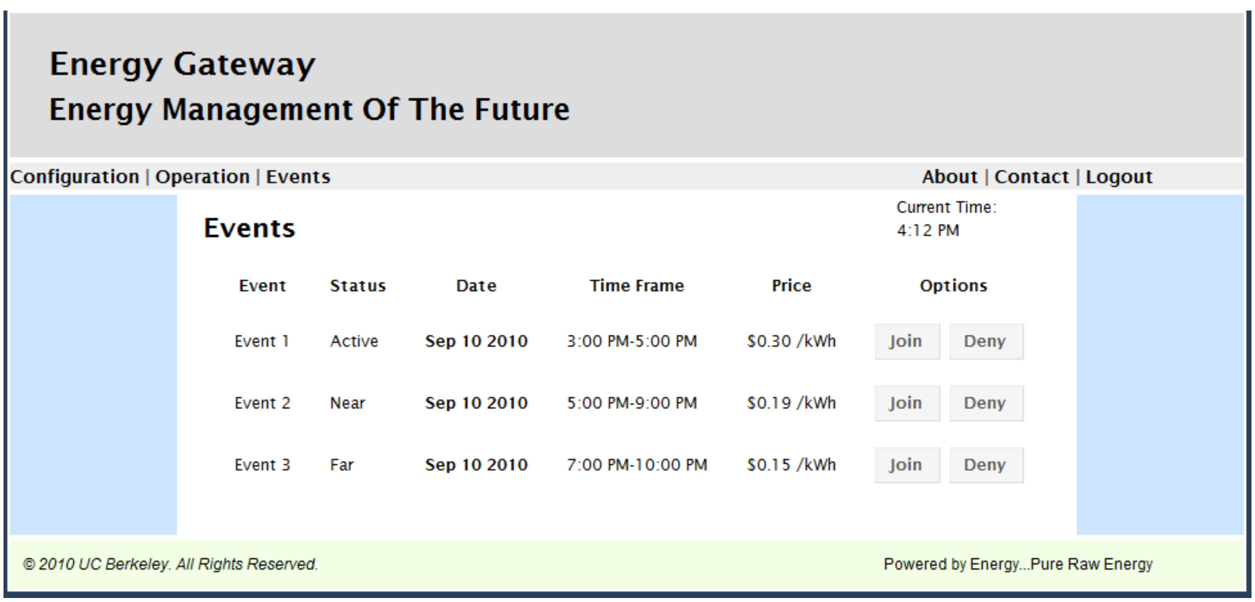

Figure 19: Events Page

Overall, these three main tabs of the user interface were built with the goal of being easily accessed from any computer or computing device on the local network, traversed in any order that the user chooses and most importantly, provide the user with the necessary tools and information to control and optimize the enclose environment.

Once the physical layouts of the pages were finalized the dynamic aspects of the webpage were developed. Javascript was at this time adopted as the official client-side scripting language of this project with future standardization in mind. At the beginning, Javascript provided very basic tools to transform and update the webpage depending on the users' action, but the interface was still lacking the connectivity that would allow the UI to communicate with the Energy Gateway. The solution to this problem first began with the installation of an Apache webserver on the same device that the UI resided. Because Javascript only provided front-end functionality, PHP was then realized as the standard server-scripting language and a potential candidate to do most of the backend communication transactions between the Energy Gateway and the web UI. Naturally AJAX was also taken on and used as the primary communication medium between Javascript and PHP. The only problem remaining was to bridge the gap between the server and the Energy Gateway and this was done through the use of sockets. This decision was made based upon the conclusion that the Energy Gateway would probably sit on the same machine as the web UI and sockets would provide a fast prototyping method to demonstrate the capabilities of the Gateway system. Though there were some problems with the socket communication, it was quickly resolved in constructing a clean and well-defined format in transferring data from UI to Gateway and vice versa.

Figures 20 and 21 are simple flow charts of how the web UI communicates with the Gateway as well as with itself with full bi-communication functionality.

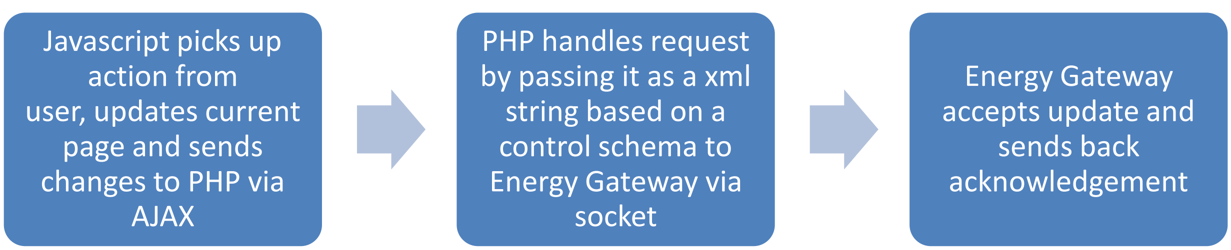

Figure 20: Downstream Data Flow Diagram

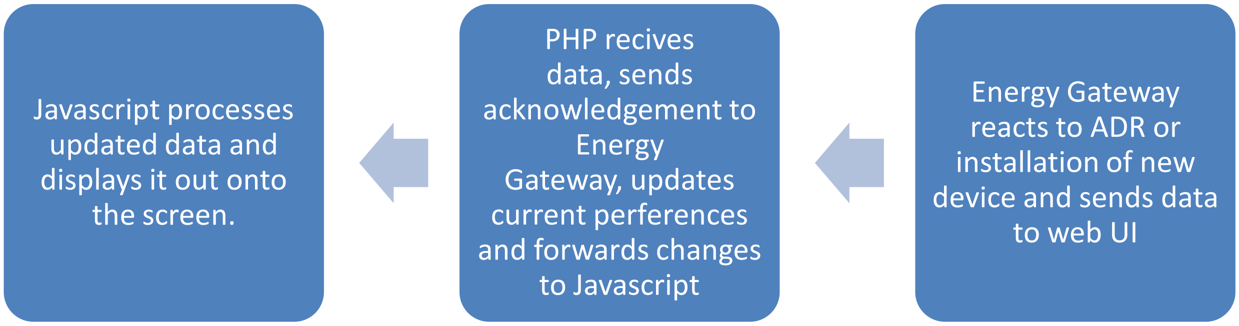

Figure 21: Upstream Data Flow Diagram

5.4.4.2 Conclusion

At the present, a fully functioning web UI has been created to handle updates and send requests to the Energy Gateway to change preferences. Basic override functionality and control over appliances have been developed and most if not all communication issues have been resolved.

More work still needs to be done on the UI to provide users with a greater sense of comfortable and intuitive experience, which will be the main focus for the remainder of the project. There is already work underway to shift platforms from pure HTML and CSS to the Drupal platform and some investigation into java swing, flash and other GUI development software to develop more aesthetically pleasing apps and features on the web page.

5.4.5 Laptop/Desktop power management

Students at UC Berkeley have developed a general theory for developing distributed algorithms for plug load management of devices with energy storage capabilities (e.g. laptops with batteries, desktops with UPSes, etc.). The following describes the definitions of the algorithm, the algorithm itself, and simulations of the algorithm. UCB has made use of the notion of a control gateway in the architectural sense of the telecommunications layer that sends a demand response signal from an ISO/RTO or utility/aggregator to a DRAS from which a "smart energy box" takes this signal and passes it to a control gateway:

Definition 0.1 *A control gateway administers load control algorithms.*

Definition 0.2*A zone, denoted by Z(k,t), is a collection of loads/devices under the purview of a control gateway where k represents the specific control gateway acting on that zone at the discrete time t.*

Definition 0.3 *We say a device belongs to a zone Z(k,t) if that device is under the purview of a control gateway k at the discrete time t.*

Definition 0.4 *All devices belong to a* <u>*null zone*</u>*, denoted by Z(0,t), if they have never been under the purview of any control gateway up until discrete time t.*

Definition 0.5 *Suppose a device d that belonged to Z(k,t1) at time t1 now belongs to Z(k',t2) at time t2 for control gateways k and k'. We say that a device* <u>*leaves*</u>*Z(k) and* <u>*arrives to*</u> *or* <u>*enters*</u> *Z(k').*

Definition 0.6 *We say that a load or device is* <u>*stationary on [t1,t2]*</u> *if that device belongs to Z(k,t1) and does not leave until discrete time t2. A load or device is said to be* <u>*strictly-stationary*</u> *if that load/device belongs to Z(k, t) for any discrete time t over an entire time series. We say that a device is* <u>*non-stationary on [t1,t2]*</u> *if a device that belonged to Z(k,t1) up until t1 leaves at or after that time and enters Z(k',t2) at or before t2.*

Given *N* electric devices, for each *i*th device we define:

Definition1.1 *The* <u>*position*</u>**v**(i,t) = <*,*,*..,*> *of the i*th*device at a discrete time step t is a row vector whose elements represent information (denoted by *) about a power-consuming load at the particular time step t.*

Definition 1.2 *A* <u>*trace matrix of N positions*</u> *at the discrete time t is a matrix representation, which we will denote by M(N,t) where N refers to the number of rows in the matrix and t refers to the current time step, of information about particular devices at time step t whereby the position of the ith device corresponds to the ith row of the matrix at time t.*

Definition 1.3 *A* <u>*power trace*</u>*T(i,x) is a function that maps an element x of the position of a device to a real number that represents the expected power consumption of a load OR is the empirical/measured power (typically in watts) of the device at the discrete time t.*

Definition 1.4*The* <u>*capacity*</u>*, denoted by Chi(i,t), of a device represents information about the amount of energy the i*th *device has stored at a particular time t. The capacity of a device can be an element of the device's position if information about a device's stored energy capacity is pertinent to the energy management objectives of the algorithm.*

Definition 1.5*The* <u>*connection state*</u>*y(i,t) of the i*th*device is a Boolean element of a device's position that indicates whether a device is connected or disconnected from an electric outlet: true/1 if it is connected, false/0 if it is disconnected at the discrete time t.*

Definition 1.6 *The* <u>*operation state*</u> *of a device is a Boolean element of a device's position that indicates weather a device is on or not: true/1 if it is on, false/0 if it is off.*

We assume, for the time being, that all loads are strictly stationary, their operation state is always ON, and *N* is fixed throughout all time steps. It is important to distinguish between the connection state and the operation state of a device since a load could be off but still drawing power.

Sort and Assign Method (for loads with energy storage)

Suppose we have *N* strictly stationary loads. Let the position of the *i*th device

$$\mathbf{v}(i,t) = \langle i,\ t,\ Chi(i,t),\ T(i,chi(i,t)),\ y(i,t) \rangle$$

for*i*= 1, 2, …, *N*, and so we have a trace matrix M(N,t_0) at the initial time t_0 whose rows are

$$M(N,t) = \begin{bmatrix} [1 & t\_0 & chi(1,t\_0) & T(1,chi(1,t\_0)) & y(1,t\_0)] \\ [2 & t\_0 & chi(2,t\_0) & T(2,chi(2,t\_0)) & y(2,t\_0)] \\ [\ldots & \ldots & \ldots & \ldots & \ldots] \\ [i & t\_0 & chi(i,t\_0) & T(i, chi(i,t\_0)) & y(i,t\_0)] \\ [\ldots & \ldots & \ldots & \ldots & \ldots] \\ [N & t\_0 & chi(N,t\_0) & T(N, chi(N,t\_0)) & y(N,t\_0)] \end{bmatrix}$$

We assume that chi(i,t_0) for *i*= 1, 2, …, *N* are Gaussian distributed over all *N* devices. Suppose each device is a laptop. So each laptop battery has a capacity selected at random and the distribution of all battery capacities is normal. Furthermore, at the initial time t_0 we assume y(i,t_0) = 1 for each *i*th laptop; and so every laptop is connected, drawing power, and has a random capacity. Since the power trace is a function of capacity, the power trace of each laptop is random also.

Our objective is to minimize the sum of the traces over every time step (in the context of demand response) so that no laptop battery ever reaches chi(i,t) = 0. We attempt to do this by setting some load curtailment objective that is determined either by some control gateway *k* or is computed on the basis of optimizing for minimized curtailment of devices in a zone Z(k,t) over all t during the demand response event. We formulate our curtailment objective numerically and iterate over every time step taking note of the fact that power traces over a complete battery charging cycle exhibit exponentially decaying curves that approach some steady-state operation power. This can be seen empirically in the relationship between battery capacity and power trace shown in Figures 22 and 23:

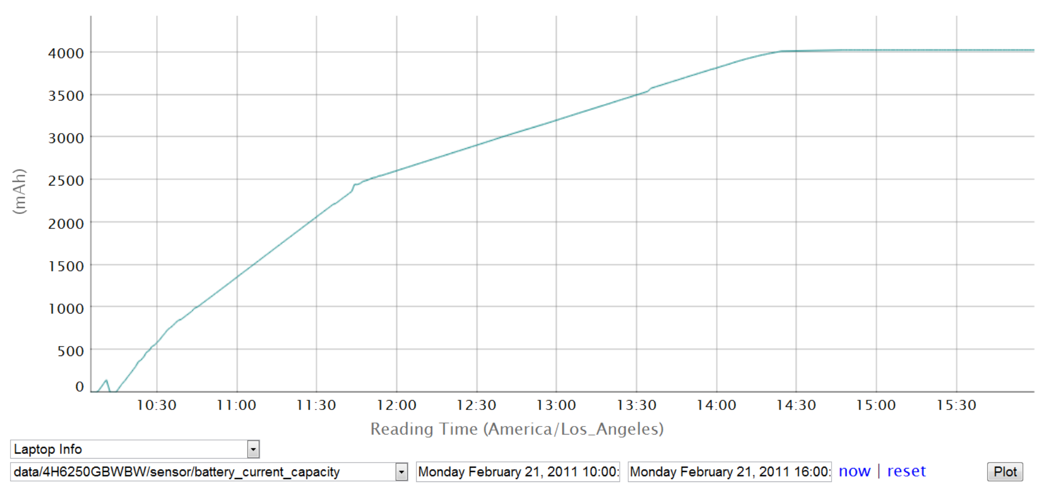

Figure 22: Battery Capacity over time

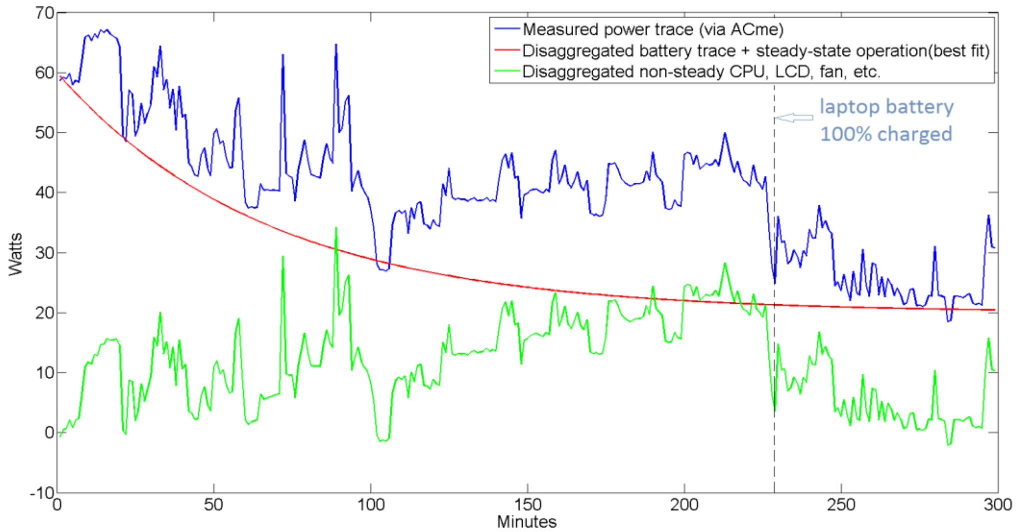

Figure 23: Power trace as a function of capacity

Since we would like to minimize power delivery to all of the laptops during a DR event, we want to stay as close to full battery capacity as possible all while disconnecting and reconnecting laptops from a power source when necessary. In our initial model, we did not have any notion about the relationship between capacity and discharge rates. So for our simulation we assume that a battery takes an equal amount of time to completely charge as it does to completely discharge. So we set out to achieve load curtailment as follows:

Objective: min ΣT(i,x)
Subject to: Chi(i,t) > 0 (i.e. no laptop runs out of battery)

Input : M(N,t1)
Output: M(N,t2)

1. At each time step, sort rows of trace matrix in descending order of power traces
2. Determine load curtailment coefficient "c"
   - If c is already given let ΣT(j,chi(j,t1)) <= c*Σ T(i,chi(i,t1))
     where j = 1',2',...N' are the indices of each laptop after being sorted.
   - else, determine c numerically by iterating through all the time steps in a demand response event by inspecting each c = 0.0 – 1.0.

- We pick the smallest c for which ∫ΣT(j,chi(j,t1)) is minimized wherej's are the laptops that are charging (energy savings approach).

3. So then all i's for which y(i,t1) = 1 remain y(j,t2) = 1 for all j's and the remaining i's, call them "i less j," become y(i less j, t2) = 0 whereby Σ T(j,chi(j,t2)) <= c*Σ T(i,chi(i,t1))
4. If we set loadThresh = 100 mAh (for instance), for any Chi(i less j, t1) <loadThresh, set y("i less j", t2) = 1 (so then the "i less jth" laptop is connected at t2 and is allowed to charge and draw power).
5. Return trace matrix M(N, t2) in ascending order of i's.

At each time step we are returned a trace matrix whose right-most column vector contains 1's and 0's that indicate whether a laptop is charging or not. For each jth laptop that charges, the capacity Chi(j,t2) > Chi(j,t1) and the expected T(j,chi(j,t2)) < T(j,chi(j,t1)). And for each laptop that discharges on [t1,t2], Chi("i less j",t2) < Chi(i,t1) and the expected T("i less j",chi(i,t2)) > T(i,chi(i,t1)).

