A Framework for Smart Location-Based Automated Energy Controls in a Green Building Testbed

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Abstract—**Current building designs are not energy-efficient enough due to many reasons. One of them is the centralized control and fixed running policies (e.g. HVAC system) without considering the occupants' actual usage and adjusting the energy consumption accordingly. In this paper, we discuss our multi-disciplinary project on a green building testbed on which we introduce mobile location service into the energy policy control by using the now popular GPS-embedded smart phones. Every occupant in the building who has a smart phone is able to monitor their usage and adjust their own energy policy in real-time. This changes the centralized control inside the building into a distributed control paradigm. It allows the occupants with different roles to participate in the energy consumption reduction efforts. Latest information technologies such as mobile smart device-based location service, distributed control, and cloud computing are used in this project. The major idea and experimental system is expected to be applied to not only green buildings but also vast number of the conventional buildings to reduce the energy consumption without sacrificing the human comfort and convenience.**

Index Terms—**Location Service, Green Building, Energy Efficiency, Energy Policy, Distributed Policy Control, Smart Energy**

I. INTRODUCTION

BUILDINGS are an important environment designed to serve the human needs for multiple purposes. Most of people spend more than 90% of their time in different buildings. Buildings consume a significant portion of the total energy consumption in United States. According to a recent research study [1], buildings consume 71% of the total electricity and 39% of the total energy usage. The buildings also contribute 38% of the total carbon dioxide emission. On the other hand, the ever-increasing costs of traditional fossil fuels and their negative impacts on the planet's climate and ecological balance urge us to improve the energy efficiency in the buildings besides finding new clean-energy sources.

Most of the buildings' design, however, is not efficient. There are many factors contributing to the problem: materials used, building envelope, building structures, equipments efficiency, the operation mode, climate and weather, and even the occupants' awareness and sensitiveness to the price of energy. Of these factors, some are changeable and are common for all the buildings including both green buildings and conventional buildings. In our case, we basically focus on two key points that we can make use of in reducing the energy consumption:

(1) Use ***distributed*** and dynamic energy monitoring and policy controls instead of the conventional centralized control (like HVAC) to adjust the energy consumption;

(2) Involve occupants' ***awareness*** and online active ***participation*** into the energy-saving policy decision and implementation process.

To achieve these goals, in our multi-disciplinary project, we use the latest information technologies such as mobile smart phone with location service, distributed control, and cloud computing to actively involve the occupants in the energy-saving process. Energy-saving policies from multiple sources such as individuals and organizations are considered in an integrated policy framework in deciding the final energy saving strategies. We aim to create an energy-efficiency testbed that can be easily migrated to all kinds of buildings and achieve energy savings on a large scale. The major ideas and designs for our project are under experimentation in our testbed.

The rest of this paper is organized as follows. Section II describes the green building testbed we are experimenting with. Section III includes our major key ideas and the corresponding discussion. We discuss some related work in Section IV. Section V presents the conclusions and future work.

II. TESTBED DESCRIPTIONS

The testbed of our project is the Brauer Hall [2] in Washington University in Saint Louis which is a new green building housing the Department of Energy, Environment and Chemical Engineering (EECE) and has the latest in energy monitoring technology. It is a building with U. S. Green Building Council (USGBC) [3] LEED (Leadership in Energy

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and Environmental Design) "gold" certification [4]. It also received over 7 national awards for its green design features. Fig.1 shows the exterior of the building and an experimental online web page which displays the real-time energy consumption data for the building. So far, it is a centralized monitoring, display, and storage system without occupants' participation.

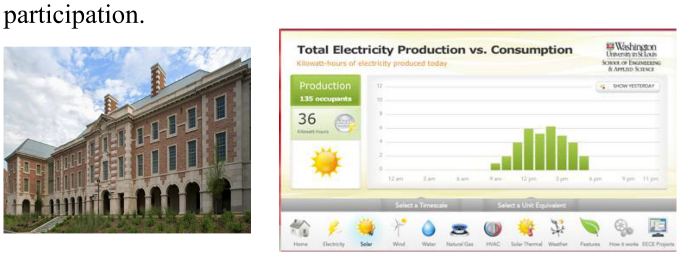

Fig. 1. Brauer Hall exterior and an online energy usage display webpage
http://buildingdashboard.com/clients/washu/seas/brauer/