Following are some preliminary results of curtailment studies presented during our March 15, 2011, progress meeting using a simulation of *N*=50 strictly stationary laptops belonging to the same zone that followed the above definitions and procedures. Figures on the left represent aggregate load over time (i.e. the sum of all power traces ΣT(i,chi(i,t))) and figures on the right represent the toggling of laptops from connected to unconnected states and vice versa. Figure 24 shows the behavior of a correctly managed, optimally chosen curtailment coefficient. Figure 25 displays the behavior of a non-optimally chosen curtailment coefficient

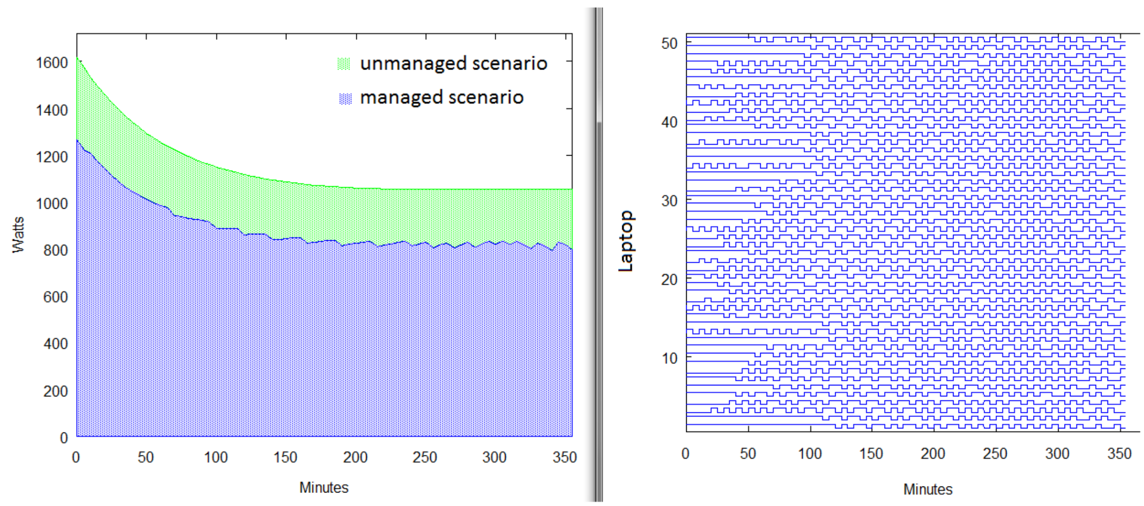

Figure 24: Results for Optimally Chosen Curtailment Coefficient

For optimally chosen c=0.79, we achieve ~20% load shed throughout an entire 6-hour simulated demand response event (as visually seen as the green band)

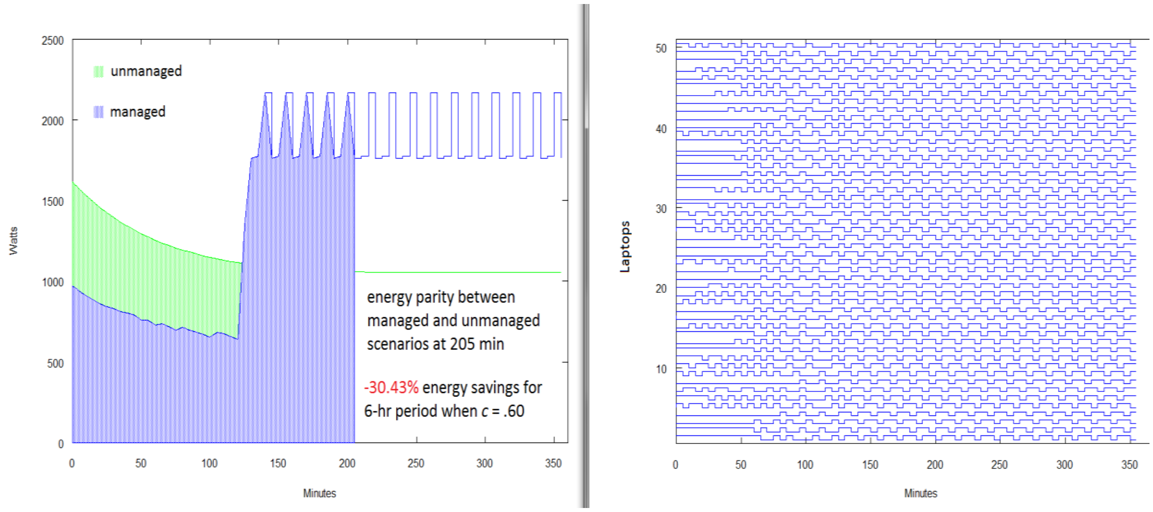

Figure 25: Results for Non-optimally Chosen Curtailment Coefficient

For non-optimally chosen c=0.60, we achieve ~40% load shed for the first 2 hours, but offset load shed at the outset for load surge near t=125 min.

Since March 15, UCB has developed a more robust simulation tool that initializes a trace matrix by taking as input a charge curve, discharge curve, and power trace. Hereafter, UCB intends to build a Poisson arrival model for non-stationary loads that enter and leave zones in an aleatoric fashion. This analysis of laptop control will be reproduced in a similar fashion for office desktops.

5.4.6 Printer Control

LaserJet printers have been noted as a possible source of peak load shedding for demand response events. Tests have been run on the power characteristics at warm up, active, and standby state of small scale LaserJet printers. An HP LaserJet 2035n was tested for power characteristicsdue to its ubiquitous presence in Sutardja Dai Hall as was discovered in the Plugload Audit. Figure 26 shows a plot of the actual power over a given print period of a 25 page document followed by a 30 page document to test the in-between characteristics. We can see a peak of around 700W and then steady operation at around 500W. In between documents there is a drop to around 250W before the next document printing task is initiated. The instantaneous actual power then drops to around 8W for a cool down period of 20 seconds before it reaches idle state at 0W.

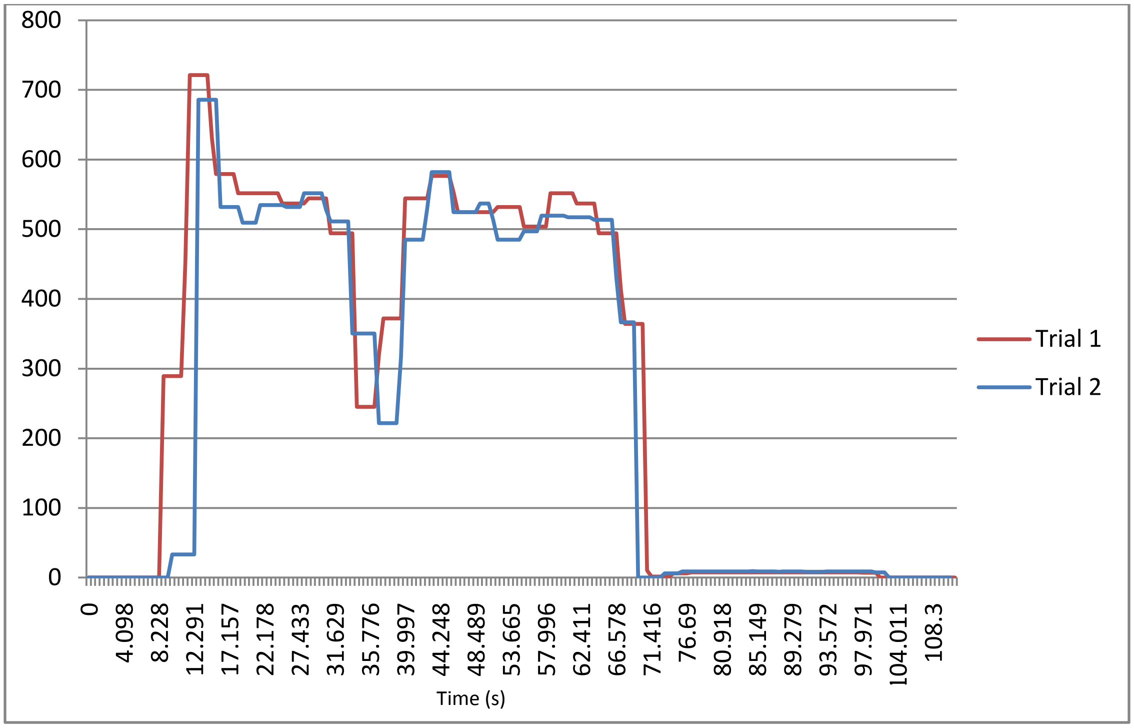

Figure 26: HP 2035n LaserJet Print Behavior

Larger scale printers with duplex capabilities and larger volume outputs were also explored. Resources were limited so data was acquired directly from HP's website. Table 1 compares various power characteristics for small, medium and large office printers.

TYPE	Active (W)	Standby (W)	Off (W)
*HP 2035n (Small)	500	0	0
HP 5550dn (Medium)	630	24	0.3
HP CP6015x Color (Large)	1200	18.9	0.3

*verified by laboratory test

Table 1: Comparison of Printers of Varying Size

Various forms of control of LaserJet printers have been proposed for demand response. Twooptions for control involve the designation of a DR printer for each floor that documents are sent to. This limits the amount of printers to be used at any given time.

5.4.6.1 Strategy 1:

The first strategy, shown in Figure 27 is to designate a single DR printer to each floor that is connected via a printer network in which a server network can communicate to ensure that only one document is printed at a given time. A queue is used and documents are printed in the order of submission. We can select the DR printers based on their characteristic power behavior, most dependent on the idle state and their large scale printing capabilities for multiple documents. With this system, at any given time we know that the peak power being used for printing is limited to the maximum active power consumption of one printer. This would equate to a constant of around 500-650W depending on the printer of choice. The advantage this system provides is the minimal amount of printers to keep track of on the network. It simplifies the server system communication. The disadvantage to the system is that employees will be required to leave their desks for their documents and they will only have a relative idea of when their document should be finished printing.

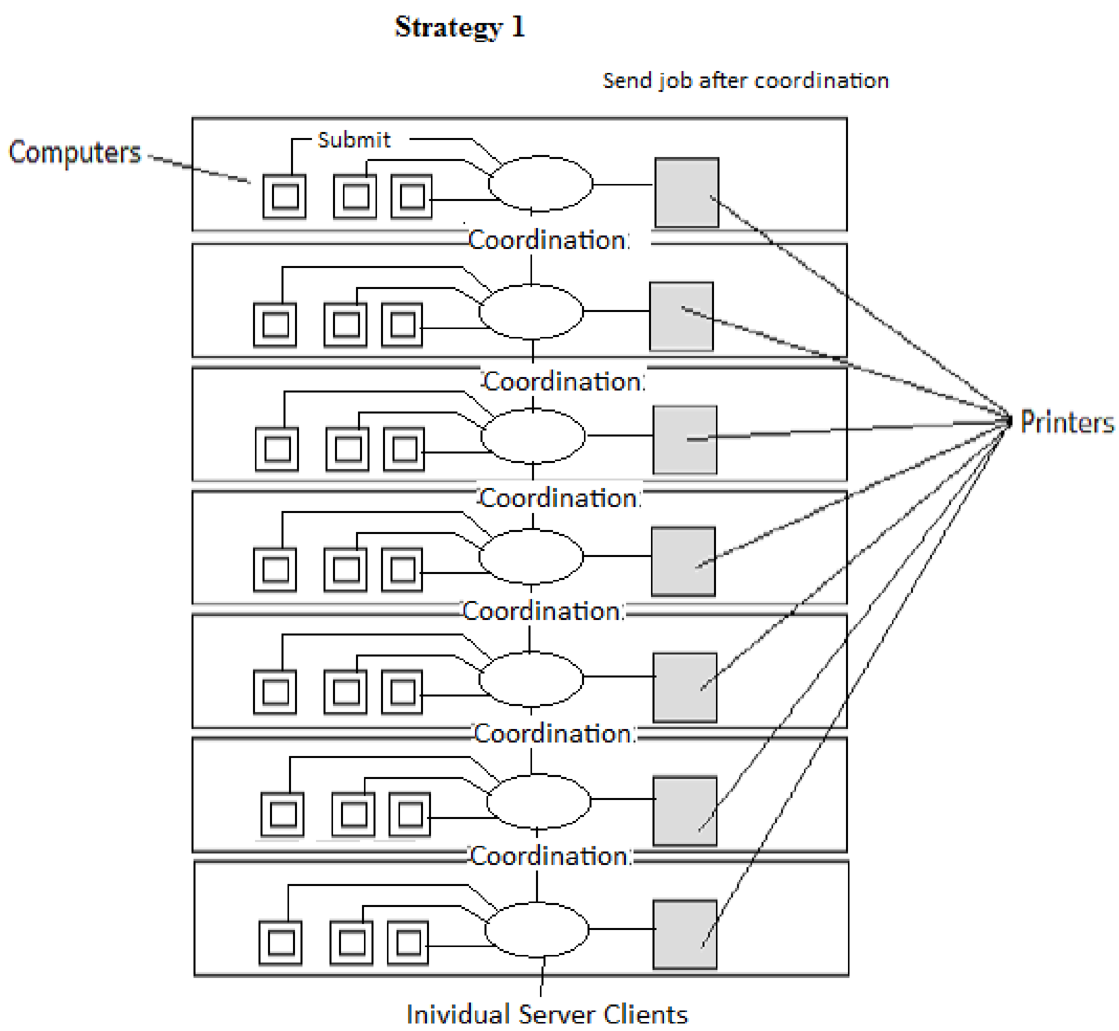

Figure 27: Strategy 1 Design

5.4.6.2 Strategy 2:

The second strategy, shown in Figure 28 is to connect all printers in the building with one server. The server will simply sort through the documents and then one by one send documents to their respective printers. The advantage this strategy provides is that there is no need for multiple server clients that must communicate with each other for proper operation. Another major advantage of this system is that users will not need to leave their desks to pick up their documents from a central printer but can continue to work and have their document handily available to them. The disadvantage to this system is that printers cannot be chosen based on their positive energy properties during a demand response event. There will only be one printer functioning at a given time but this load may be anywhere from 500-1200W and will vary with time causing some uncertainty.

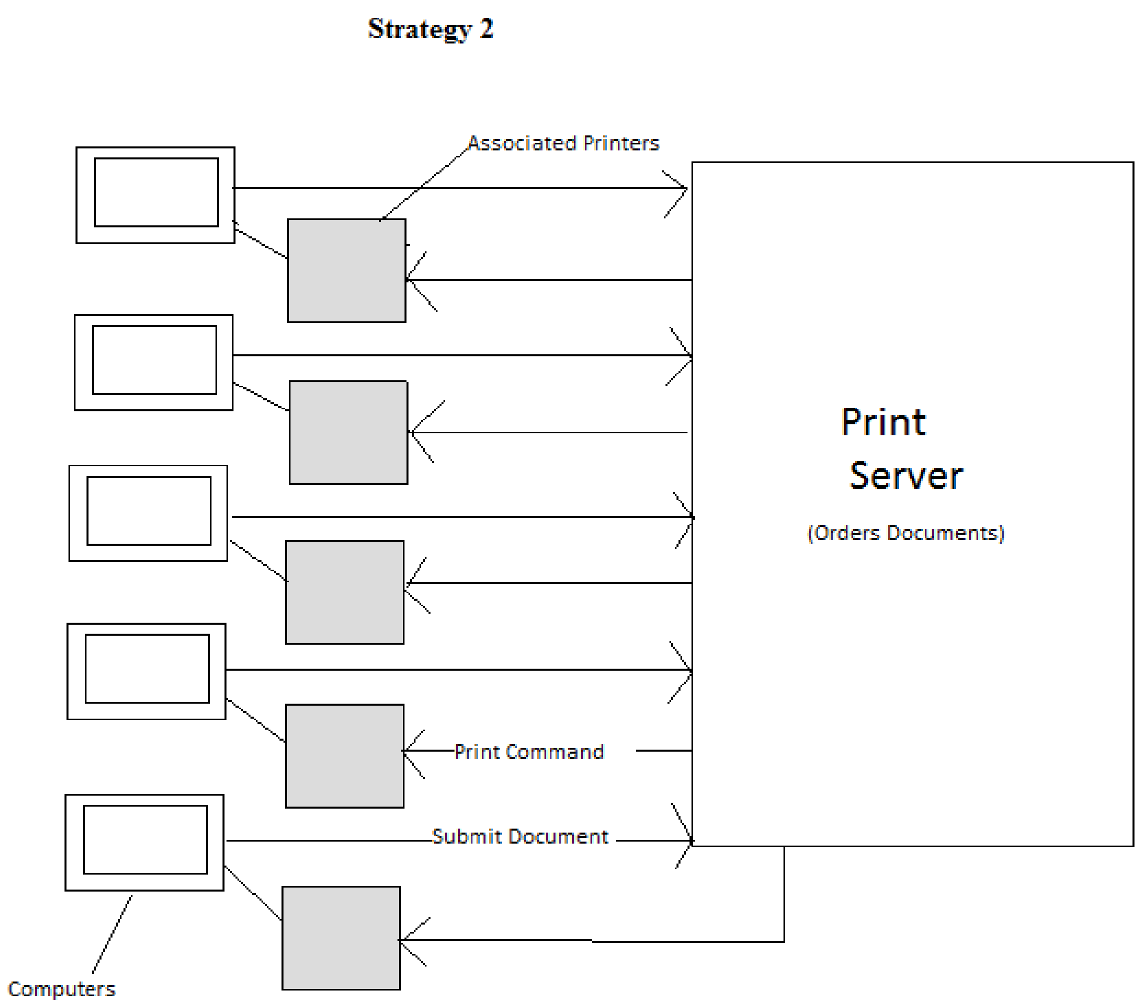

Figure 28: Strategy 2 Design

5.4.6.3 Conclusion:

Further investigation will be discussed about the hardware requirements for these strategies as well as further details to control such as document queue ordering, printer selection, and whether batch jobs should be handled together or documents should be printed in order of submission. As more tests are run, UCB will be able to assess whether we can achieve savings due to printer warm-up and cool-down by combining print jobs submitted to the same printer and run a print cycle that prints all documents for one printer at a given time and then moves on to the jobs at the next printer.

5.5 Control Architecture

5.5.1 JADE

After careful evaluationby both SCR and UCB, Java-based Agent Development Environment (JADE) was selected as the communication and control framework for DIADR.

JADE is an open source agent development platform developed mainly by TILab and supported by a number of academic and industrial partners including Siemens. JADE provides a middle-ware to simplify the implementation of multi-agent systems complying with the FIPA specifications for interoperability. It also provides a set of tools that supports the debugging and deployment of an agent system. The agent platform can be distributed across machines (without the need to share the same OS) and the configuration can be controlled via a remote GUI. The communication architecture offers flexible and efficient messaging, where JADE creates and manages a queue of incoming ACL messages, private to each agent. Agents can access their queue via a combination of several modes: blocking, polling, timeout and pattern matching. Figure 29shows the agent system designed for DIADR hosted by Siemens Smart Energy Box and local gateway controllers.

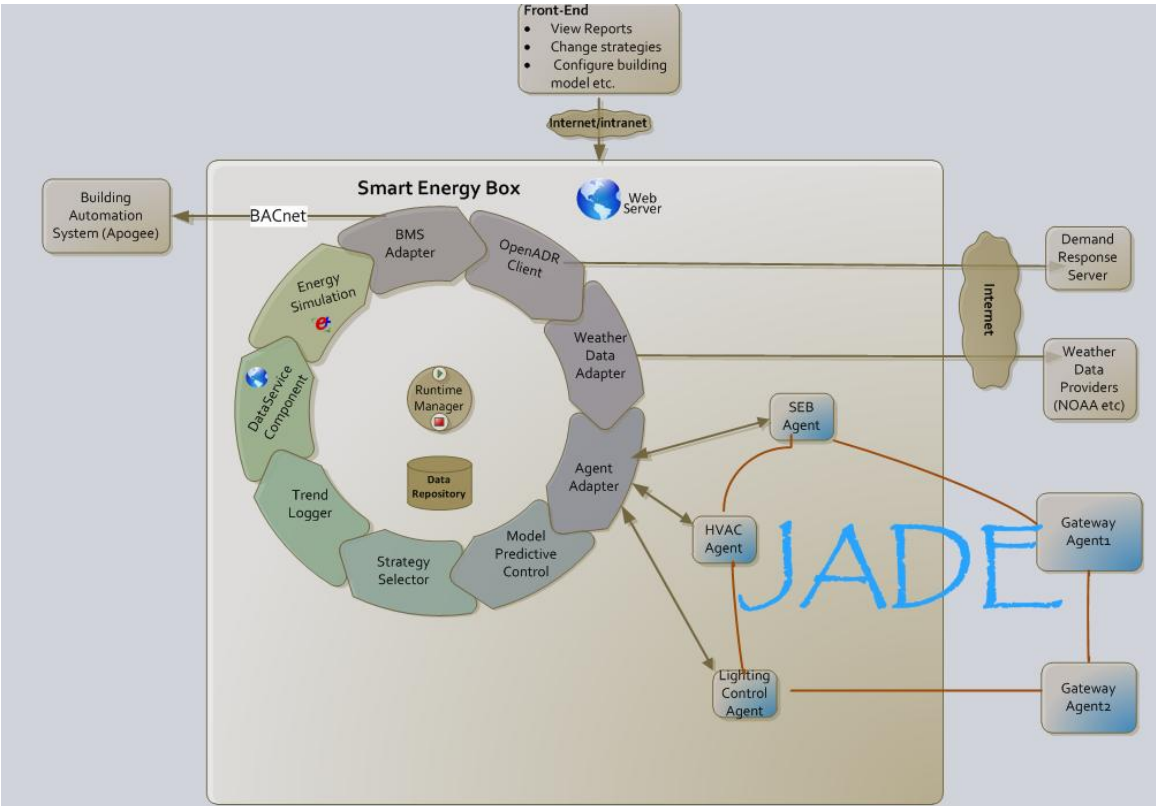

Figure 29: JADE based DIADR communication and control platform

In Figure 29, the intelligent decision making for the DIADR system are distributed to agents, including the SEB agent, which receives the DR signal and coordinates the whole building demand reduction; HVAC and Lighting control agents manage the load shedding from the HVAC system and lighting system respectively. Gateway agents control distributed loads and schedule local load curtailment during a DR event.The Siemens Smart Energy box connects the SEB agent to the DR server and an operator GUI. It also provides interfaces for the HVAC Agent andthe Lighting Control Agent to access building automation systems through a BACnet adaptor. Through an agent function registering process, JADE provides a full service oriented architecture.

5.6 Simulation Based Demonstration

5.6.1 Energy Plus Model

Energy Plus[5] is a program used by professionals in HVAC, architecture, and power systems and civil engineering as a powerful tool for design. Energy Plus can also be used for simulations as will be used in this project. An Energy Plus model[6] was built by Lawrence Berkeley National Laboratory to run simulations on HVAC and lighting loads in Sutardja Dai Hall.

5.6.1.1 Simulation Results

Instead of using a pre-programmed DR strategy, SCR has worked on dynamic demand response generation upon receiving a DR signal. To achieve optimal energy management, the building model developed by LBNL was used to test all possible control strategies by predicting the future behavior and performance (energy consumption and thermal comfort) and finding the best strategy.However, we note that accurate mathematical modeling of the building's thermal behavior is very difficult. Furthermore, the prediction of future operating conditions (climate, internal heat gains) will also be inaccurate; and thermal comfort is difficult to define quantitatively. Hence with our approach, we decided to start using a numeric tool to model the building instead of a detailed analytic model.

Energy Plus was the tool selected to evaluate DR strategies and to search for the optimal control strategy. Since Sutardja Dai Hall has over 100 zone set points and control variables adjustable for building energy management, to search for the optimal one in this big space is computationally demanding.In parallel to the investigation of efficient optimization algorithms, we considered suboptimal control strategy development. Instead of searching for the best strategy in a huge space, our DR management makes a dynamic control selection from a DR strategy list. These DR strategies are created manually for representative weather and occupancy patterns. Figure 30 shows the suboptimal DR management and control compared with pre-programmed demand response.

[5] Energy Plus is an open source program that can be downloaded at: http://apps1.eere.energy.gov/buildings/energyplus/

[6] The Energy Plus model building process, calibration process, and theory validation is explained in more detail in Section 7: Appendix.

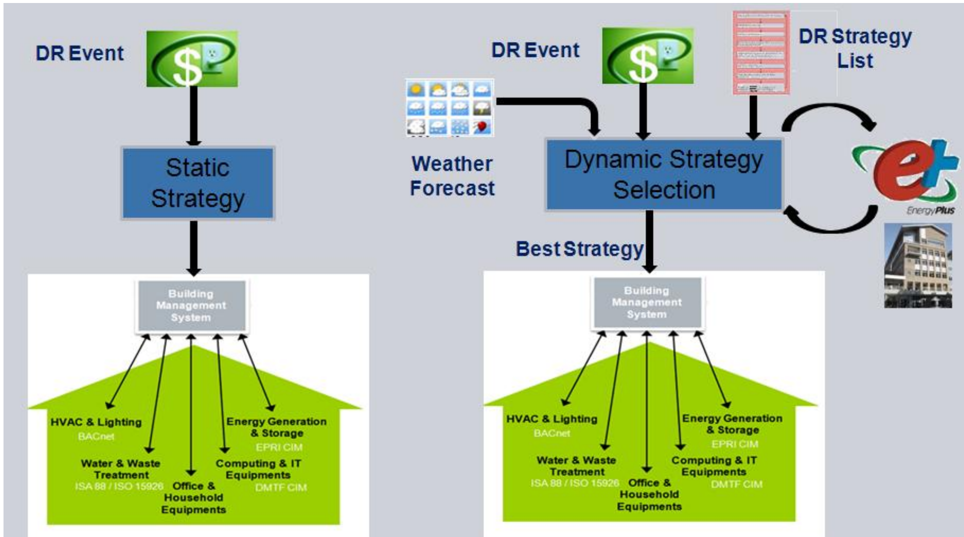

Figure 30: Suboptimal Central Load DR Management and Control

As shown in Figure 30, the best DR control strategy for each typical weather pattern is added to a DR strategy list. During the run time, upon receiving a Day-ahead DR event, SEB Strategy Selector uses Energy Plus and the weather forecast to evaluate each strategy and chooses the one that provides either minimal energy cost (for PDP type DR) or maximal peak-load reduction (Demand Bidding Program) while making sure the occupants' comfort needs are still met.

SCR collected historic weather data in Berkeley for the last ten years and began profiling the weather pattern during the month of August. For doing this, a template weather epw data file was downloaded from EnergyPlus. The weather file downloaded is for Berkeley area, having the zip code of 94720 and is included in California Climate zone 3. We used this parameter to get a sample epw data file. Then we use WeatherUnderground to get all historic weather data from the years 1999 to 2009. The WeatherUnderground site allows us download hourly historic weather data by inputting the following parameters: zip code, city name, weather forecast station code and year, month and date.

SCR has created more than 300 comma delimited text files for August between 1999 and 2009. We then applied MATLAB scripts to process these 300+ data files. As a result, we generated an 11X31X24X4 weather data matrix and did a weather pattern analysis. As there are more than 36 weather parameters for each hour, as the starting point, we focused on four weather data parameters: dry bulb temperature, dew point temperature, relative humidity and wind speed. See Figure 31 and Figure 32 below plotting pattern in the year of 1999 to 2009.

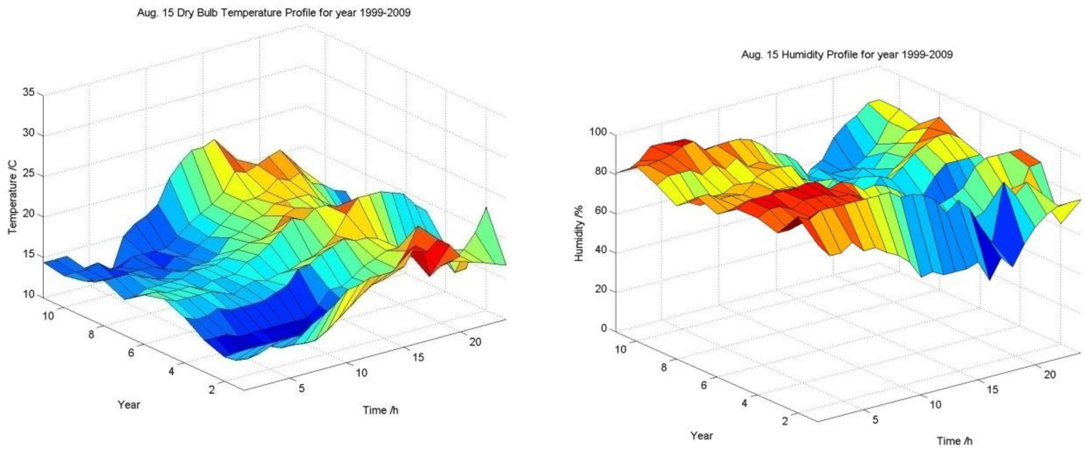

Figure 31: Dry Bulb Temperature and Humidity for August 15 for Past Ten Years

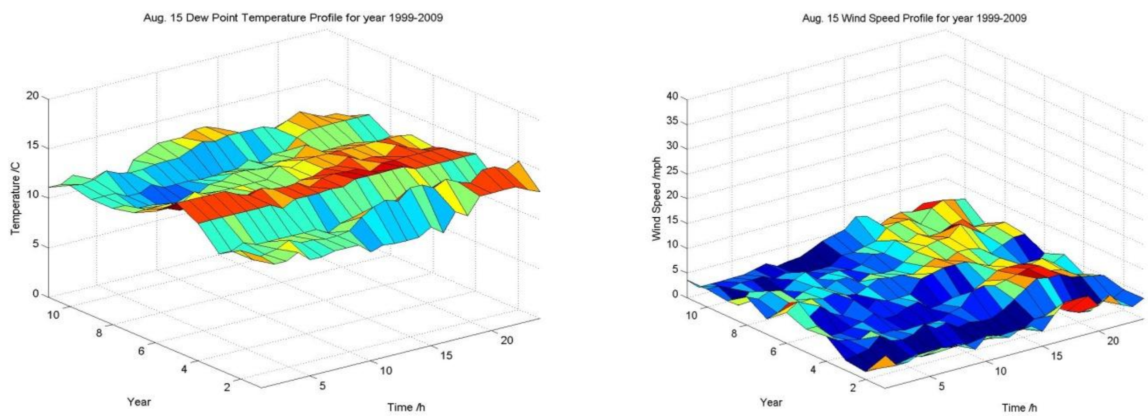

Figure 32:Dew Point Temperature and Wind Speed for August 15 for Past Ten Years

After receiving the Energy Plus Model from LBNL, SCR ran the Energy Simulation for Sutardja Dai Hall with different weather data from the year 1999 to the year 2009 and profiled the coherence between weather and energy consumption.

One sample which attracted our attention is that the daily energy consumption versus the maximal dry bulb temperature looks correlated very tightly.

Meanwhile, SCR also ran the energy simulation with different cooling set points and heating set points. Figure 33 shows the cooling energy consumption saving for the year of 2005 with six different cooling set points. The heating setpoint remains the same.

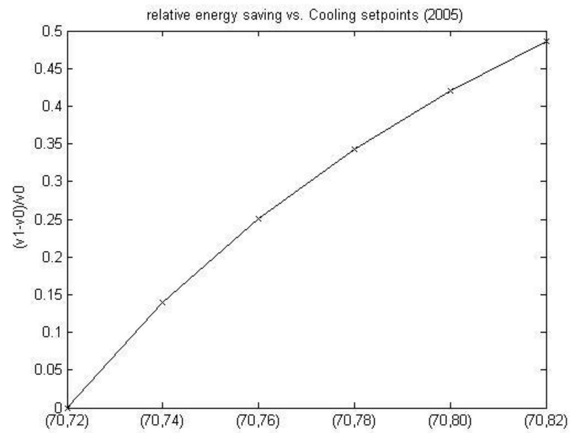

Figure 33: Energy Saving vs. Cooling Set Points

For demand response, SCR tried the Energy Plus simulation for different pre-cooling strategies. This simulation was focused on finding a good control strategy for the Peak Day Price event. The scenarios for this simulation were designed based on the paper by Peng Xu titled "Evaluation of Demand Shifting with Thermal Mass in Two Large Commercial Buildings". The detailed pre cooling strategy can be described by the following chart:

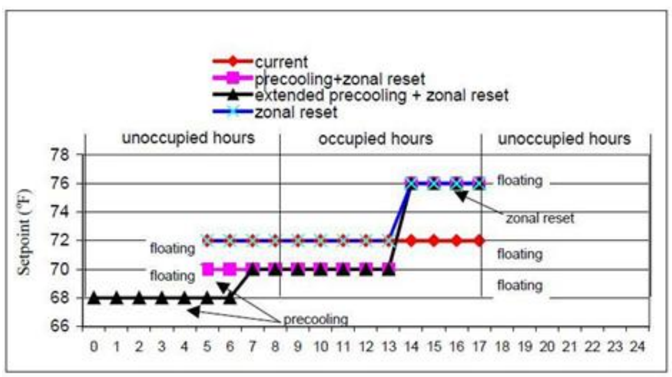

Figure 34: Different Pre-Cooling Strategy for demand response

Based on the above four strategies, SCR ran the pre-cooling simulation and got the following profile chart (Figure 35). The conclusion for this simulation is that a pre cooling strategy does not improve energy savings in Berkeley. The reason is that during the night hours, the temperature is relatively low and even heating is required. To support this claim, we can see another simulation chart which runs in Phoenix (Figure36). As the Phoenix displays very high temperature during the night time, the energy consumption for pre-cooling displays a substantial impact in according with different strategies.

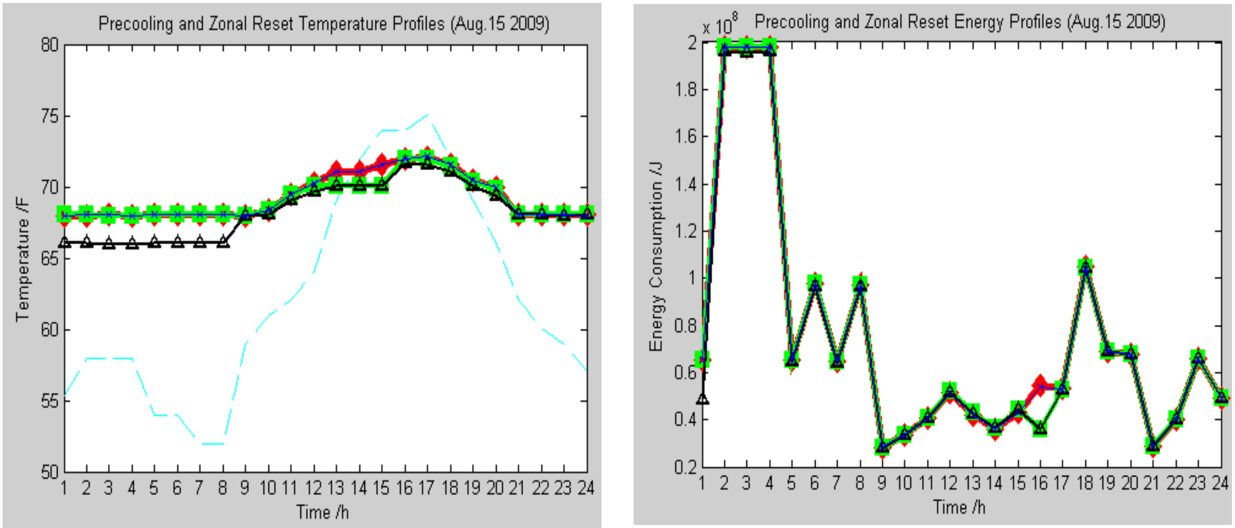

Figure 35: Energy Simulation for different pre-cooling strategy using Berkeley weather

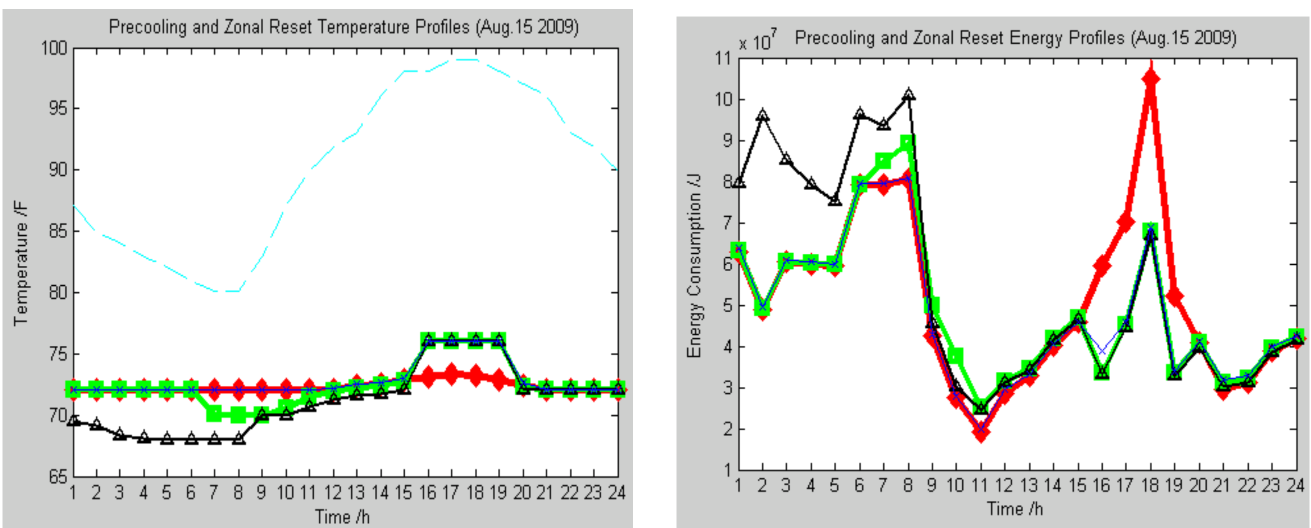

Figure 36: Energy Simulation for different pre-cooling strategy using Phoenix weather

The results shown above apply one schedule for all the set points. To include the occupancy model into the DR strategy, we have to consider multi-zone set points. However, we think it is unnecessary to treat each zone independently for all 95 thermal zones; it makes sense to classify the different zones with their functioning description. Currently, we propose 7 categories:

- Schedule for Office (s_strongN);
- Schedule for Computer room (s_strongA) ;
- Schedule for Auditorium (s_audit);
- Schedule for Conference (s_conf);

- Schedule for hallway (s_fair);
- Schedule for restroom, lounge room (s_fairP);
- Schedule for classroom (s_clasm);

According to the above classification, we ran the simulation by specifying 7 cooling schedules and 7 heating schedules. In varying the types of thermal zones, we have different scheduling.

As one set of set points, SCR ran the simulation with the following hourly values:

daily time	s_fair	s_fairP	s_strongA	s_conf	s_audit	s_clasm	s_strongN
12:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
1:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
2:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
3:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
4:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
5:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
6:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
7:00 AM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(68, 72)
8:00 AM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(67, 77)	(68, 72)	(68, 72)
9:00 AM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(67, 77)	(68, 72)	(68, 72)
10:00 AM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(68, 72)	(68, 72)	(68, 72)
11:00 AM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(68, 72)	(68, 72)	(68, 72)
12:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(68, 72)	(67, 77)	(68, 72)
1:00 PM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(67, 77)	(68, 72)	(68, 72)
2:00 PM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(67, 77)	(68, 72)	(68, 72)
3:00 PM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(67, 77)	(68, 72)	(68, 72)
4:00 PM	(67, 77)	(68, 76)	(68, 72)	(68, 72)	(68, 72)	(68, 72)	(68, 72)
5:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(68, 72)	(68, 72)	(68, 72)
6:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(68, 72)	(68, 72)	(68, 72)
7:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(68, 72)
8:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
9:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)

10:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)
11:00 PM	(67, 77)	(68, 76)	(68, 72)	(67, 77)	(67, 77)	(67, 77)	(67, 77)

Table 2: Hourly heating/cooling setpoints per category of building.

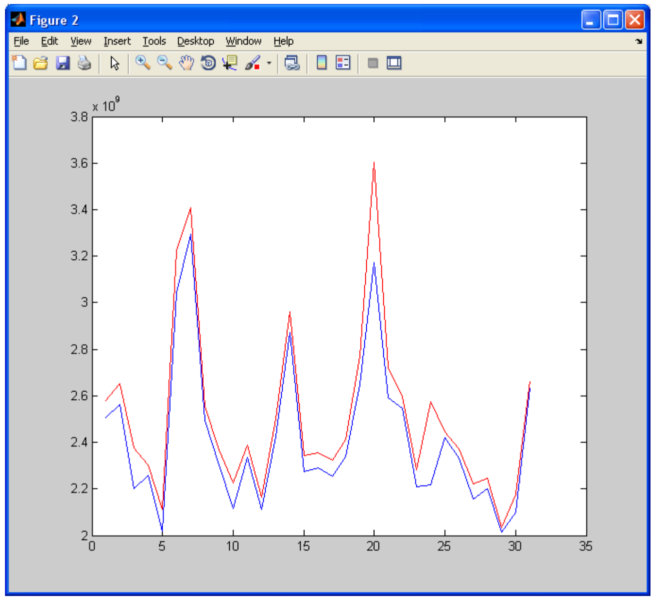

Figure 37: Energy saving corresponding to Multi-zone set points

Figure 37 above displays the total daily energy consumption for August of the year 2009. The red line represents the baseline consumption with the set point always (68, 72). The blue line represents the energy consumption with the different set points and different scheduling. It displays the trend that energy could be saved if we classify different areas and give different set pointsdefining different thermal zones.

During the research process to find an optimal central load DR control strategy, SCR explored the utilization of Building Controls Virtual Test Bed (BCVTB) by LBNLto connect MATLAB with Energy Plus for certain elements of the building energy simulation. SCRhasconcluded that BCVTB enables the communication between MATLAB and EnergyPlus and the synchronizationof co-simulation. However, an unknown mechanism in BCVTB adds uncertainties into simulation outputs.So SCR decided not to use BCVTB in the project. Instead, SCR discovered an alternative platform for DR control strategy research called MLE+ developed by the University of Pennsylvania. Extensive tests showed thatMLE+ provides a simpler, however, much more reliable way tosynchronize the simulation between MATLAB and EnergyPlus. We are able to write sophisticated temperature set points strategy in MATLAB, and send it to EnergyPlus for building simulation.

6 Products of the Project

6.1 Website or other Internet sites with results of this project.

A website has been created and provides the deliverables and the quarterly reports thus far in the project: http://i4energy.org/diadr-project-sutardja-dai-hall-0

The user interface for the commercial gateway has been developed as a result of this project. We employ XML over sockets to pass information between the gateway-OSGi container and a gateway web user interface written in PHP that allows users in an office setting to define preferences for devices participating in a demand response event.

Currently the user has the ability to set device priorities in the order of whichdevices may be shut down, to override control from the gateway, to toggle devices onand off remotely through the user interface, to view power consumption data ofdevices that are being metered, and to view a schedule of upcoming demand responseevents.

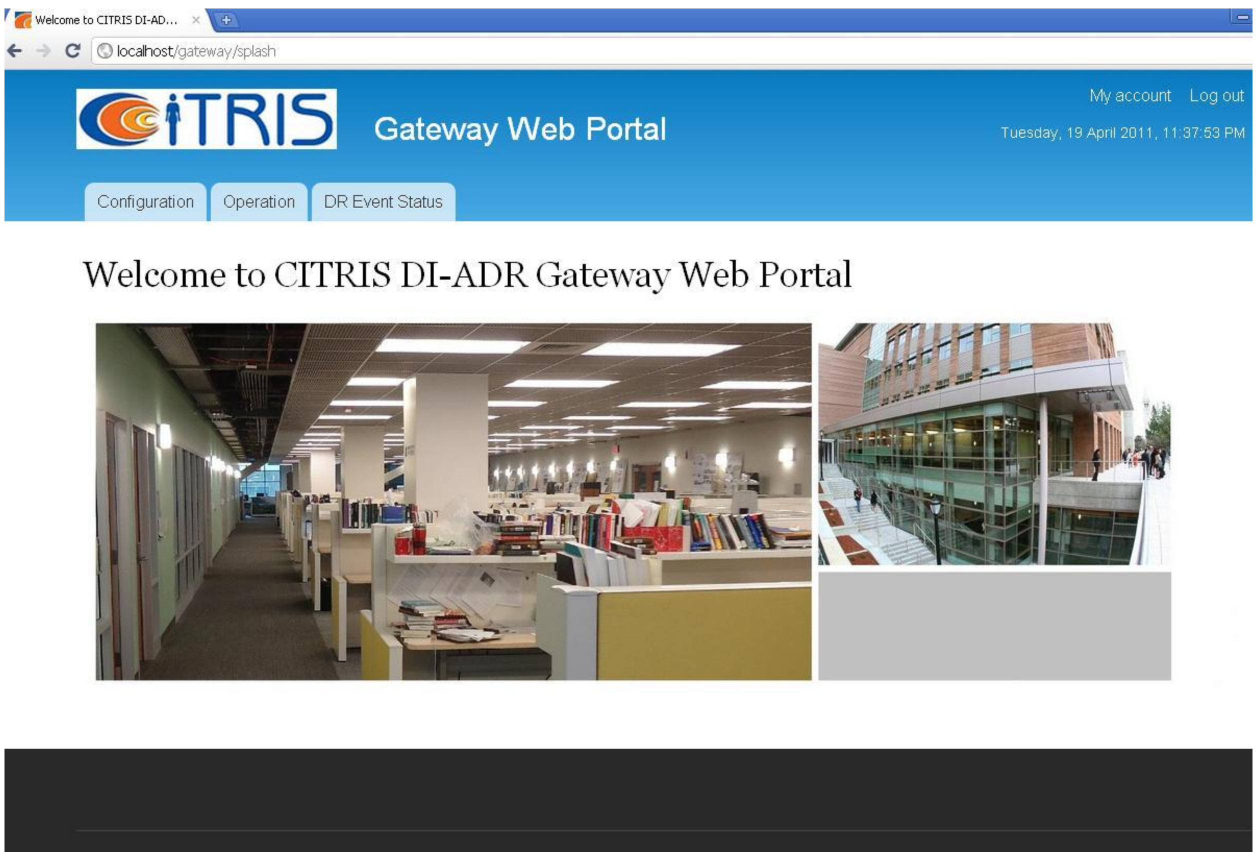

Figure 38: Screenshot of the Homepage for the Web Portal

Figure 39: Screenshot of the Operation Tab

6.1 Networks or collaborations fostered.

This project is a joint effort between UCBerkeley, LBNL and Siemens. The project was facilitated by CITRIS. Other collaborations include: Dhaani Systems who has developed a tool to manage computer power; Raritan who has a switchable power strip that also measures energy consumption, WattStopper who has helped link the WattStopper lighting controls in the building to the Siemens Smart Energy Box. In addition, the project has developed collaborations across campus.

6.2 Technologies/Techniques.

6.2.1 Commercial Energy Gateway

The Commercial Energy Gateway (CEG) is a communication and control software package, developed to be an open-source and open-standard architecture for use in commercial spaces. The essential functionality of the CEG originates from the Energy Information Gateway (EIG or Gateway for short) originally developed for residential spaces and easily converted to the commercial side. The primary purpose of the EIG is to empower users to manage their energy usage more effectively. In a commercial setting such as for the commercial demand response, this amounts to establishing communication and control between appliances in the CEG's sphere of influence and communicating energy and control information to the user in a practical manner. The sphere of influence may include lighting, smart appliances that can be controlled directly as well as "dumb" appliances, which can be controlled through the use of load switches or switchable power strips (SPS) that can be directly controlled by the Commercial Energy Gateway. Central to the operation and success of this project is enabling widespread connectivity over several communications media (e.g. WiFi, ZigBee, Zwave, LAN, etc), which make up the current marketplace of smart communicating energy products. The Gateway also relies on a Web User Interface (UI) that is in the process of being developed.

The increase in improved submetering and tools for parameter measurement (such as lighting sensors, motion sensors, and infrared sensors) in commercial buildings across California has opened the realm of the commercial space to the possibility of advanced energy consumption monitoring and control. These new meters have the ability to enable ZigBee communication with devices inside what is known as the CAN, or Commercial Area Network (also known as the Commercial Energy Network, or CEN). While this radio is not currently enabled, its placement in the smart meter has spurred a small but rapidly growing industry of so called "smart" energy appliances and devices which intend to communicate with the smart meter and beyond. What is lacking in this space is a set standard of communication between these devices. While some might utilize ZigBee (a proprietary standard) or Zwave, others rely on Wi-Fi or Ethernet. What results from this is a hodgepodge of devices which lack standardization and are intimidating to consumers.

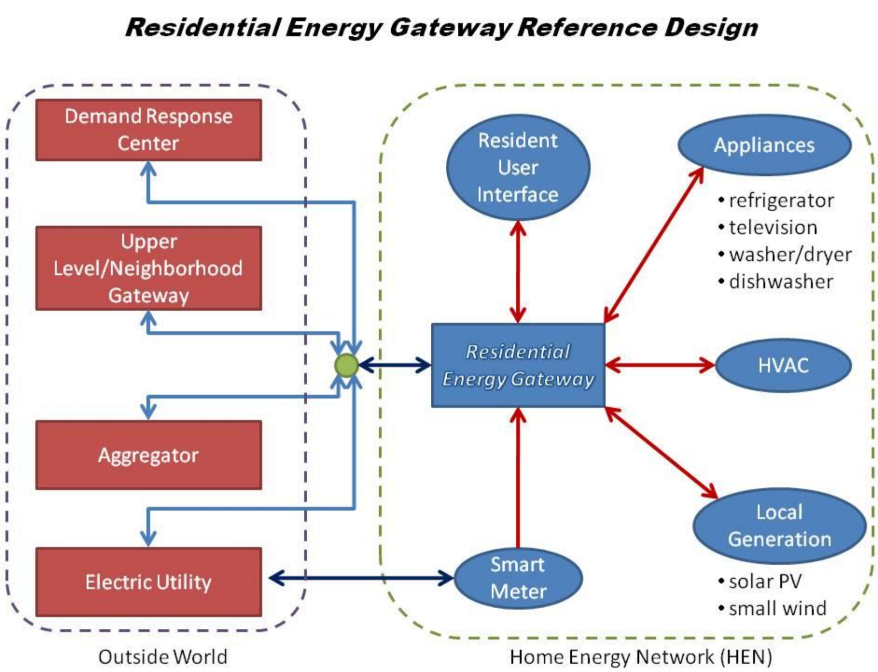

Figure 40: Energy Information Gateway in a commercial environment

The concept of an information gateway is hardly a new one. Currently, many such products exist that are designed to provide communications between the smart meter and appliances. However, the lack of standardization that so intimidates the consumer also prevents these gateways from being able to communicate with devices of a different manufacturer. For example, a GE gateway can communicate with a GE washer, but not a Maytag. These problems present themselves in a commercial office setting (with a building energy management and control system).

The Commercial Energy Gateway being developed at UC Berkeley alleviates this restriction by providing an open source standard and software package based on widely available communications protocols. A logic diagram for a commercial version of the Energy Information Gateway is shown in Figure 40. As the figure shows, within the CEN, the Gateway is able to communicate with all commercial appliances, the building management system, and the HVAC system. In addition, the Gateway is the portal through which CEN information is linked with the outside world. Perhaps most importantly, the Gateway connects to an occupant user interface, through which information about all other connected elements can be viewed.

6.2.1.1 Open Services Gateway Initiative (OSGi)

The Open Services Gateway Initiative, or OSGi, is a modular software framework for JAVA, in which the EIG, and in consequently the CEG are written. OSGi supports the dynamic integration and operation of modular, semi-self-contained, pieces of JAVA code known as "bundles". Once installed into the OSGi framework, bundles can be dynamically started, stopped, and updated, which allows for pieces of the framework to be operated on independently. OSGi is service oriented, meaning that bundles installed in the framework can create services for consumption by other bundles. The Commercial Energy Gateway makes use of the modularity and service oriented architecture of OSGi to establish robust communications with external appliances.

As an example of the use of the service oriented architecture, consider the following situation: The core software package of the CEG contains an Ethernet bundle, which creates and exports the "NetService" service to the OSGi framework. NetService provides the capability for an external appliance to connect to the Gateway over a TCP/IP connection (Ethernet or WiFi. An appliance manufacturer wishing to connect his or her appliance to the CEG over a WiFi connection needs only to create and install a bundle to the OSGi framework, and direct that bundle to consume NetService. While this process may seem a bit intimidating, the EIG team has created a set of templates and detailed instructions which streamlines the creation and installation of new bundles into the framework. Making use of the service oriented architecture in OSGi, the EIG team has developed other more specialized services which provide other functionality including: participation in Demand Response events, executing appliance control, and hosting a local web user interface.

The EIG in the context of OSGi can be seen in Figure 41. Within the figure, blue ovals denote bundles and green boxes denote services. Bundles on the figure's left hand side represent the "core" bundles of the EIG. This collection is responsible for providing the services on the far right hand side of the figure. The bundles in the center of the figure: WiFi Appliance and ZigBeeAppliance, can consume the provided services. These bundles represent specific appliances within the CEN or office, such as a refrigerator or laser printer. Red lines below these bundles imply that the Gateway can support the integration of an undetermined amount of appliances, just using the services seen in the figure. As one might infer from this figure, connecting appliances within the CEN or office to the CEG allows supervisory control over these appliances to be applied. Currently, such control is enabled during a demand response event, which is obtained through a connection to an OpenADR server via OpenADRService.

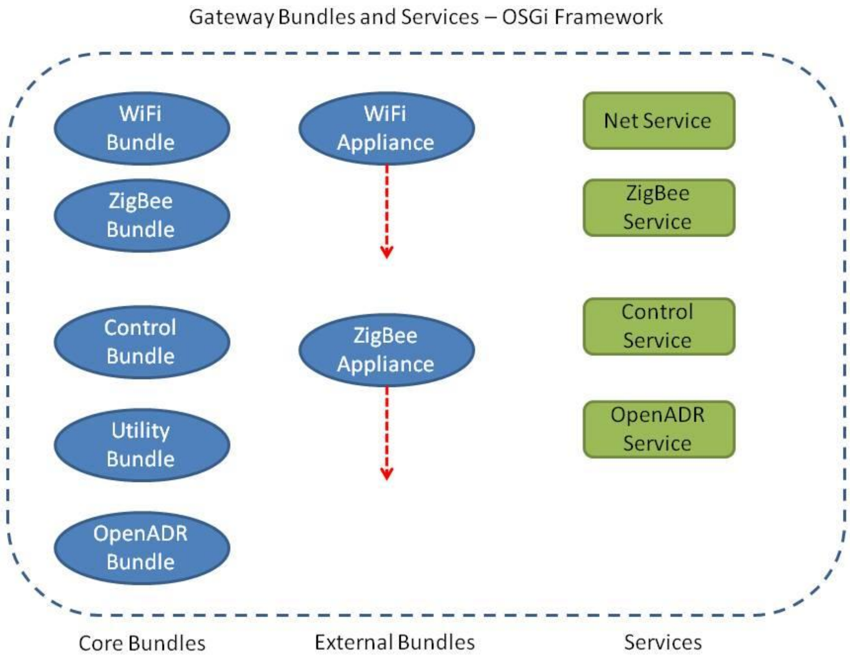

Figure 41: The EIG in the OSGi framework

6.2.1.2 XML for Data Communications

The generic nature of the EIG necessitates the use of an abstraction layer to allow communications from dissimilar sources (appliances, the smart meter, etc.). This generalization is provided via the use of XML for both communications from appliances to the Gateway and vice versa. XML is an acronym for Extensible Markup Language, which is a data format designed to organize and transport data over the web. As such it is widely used and understood. Encoding data in XML for transmission within the CEN allows for increased interoperability among devices of utilizing dissimilar operating systems, code bases, and programming languages.

The use of XML also eases the burden of data manipulation for web transport. Utilizing data encoded in XML, the EIG can simply receive data from an appliance and forward this XML data on to a web user interface or cloud resource. The parsing and displaying of XML documents is well understood and thoroughly employed in web-based environments.

6.2.1.3 Gateway architecture

SCR and UCB investigated and developed the architecture of the Gateway framework, and proposed interface between Control bundle and Xbee devices bundle as shown in Figure 42. The blue boxes are the bundles SCR is working on, and the yellow boxes are UCB's responsibility.

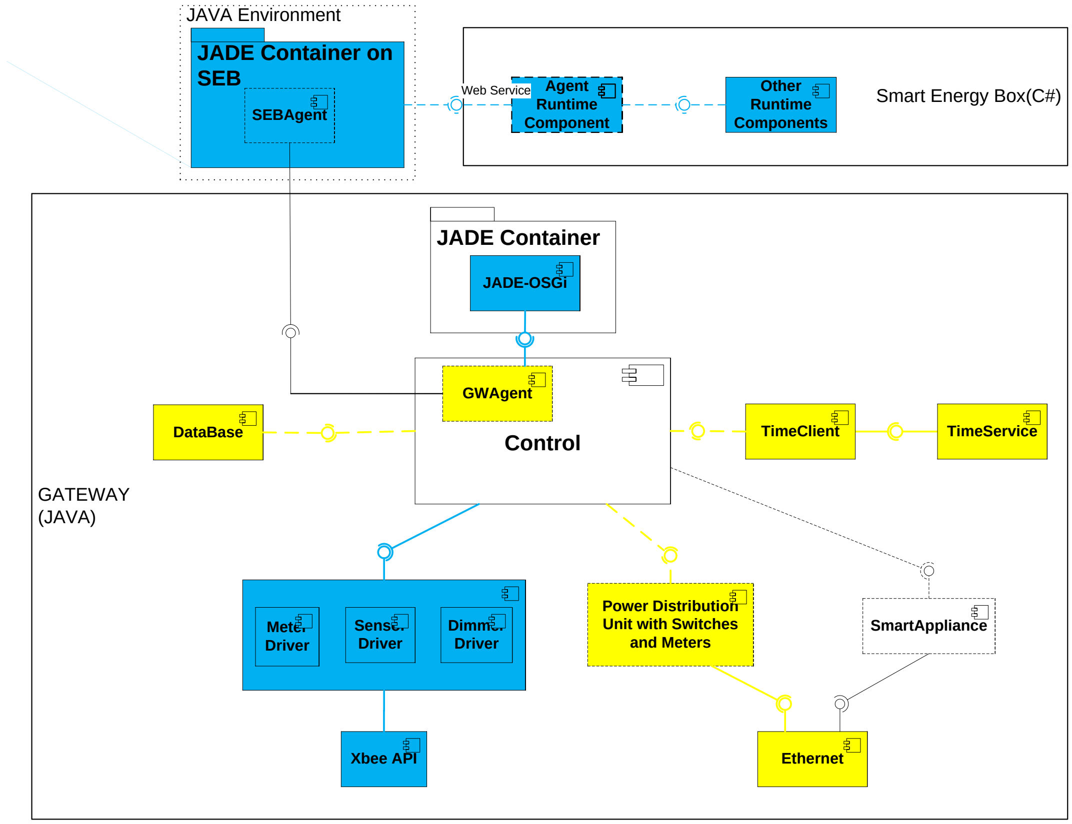

Figure 42: Gateway controller architecture

6.2.1.4 Gateway agents

SCR has implemented the Gateway agent based on JADE on top of OSGi framework as shown in Figure 43.Both JADE and OSGi are JAVA based middleware, but because the Gateway is implemented on OSGi, the JADE environment and agents have to be run have to run on top of OSGi as well. SCR found an add-on bundle that can run the JADE environment in the OSGi framework so that each JADE agent on the Gateway can be implemented as an OSGi bundle, communicating with other bundles in the Gateway.

SCR also implemented the agent-based communication between the Gateway Agent and the SEB Agent, realizing one control scenario with the following sequence chart (Figure 43), where the SEB agent gives the Gateway agent an Indirect Signal of the percentage to shed at Gateway level, and the Gateway will calculate and decide if it will apply the control. If the Gateway agrees to apply control to the plug loads, then it will return if the percentage is successfully achieved.

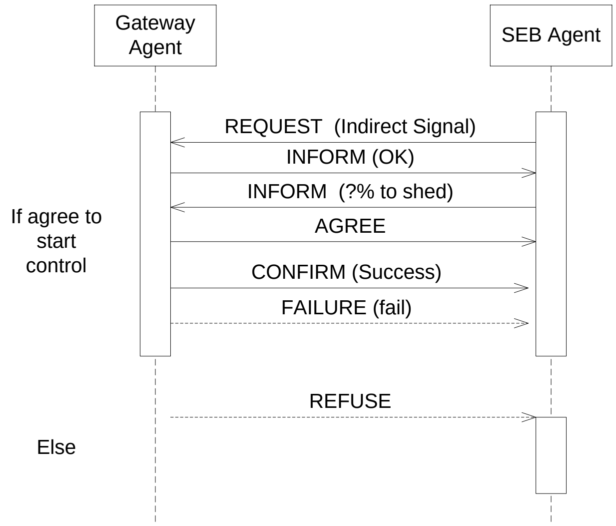

Figure 43: SEB and Gateway Agent communication for DR

Another scenario, in which the SEB will call for proposals from Gateway agents, was also implemented for market-based control approach. Figure 44 shows the sequence chart.

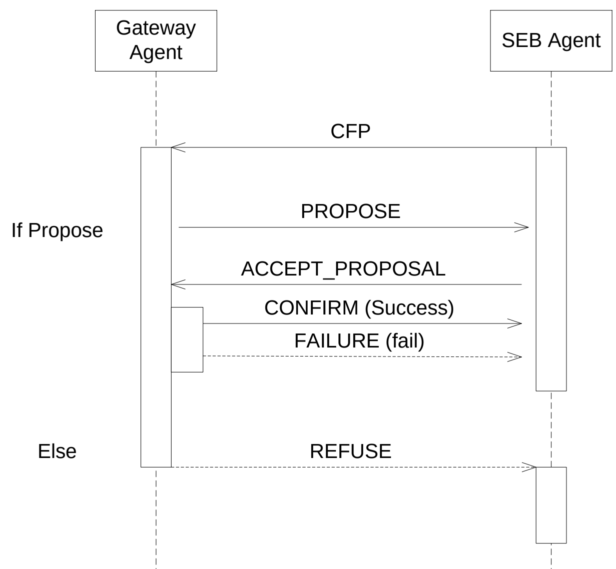

Figure 44: SEB and Gateway Agent communication based on market based approach

The Gateway Agent bundle was merged with the Control bundle where a simple control strategy was implemented according to the flow chart in Figure 45. Once the Gateway agent receives the percentage of load to shed, it will look at the light and occupancy sensors. If the office space is occupied, and the lighting level is not very high, or there are no plug loads ON, then the Gateway will refuse to shed any load. Otherwise, the Gateway will turn one or more lights down or implement appliance control to reach the goal. At the conclusion of the control action, the Gateway agent will return the result to the SEB Agent.

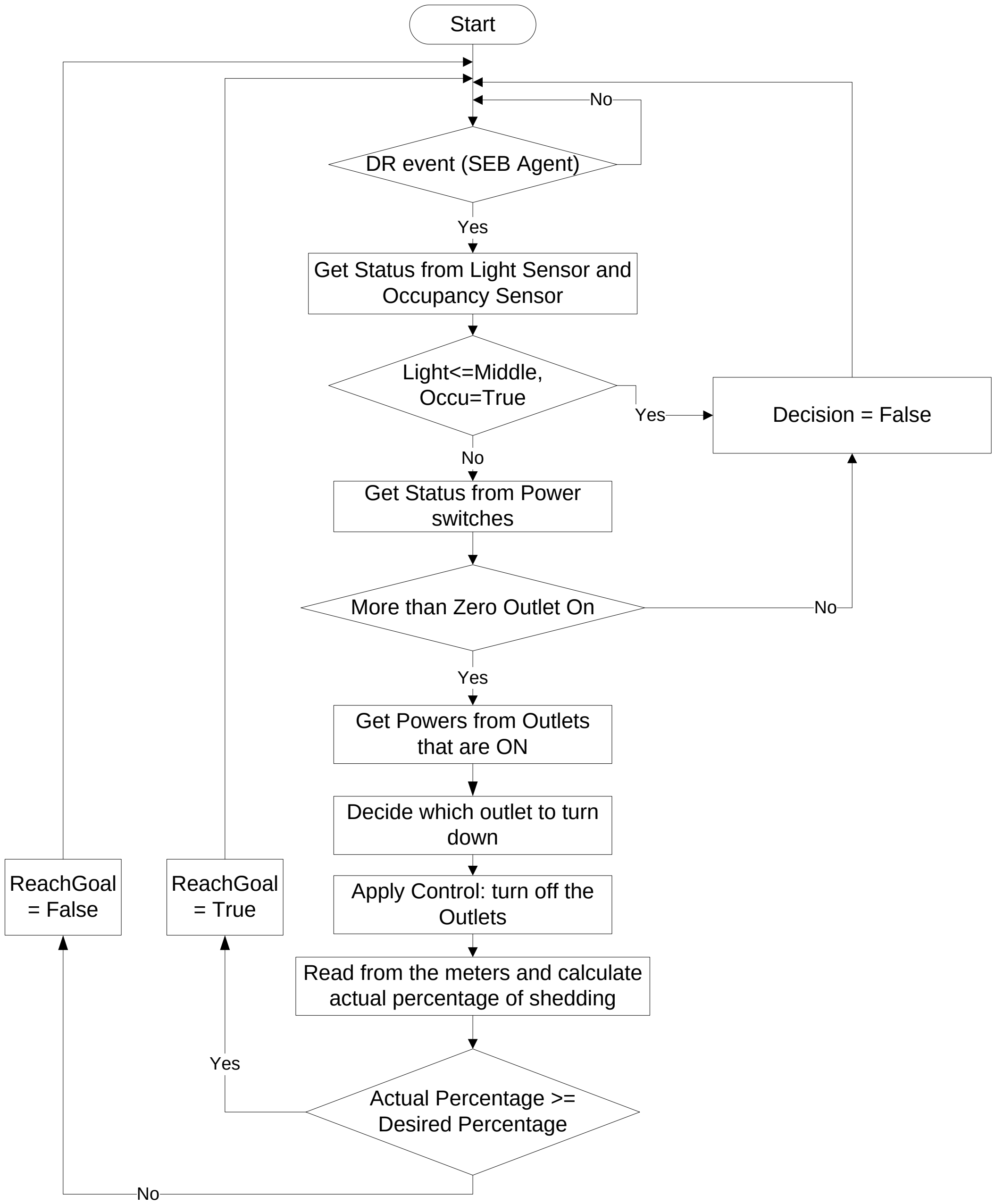

Figure 45: Gateway Control Flow Logic

6.2.1.5 Summary

SCR has proposed a multi-agent architecture for distributed demand response, and presented two scenarios based on FIPA Contract Net Protocol. In addition, SCR has proposed a lab plan for the Distributed Load DR Control Demonstration, and has drawn a basic architecture of the Gateway, based on codes from UCB and SCR. SCR has also described the two kinds of communication processes between the SEB agent and Gateway agent, and has implemented a simple control strategy within the Gateway agent to test the local controller.

The future plan for the Gateway development would be:

1. Translate and integrate the printer driver into Gateway framework.
2. Investigate and implement more complicated Gateway control strategies.

6.3 Databases

6.3.1 Plugload Audit assumptions

Key assumptions made for appliances entered into Energy Audit using Rapid Auditing Protocol

BAT- Battery, or Uninterruptible Power Supply (UPS)

- Assumption: Draws power as measured, otherwise 10% of rated capacity (1500 kWh device draws 150 W).
- Justification: Limited experiences in the building have shown constant power draw of this magnitude for UPS devices.

CAL – Calculator (Plug in kind)

- Assumption: Draws 1 watt
- Justification: Plug in Calculators are normally left plugged in and meter to 1 W.

COF – Coffee Maker

- Assumption: Draws Rated power
- Justification: Resistive elements draw their rated amount of power normally

CPU – Computer

- Assumption: Each computer draws 100 W.
- Justification: This is a reasonable approximation for now, in the future this will be adjusted to represent the distribution of computers throughout SDH.

Desk – Desk with electronic adjustable height

- Assumption: Draws 2.3 Watts
- Justification: Ten desks measured to this value assumption is that the rest do.

DOC –Laptop dock

- Assumption: Draws the same amount of power as the laptop that is plugged in
- Justification: Should not draw much power unless laptop is present

FAN – Fan

- Assumption: Draws measured amount of power when on normal speed.
- Justification: This will be the most common setting, and thus the appropriate mount of power draw

HOT – Instahot inline water heater

- Assumption: Draws rated amount of power.
- Justification: Resistive elements draw their rated power.

INK - Inkjet Printer

- Assumption: Draws measured amount of power after five minutes from plug in.
- Justification: Printer start up is over within five minutes of plugging in and turning on.

LAM – LAMP

- Assumption: Draws rated amount of power.
- Justification: Resistive elements draw their rated power.

LAS – Laser Printer

- Assumption: Draws measured amount of power after fifteen minutes from plug in.
- Justification: Most of the printers time is spent in this state after the warm up.

LCD – Liquid Crystal Display Monitor or TV

- Assumption: Draws constant amount of power when on.
- Justification: Each LCD monitor is measured for a one-time test of its power consumption. This will become a dynamic metering problem in the future.

MAC – Macintosh integrated PC and LCD screen

- Assumption: Draws 150 Watts.
- Justification: Measuring these devices is inconvenient when plugged in, 150 Watts is a reasonable expectation for computer and monitor combined

MIC – Microwave

- Assumption: Draws Rated Power.
- Justification: This is a reasonable assumption for a power hungry device. Most of the power for the microwave is consumed while it is on at rated power.

NOT – Notebook Computer

- Assumption: Draws measured power.
- Justification: These devices are easier to measure, because they can be unplugged and metered at the time of audit.

ORB –Ambient orb information display device

- Assumption: draws metered power
- Justification: N/A

PHO – Telephone or base

- Assumption: Draws 1 W
- Justification: Most units measure out to this level

REF – Refrigerator

- Assumption: Draws Rated power.
- Justification: Measured refrigerators draw this amount of power during duty cycle.

ROU – Router

- Assumption: Draws Measured power.
- Justification: N/A

SCN – Scanner

- Assumption: Draws Measured power in OFF mode.
- Justification: Most of scanners time is spent in this mode.

SER - Server

- Assumption: Each Server draws 200W

- Justification: This is a reasonable assumption for now, and will be adjusted in the future as individual servers are monitored throughout the building.

SPK – Speaker System

- Assumption: Draws measured power at 50% volume.
- Justification: This is a reasonable volume level and thus power usage.

SPS – Smart Power Strip

- Assumption: Draws 1 Watt.
- Justification: The device has to power operations.

TEA- Electron Tea Kettle

- Assumption: Draws rated amount of power.
- Justification: Resistive elements draw their rated power.

VAC –Vacuum

- Assumption: Draws Measured power when on.
- Justification: N/A

7 Appendix

7.1 Energy Plus Model

7.1.1.1 Theory Verification

Energy Plus was chosen as a valuable modeling tool to analyze various HVAC and lighting strategies in the building due to its capabilities of providing accurate dynamic results of building behavior. A verification of the simulation software was performed to verify that Energy Plus is the tool of choice to be used for determining HVAC and lighting settings. A simple three-dimensional model room (with no windows) that is cooled by a simple HVAC systemwas used for theory verification of the software. The model was run for varying time steps, in which the zone temperature was measured using Energy Plus and compared to theoretical results that were solved numerically by hand.

First we must build the single zone building. We can use a simple rectangular prism shape to develop a system with a basic heat balance equation to be solved with relative ease. Figure A-1 shows the single-zone setup.

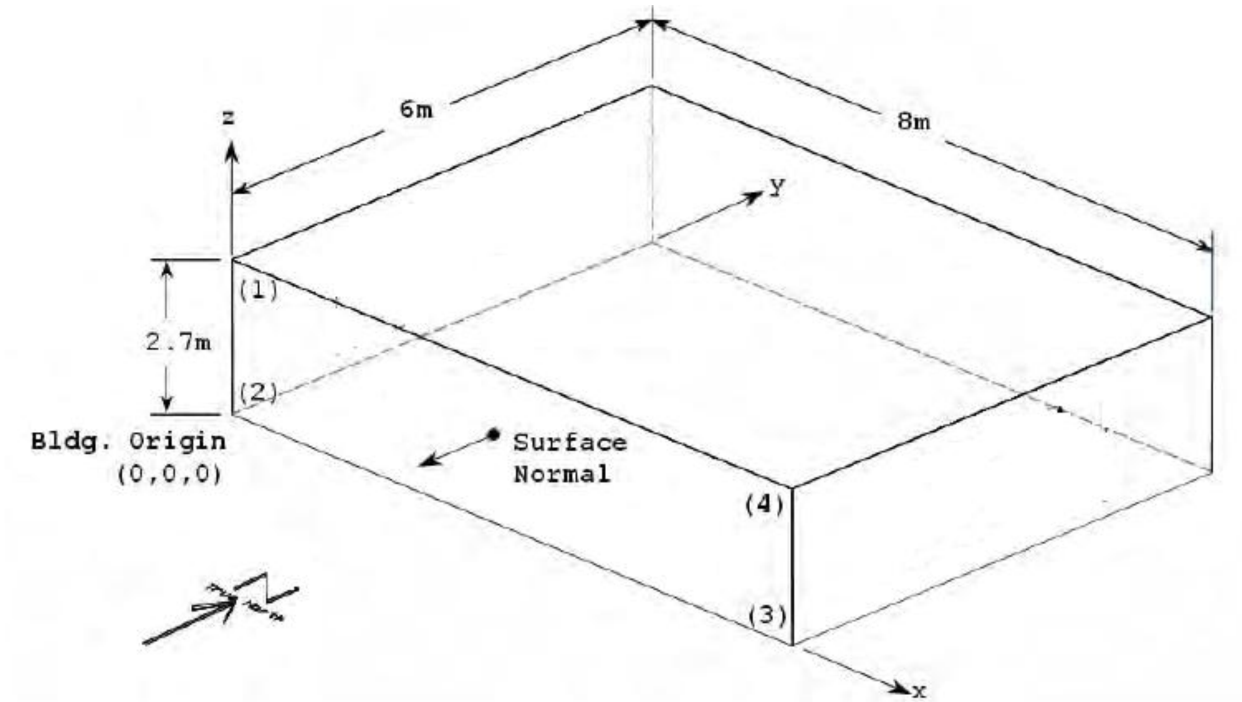

Figure A-1: Single-zone room for experiment

With the zone geometry, we must now determine the boundary and initial conditions for use in the heat balance equation for the single-zone model. In Energy Plus, when a model is run for a full day, the temperature of the building generally is initialized to a temperature close to the ground temperature specified in the **Site:GroundTemperature:BuildingSurface** category. We can set the outside temperature constant in the simulation at 90 Degrees Fahrenheit to not introduce any outside variations that will affect the step response.

To conduct the experiment, we can let the temperature drift to the outside temperature over 10 hours and then input a step by initiating the HVAC system. We then can run a constant HVAC input that will cool the building to a constant settling temperature. Thus the initial time will be the moment the HVAC system is initiated. The initial temperature will be the temperature after the time period allowed for the temperature drift. We can then measure the settling time (within 10% of final Temperature) and use that as a basis for varying simulation times in the Energy Plus model.

The general heat balance equation for the zone is derived as:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surf}} \hbar_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p \, (T_{zi} - T_z) + m_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys}$$

Where:

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$: sum of convective internal loads

$\sum_{i=1}^{N_{surf}} \hbar_i A_i (T_{si} - T_z)$: convective heat transfer from the zone surfaces

$m_{inf} C_p (T_\infty - T_z)$: heat transfer due to infiltration from outside air

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$: Heat transfer due to interzone air mixing

$\dot{Q}_{sys}$: air systems output

$C_z \frac{dT_z}{dt}$: Energy stored in zone air

$$C_z = \rho_{air} C_p C_T$$

ρ_{air}: density of air at zone temperature

C_p: Specific heat at zone air temperature

C_T: Sensible heat capacity multiplier

$$\dot{Q}_{sys} = \dot{m}_{sys} C_p (T_{sup} - T_z)$$

Where:

$\dot{m}_{sys}$: Zone supply air mass flow rate

C_p: Specific heat of air at supply temperature

T_{sup}: Air supply temperature

T_z: Zone air temperature

If we are to write out the energy balance equation for the single zone model, we will come up with neglecting the zone infiltration (only zone), and the internal gains which come from lights and occupants.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{surf}} \hbar_i A_i (T_{si} - T_z) + m_{inf} C_p (T_\infty - T_z) + \dot{m}_{sys} C_p (T_{sup} - T_z)$$

We can test the dynamic capabilities of Energy Plus by isolating variables, such as zone temperature for a single zone, while setting others, such as Outdoor Dry Bulb Temperature and radiance constant. By introducing a step input through a simple HVAC system, we are able to measure the response of the system to the initiation of the HVAC system for varied time steps.

7.1.1.2 Building Analysis

LBNL developed the Energy Plus model of Sutardja Dai Hall for use by the DIADR team. Figures A-2 through A-5 show images of the building modeled in Energy Plus.

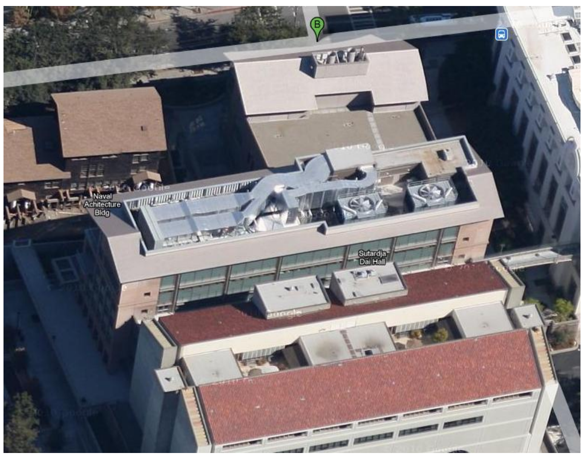

Figure A-2: South

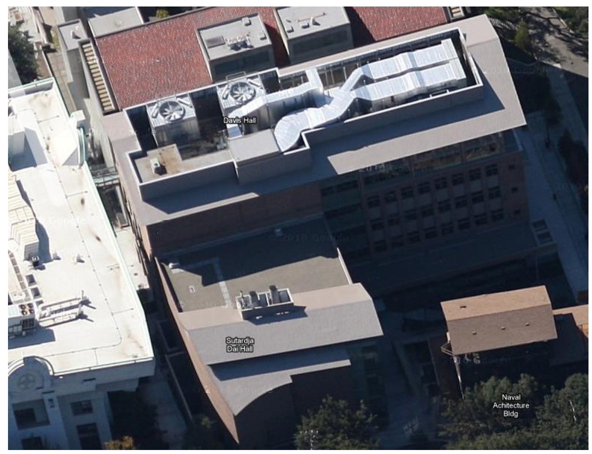

Figure A-3: North

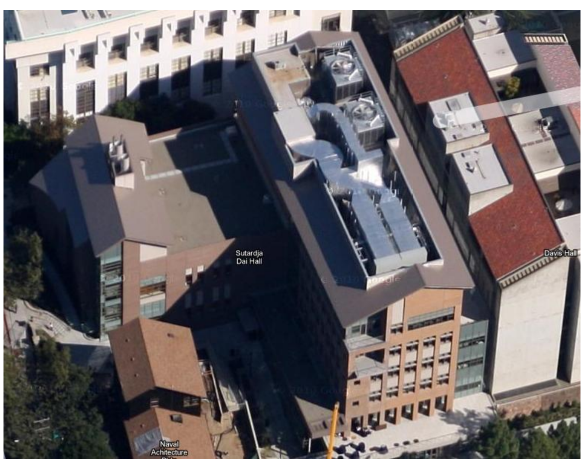

Figure A-4: West

Figure A-5: East

7.1.1.3 Data Collection

For proper modeling of the building in Energy Plus, a large amount of data was required as is shown in Table A-1.

Table A-1: Data Requirement for EnergyPlus Model Development

Architecture	
1. Location & description	1.1 Building information (description, location, floor area)
2. Weather data & utility rate	2.1 TMY weather data and real time data collection 2.2 Utility program and rate schedule
3. Architecture drawings	3.1 Architecture plan drawings 3.2 Elevation drawings (wall and glass wall)
4. Building construction	4.1 Above floor: Exterior & interior walls, floor, roof 4.2 Under floor: walls, floor, slab on grade 4.3 Glass wall
5. Shading	5.1 Exterior & interior shading
Internal Loads	
1. Occupancy & lighting & plug and misc loads	1.1 Intensities and schedules of occupancy & lighting & plug and misc loads 1.2 Intensities and schedules of other end uses (elevator, data center…)
HVAC Systems	
1. Zone Temperature	1.1 Zone temperature setpoints
2. AHU & zoning map	2.1 Outside air: % 2.2 Supply air: air flow, supply air temp
3. Cooling source	3.1 Cooling plants: brand & unit, capacity, COP, other available manufactory parameters 3.2 Chilled water: Supply & return temp setpoints 3.3 Operational schedules
4. Heating source	4.1 Heating source: type, capacity… 4.2 Hot water: Supply & return temp setpoints 4.3 Operational schedules
5. Supply & return fans	5.1 Fans: brand & unit, capacity 5.2 Air temp: Supply & return air temp setpoints 5.3 Operational schedules
6. Exhaust fans	6.1 Fans: brand & unit, capacity 6.2 Operational schedules
7. Auxiliary equipments – cooling tower	7.1 Cooling tower: brand & unit, capacity 7.2 Condenser water: Supply & return temp setpoints 7.3 Operational schedules
8. Auxiliary equipments – chilled water pumps	8.1 Pumps: brand & unit, capacity 8.2 Operational schedules
9. Auxiliary equipments – condenser water pumps	9.1 Pumps: brand & unit, capacity 9.2 Operational schedules
10. Auxiliary equipments – hot water pumps	10.1 Pumps: brand & unit, capacity 10.2 Operational schedules

7.1.1.4 E+ Zone Mapping

The HVAC control zones for Sutardja Dai Hall were explored and separated for proper modeling. Figures A-6 through A-19 display the building control zones and the correlating Energy Plus Zones developed.

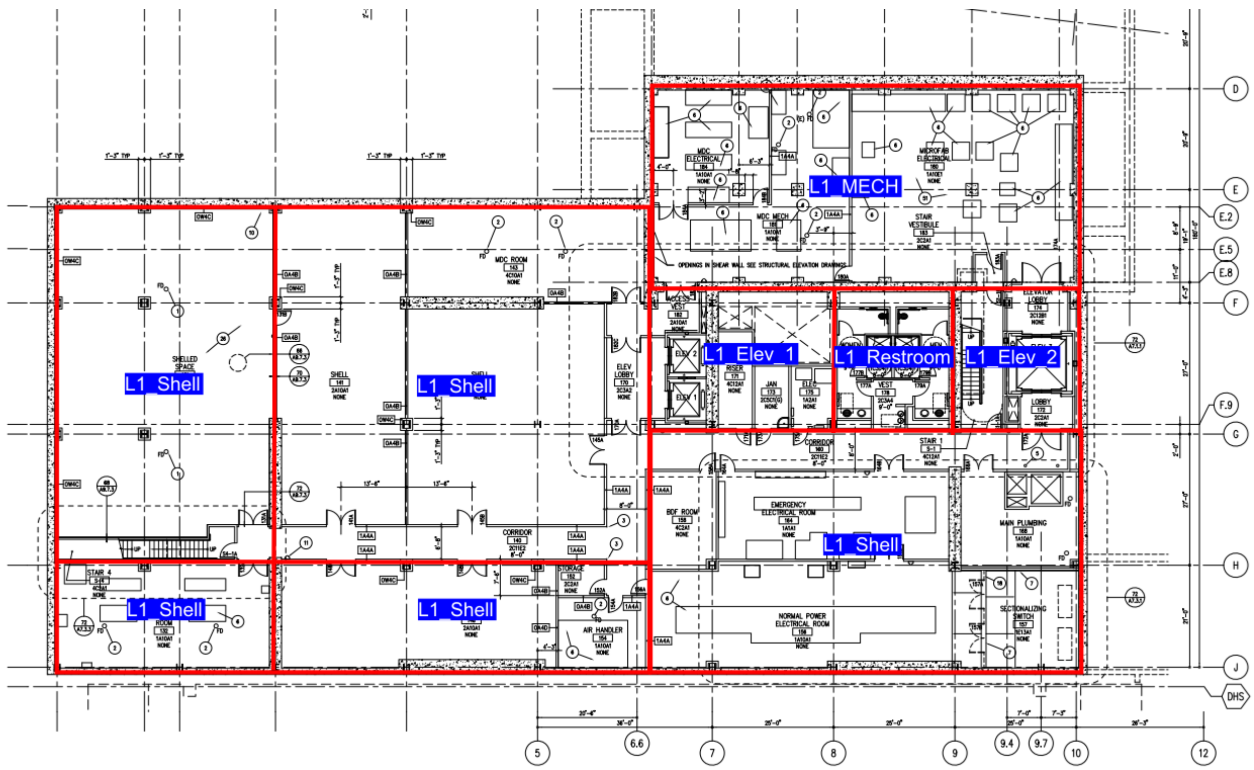

Figure A-6: Building Zone Map – Level 1

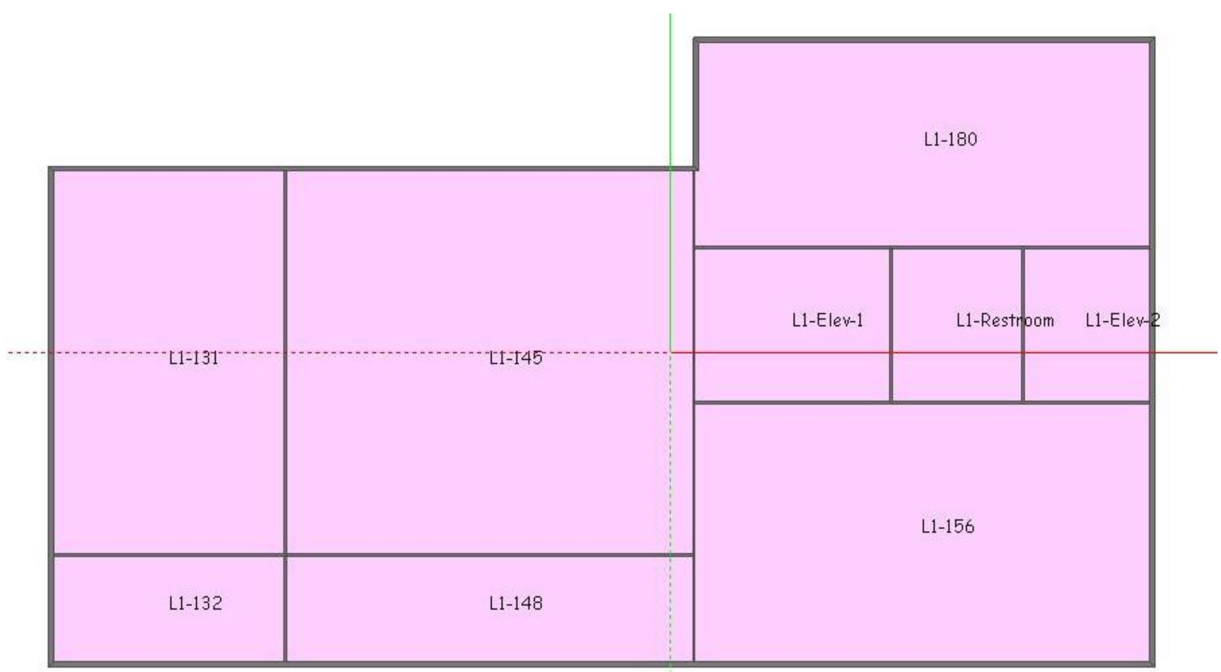

Figure A-7: E+ Zone Map – L1

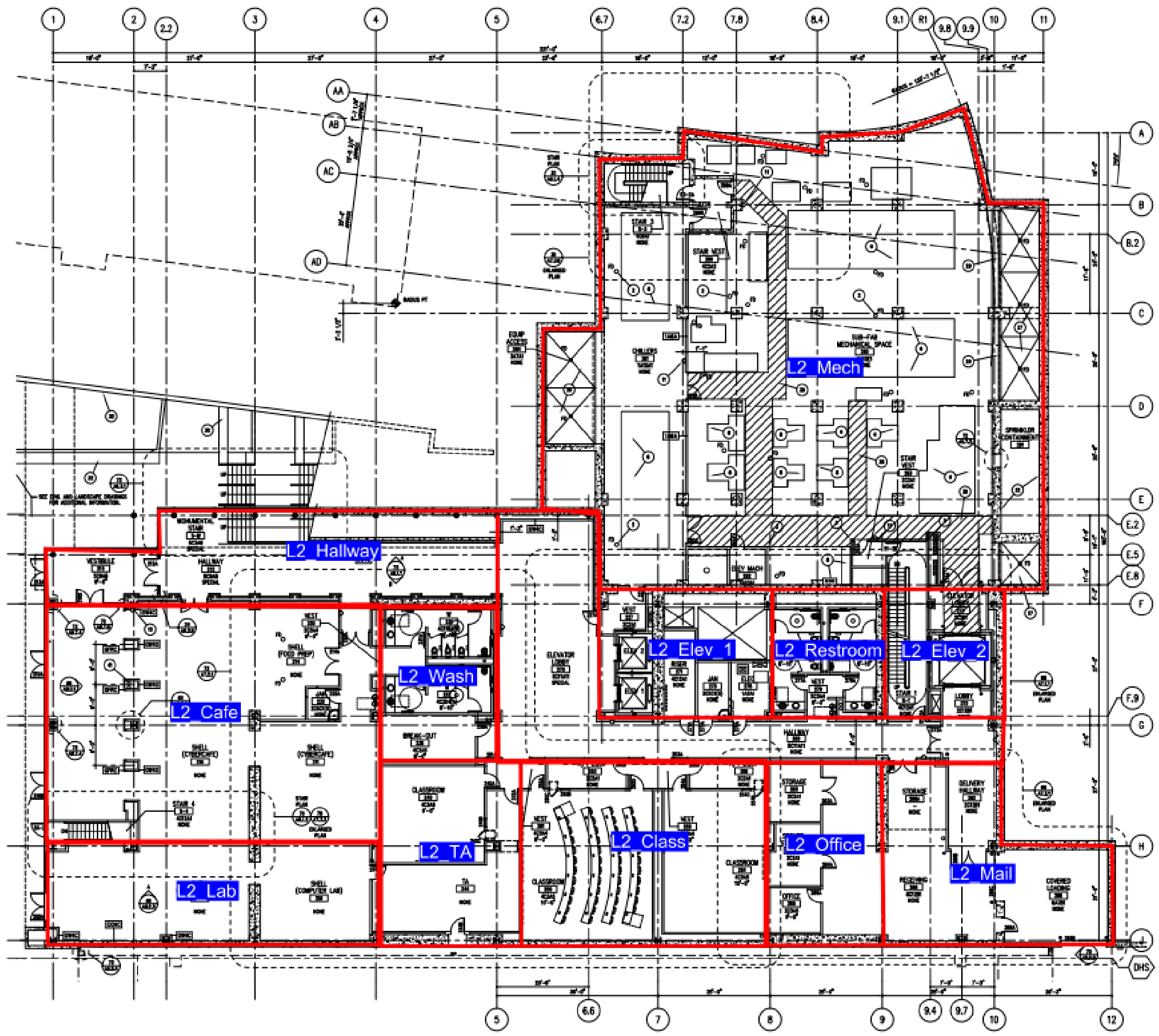

Figure A-8: Building Zone Map – Level 2

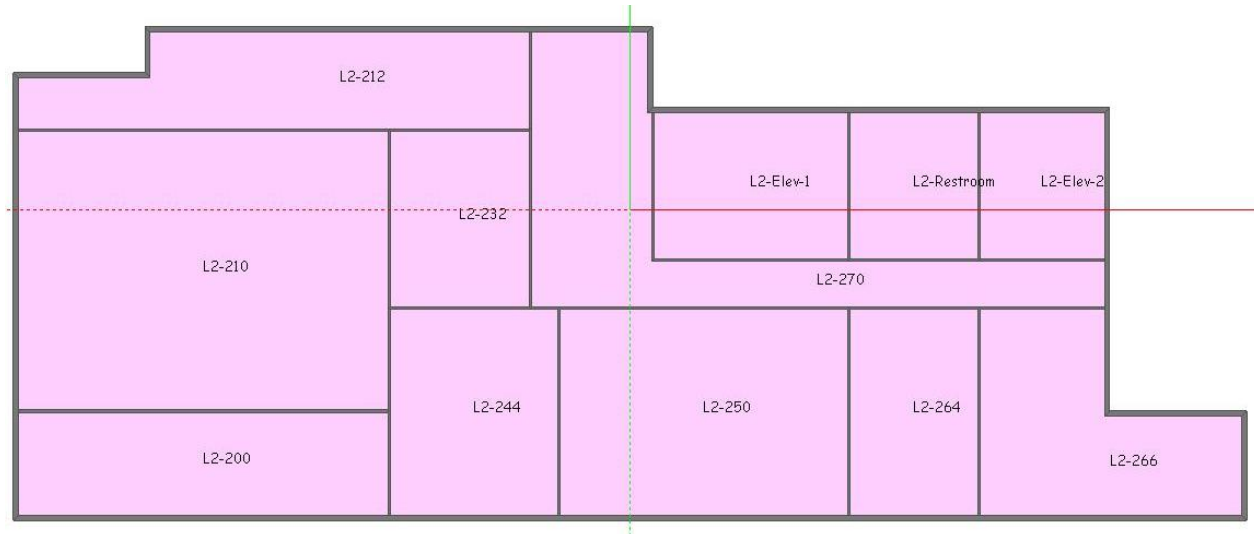

Figure A-9: E+ Zone Map – L2

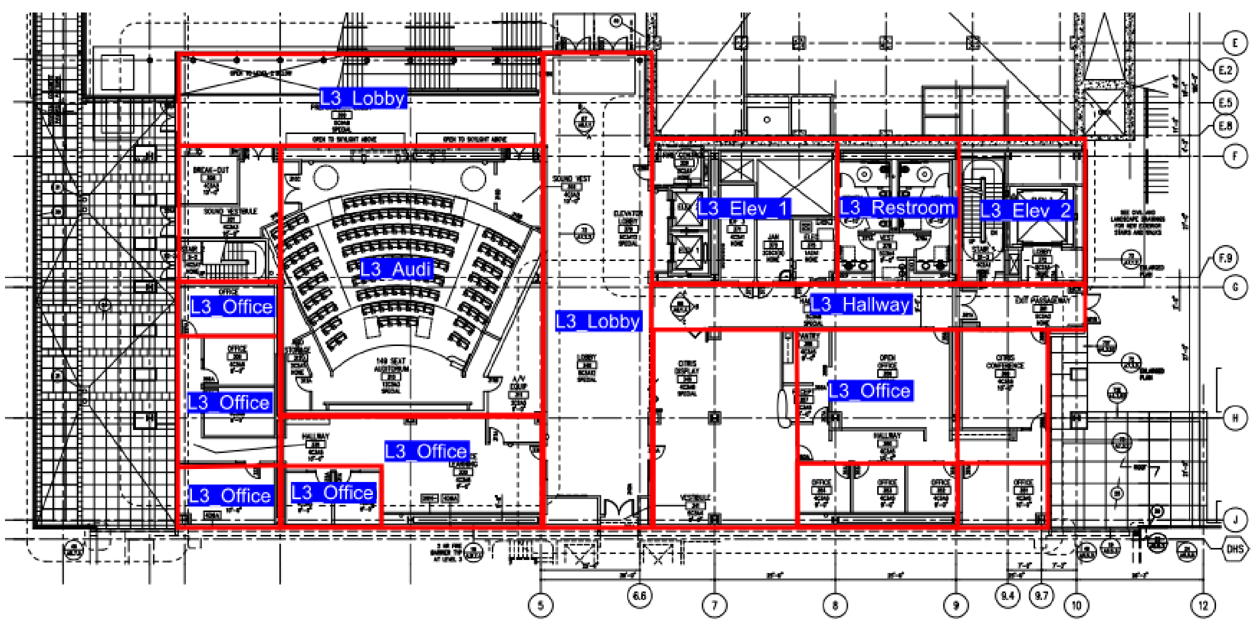

Figure A-10: Building Zone Map – Level 3

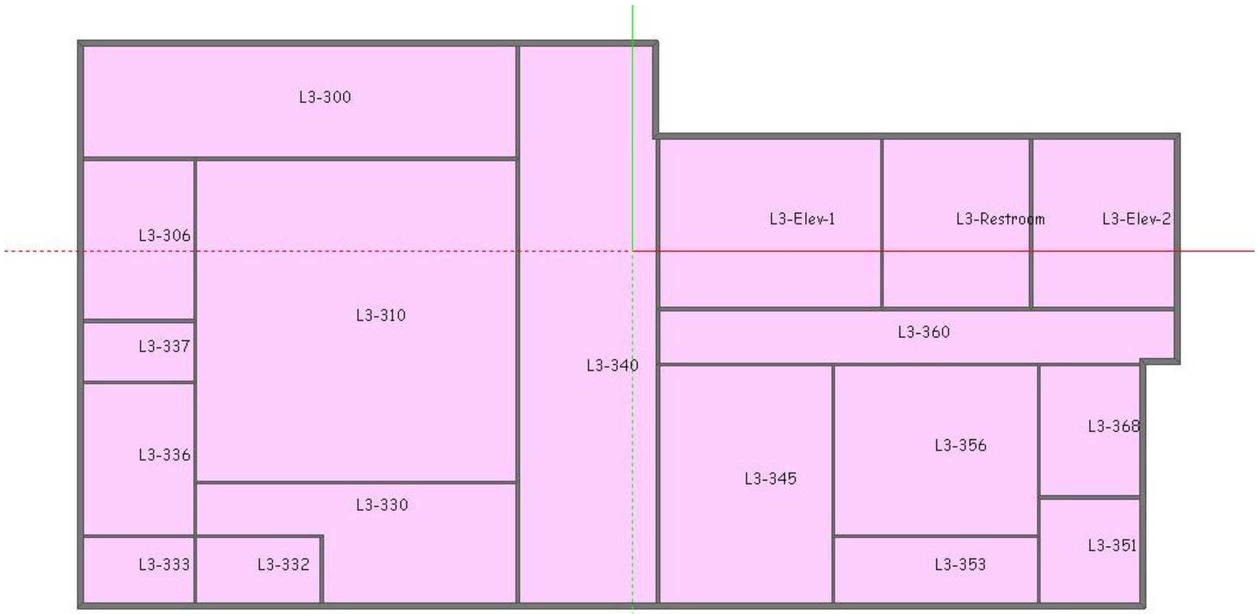

Figure A-11: E+ Zone Map – L3

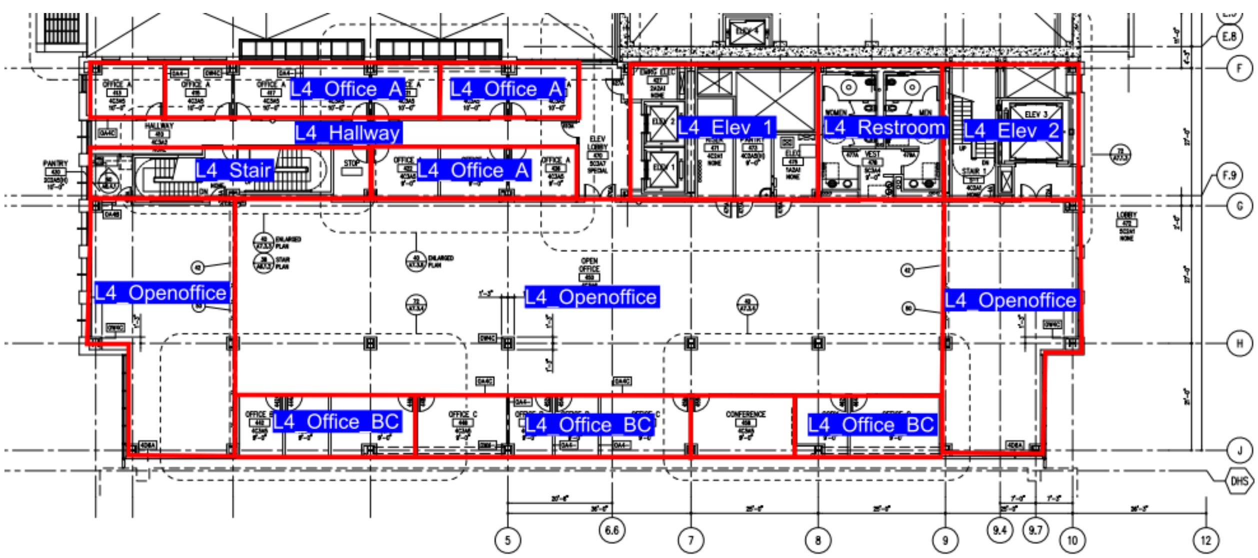

Figure A-12: Level 4

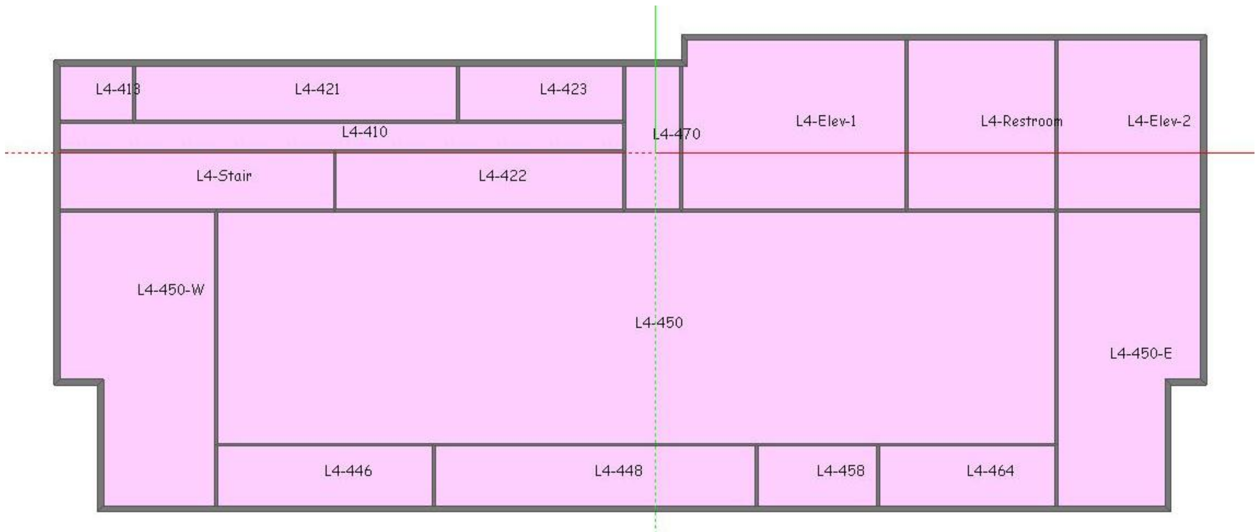

Figure A-13: E+ Zone Map – L4

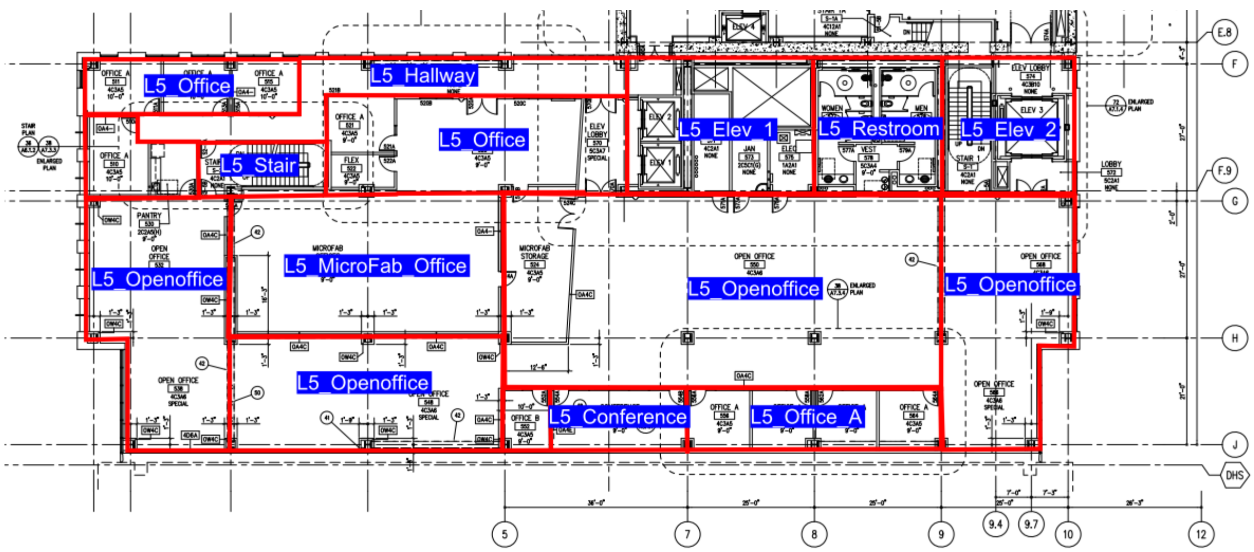

Figure A-14: Level 5

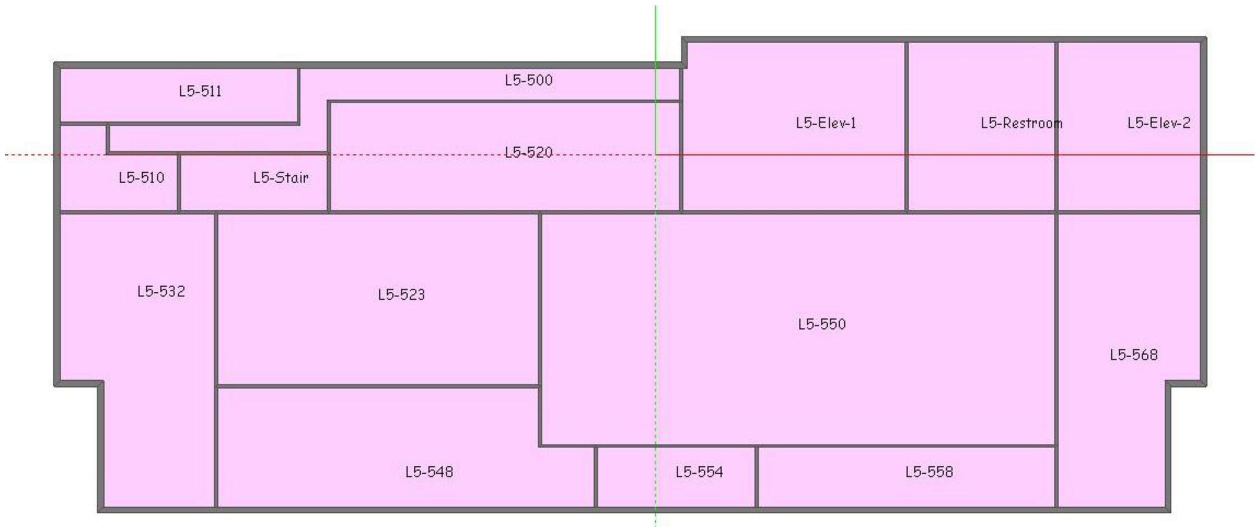

Figure A-15: E+ Zone Map – L5

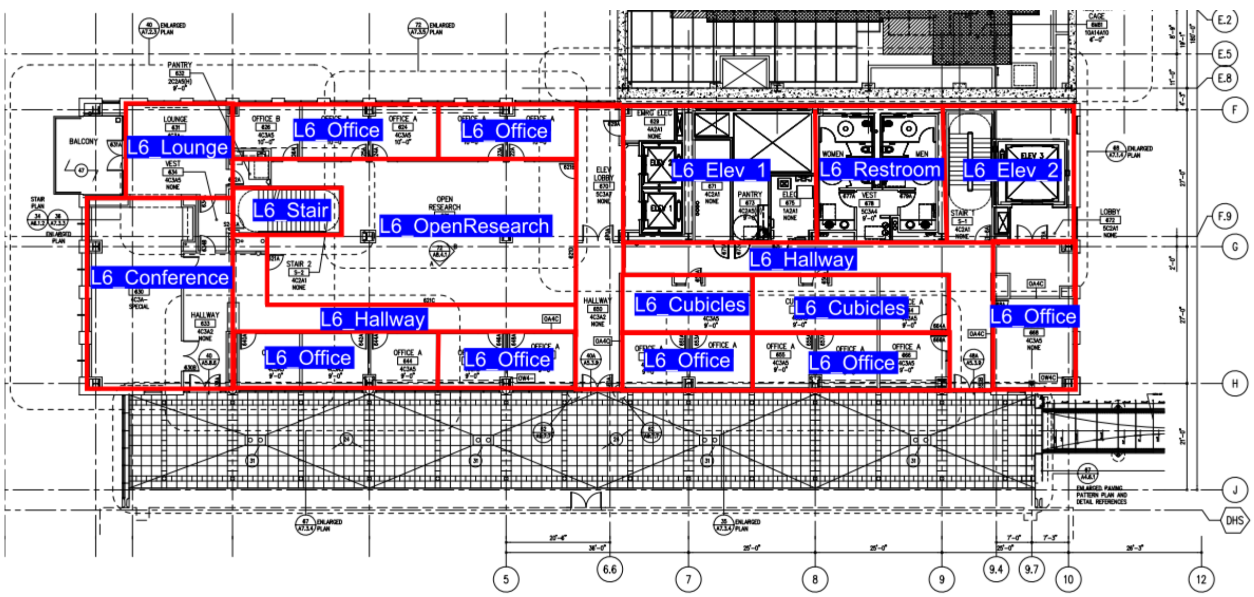

Figure A-16: Level 6

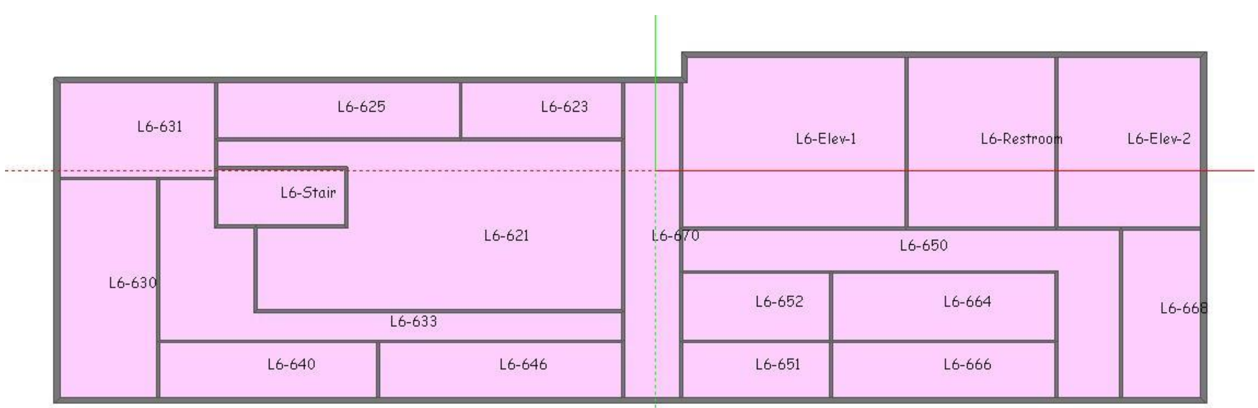

Figure A-17: E+ Zone Map – L6

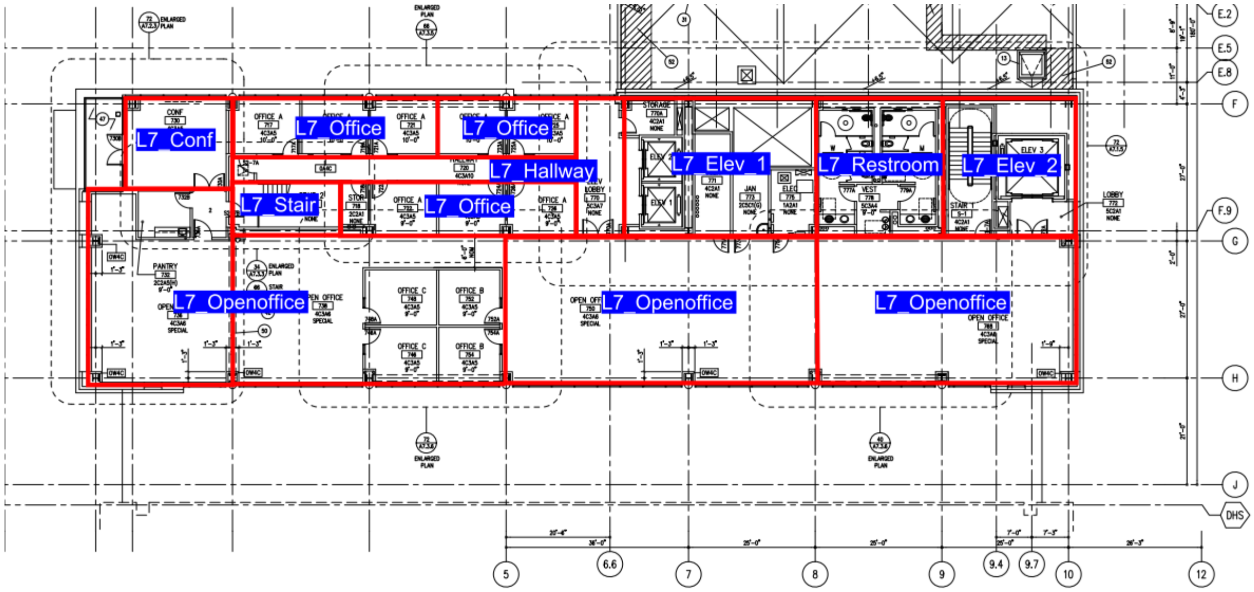

Figure A-18: Level 7

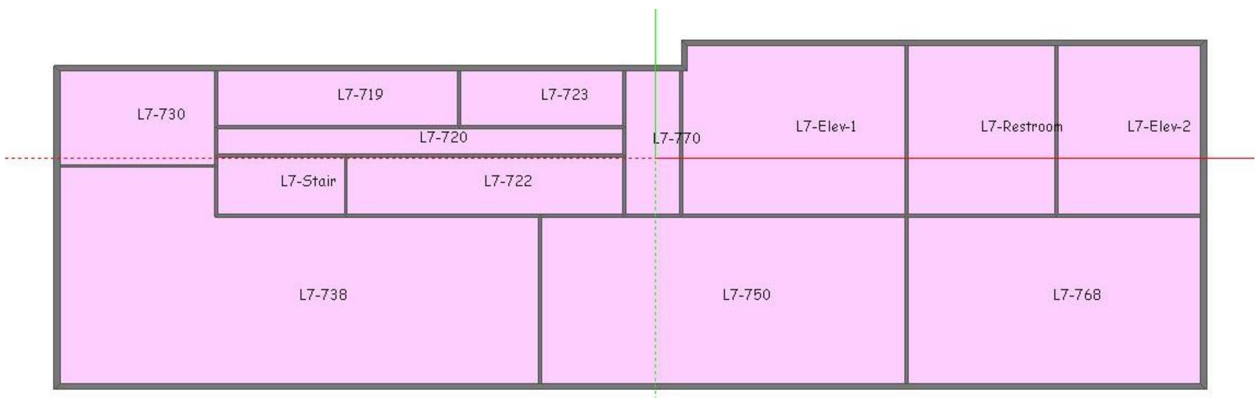

Figure A-19: E+ Zone Map – L7

7.1.1.5 Model Calibration

LBNL is in the process of finalizing the Energy Plus model development and calibrating the model by using whole building and sub-metered electricity usage data.

LBNL completed the preliminary development of the Energy Plus model that included the physical modeling effort in December and shared this preliminary model with the project team at the beginning of January. To complete the building modeling effort, first each control zone is identified and each of these zones were developed as an Energy Plus zone so that there is one-to-one correspondence between the actual controls zones and the Energy Plus zones. Starting in January, LBNL continued the model development effort by building the HVAC systems for the nanofabrication facility in Sutardja Dai Hall (SDH). The following systems were developed:

- **AHU 1A&1B**: AHU 1A&1B serve as the dedicated outside air systems (DOAS) to the nanofab facility, providing the fresh air to recirculation air handing units for maintaining indoor comfort. Similar to the modeling of the AHU 2A&2B for the offices in SDH, nanofab is also mapped into E+ control zones and each zone is modeled by separate thermostats.

- **CleanroomRAHUs (Recirculation Air Handing Unit)**: CleanroomRAHUs take the fresh air from the DOAS system (AHU 1A&1B) and mix with the return air to provide recirculation air to the MICROFAB. There are 3 to 4 RAHUs for each building zone. In EnergyPlus, two or more RAHUs cannot be placed in each corresponding EnergyPlus control zone. Therefore, one big RAHU with same cooling capacity and supply air flow was modeled in the simulation.

- **Exhaust Air System**: (Ex 1-4) Exhaust Air Systems, exhausting air from the nanofab mechanical room and CHEM room, are modeled in EnergyPlus.

The preliminary SDH EnergyPlus model completed in January had a simulation error related to the development of the absorption chiller. To continue the development, the electric chiller model was developed and used to debug the rest of building HVAC system. With assistance from Siemens team, zone thermostats were modified to control each EnergyPlus zone separately. In the meantime, the issue with the absorption chiller modeling was brought to LBNL's Simulation Group and was resolved with their assistance. The entire building, with its two chillers, was fully modeled towards the end of February. The simulation results were summarized so that they can be compared to the measured whole building energy usage.

LBNL started to calibrate the EnergyPlus model by using the data available from the whole building power and submetering equipment.

At first, LBNL conducted detailed data analysis and visualization of the measured whole building electrical usage and the breakdown of electrical usage for each sub-metered point to evaluate electric usage in SDH. After evaluating the electrical data, LBNL proposed the following procedure for the model calibration:

- **Actual Weather Data**: Siemens provided LBNL with the actual weather data of Berkeley for 2010. LBNL ran the model using this actual weather data and compared the simulation results to the measured whole building energy usage.

- **Lighting and Receptacles**: The initial EnergyPlus model used ASHRAE 90.1 as default for densities and schedules for the lighting and receptacle loads. In order to calibrate the default values with the measured usage data, the measured energy use data at each sub-metered point was analyzed and measured lighting and receptacle loads replaced the default values.

- **Plug Load Audit**: With help from the plug load audits that were conducted by UC Berkeley, LBNL calibrated the density and magnitude of the plug loads for most of the SDH.

- **Actual Operation of the HVAC System**: LBNL accessed the building energy management system, recorded the actual operation of each component of the HVAC system and later used this information for calibration. The trended points included measured zone temperature setpoints, supply & exhaust air flow of each fan system (AHU 1A&1B, AHU 2A&2B, AHU 3 and AHU 4, RAHUs, Exhaust fans), chiller water temperature setpoints for primary & secondary loops.

- **Chillers' Performance Curves**: LBNL developed the actual performance curves to replace the default parameters for both electric chiller and absorption chiller. The new curves were developed by using manufacturers' test data under rated conditions.

Calibration of the model and comparison of the measured and simulated building performance were completed by the end of March. The results are summarized in the next section.

7.1.1.6 Comparison Results of Monthly Electricity Usage

Figure A-20 below shows a comparison of measured versus simulated electricity use for each month were data were available and reliable. A +/- 10% error bar is added to the measured data to show how the simulated data compares.

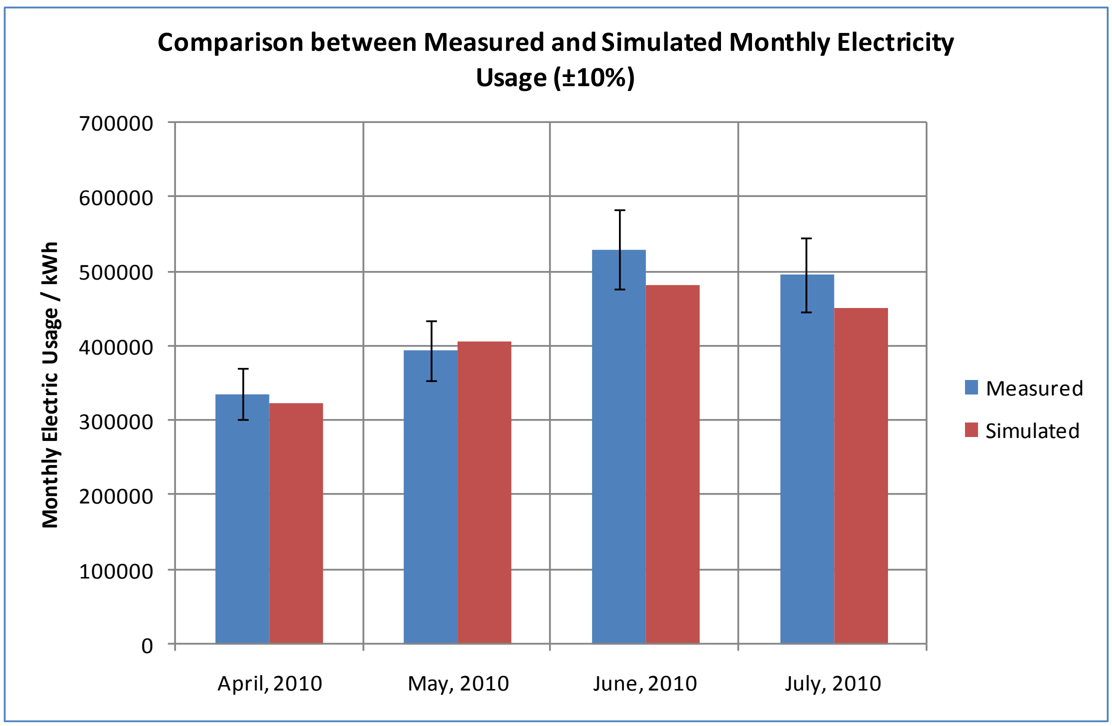

Figure A-20: Measured vs. Simulated Electricity Use for Each Month

Summary of Comparison Results for Each Submetering Point:

To further investigate and evaluate the performance of the simulation model, we developed the same analysis for each of the sub-meters. For each sub-metered data point, we compared the measured versus simulated data. The results are summarized in Table A-2 below:

Main Substation	Main Point	Serve As	Average Demand Power (kW)	Simulated Demand Power (kW)	Difference (kW)	Difference (%)
MSA	CH2	Electric Chiller	83.09	54.50	-8.59	**-10%**
	CD41A	AHU 3-4 and Heat Water Pumps	17.69	18.89	1.2	**6.8%**
	CD4RA	AHU 2A&2B Return Fans EX 1-4	50.96	61.25	10.29	**20.2%**
	ATS-E01	AHU 1A&1B Chilled Water Pumps	94.57	85.01	-9.56	**-10.1%**
	ATS-ES	Elevators RTU ..	28.74	27.45	-1.29	**-4.5%**
	ATS-MDC	MDC	20.20	20.00	-0.2	**-1.0%**
MSB	MS41B	Fab Mech	155.35	149.00	-6.35	**-4.1%**
	ATS-E02	Server	22.38	20.00	-2.38	**-10.6%**
	ATS-EL	Fab Exhaust Fans 1-4	120.00	126.34	6.34	**5.3%**
	CB41A	L2-7 Lighting and receptacle meters	59.60	65.76	6.16	**10.3%**

Table A-2: Comparison of Simulated and Actual Demand Power

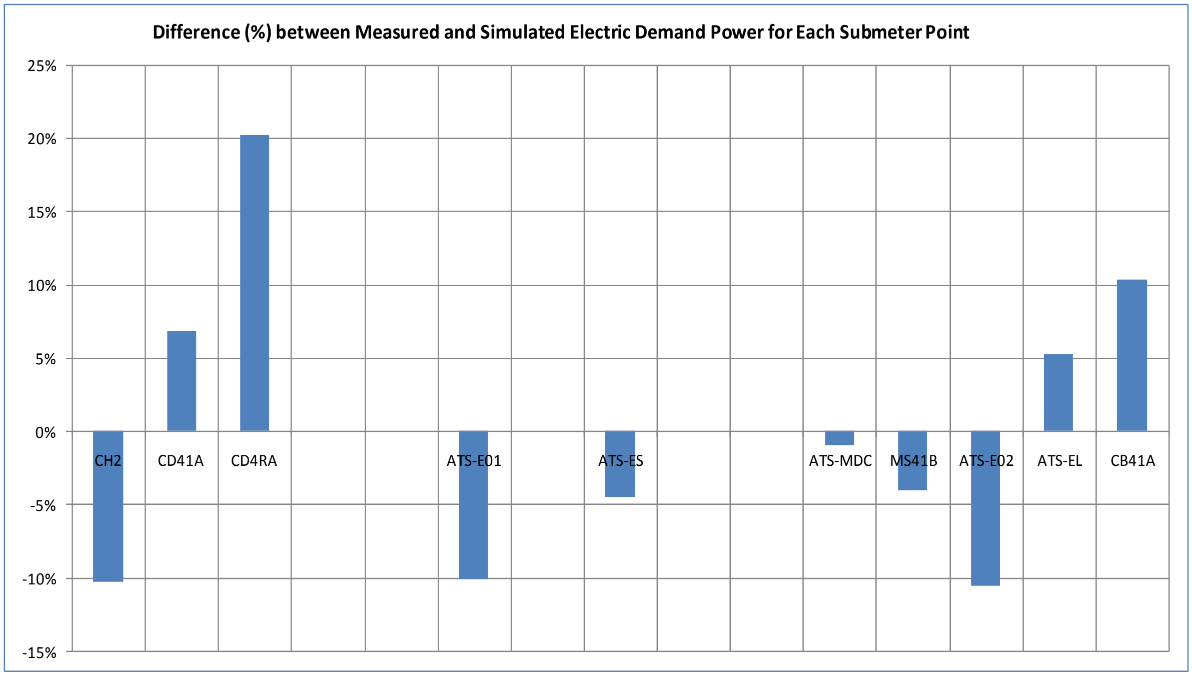

Figure A-21: Error Between Measured and Simulated Electric Demand for Each Submeter Point

With the exception of CD4RA, which contains sub-metered data for the AHUs 2A and 2B as well as return and exhaust fans, simulation model is within +/- 10.6% of the measured sub-metered data.

LBNL is developing a strategy to further investigate the discrepancies in simulated versus measured data related to the CD4RA. One way to do this will be to compare the time series data. In the meantime, the model will be used for developing DR strategies.