There are several reasons why we picked Brauer Hall as the experimentation testbed for our ideas. First, Brauer Hall is a large office building which has a typical centrally controlled energy system installed, e.g., the centrally controlled energy-intense HVAC system. Second, there are multiple organizations like departments, floors, labs, rooms, and individuals residing in the building which makes it convenient for experimenting with energy-saving policies from multiple sources. For example, different labs may have their own energy-saving policies and when combined with the individual occupants' energy saving policies we need an appropriate mechanism to decide the final strategies. Third, we have been monitoring the energy consumption in this building for the last several years and we are familiar with the running mechanisms of the energy system. The devices that are already-installed will also be helpful in our experimentation. Finally, the occupants of the building are willing to participate in the experimental process since most of them are students, researchers, and faculty members in energy related areas.

III. Key Ideas and Designs

In this section, we present the details of our ideas and designs.

A. Overall Structure

There are multiple design components and aspects which interact with each other and form a complete structure of our project to fulfill the goals. We depict them in Fig. 2.

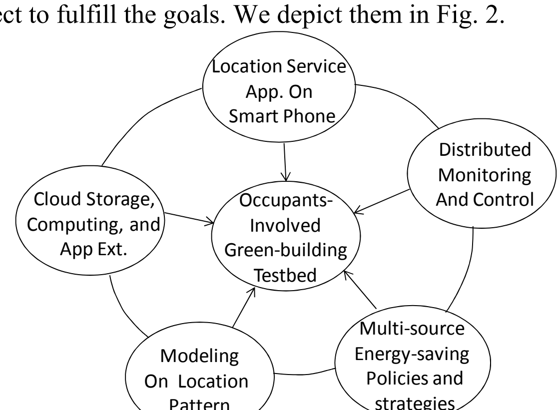

Fig. 2. Overall structure of our design with components and their interaction

The key design components include: energy monitoring, mobile devices based distributed remote control, location application on smart phone, multi-source energy-saving policies and strategies, cloud computing platform based data storage and application, and energy data modeling and strategy formation. We discuss each of these below.

B. Energy Monitoring

To achieve the goal, we will monitor the energy consumption not only for the whole building, but also in multiple granularities like departments, floors, labs, rooms and individuals. This requires us to install monitoring devices into different levels of the building-side grid containing breaker and panels. We currently use both the centrally located high-end commercial metering devices and the low-end panel and power strip level metering devices.

We also envision developing a future "Smart Everything" living building environment in which all the electric devices are smart and are able to not only record energy data and upload them automatically through IP network, but also enforce the control and energy-saving policy in real-time and support remote configuration. However, currently there is no one company or research organization that can provide all the products for different sensing and monitoring purposes. One underlying reason may be that this is still an emerging research area, and there are not enough hardware and software available. The standardization process and the broad acceptance of such devices in industry are also not as mature as those for Internet devices such as routers and switches.

Thus, we divide our research efforts into two basic categories. First, we try to integrate the energy sensing and monitoring with networking capability to create an automated data collection, storage, and display system. Our idea is to create a "Smart Box" as an extended box for different sensors and meters without data storage and networking capability. By doing this, we create a common protocol for different sensing and monitoring devices and let them work in a uniform and automated way. We are designing a preliminary suite of protocols and interfaces for interconnecting multiple smart boxes and providing the extensible Application Programming Interface (API) for further functional extension. The results of our work may possibly contribute to the IETF community by interacting with the IETF EMAN (Energy Management) working group. Of course, compatibility will be a big issue when creating such smart box, and we are starting from some common devices and extend the compatible list gradually.

Second, the energy-saving policy will be applied with automation. We need the operation plane (panel, breaker, power strips, etc.) to be also smart to control the on/off status of the circuits and appliances. These devices are with IP-based capability so that they can be configured and notified in real-time to accomplish the designated strategies and policies.

As shown in Fig. 3, existing panels are extended by external smart boxes with monitoring, networking, and control modules; existing sensors are extended by integrating external monitoring, networking and control modules; new smart panels aware of our new technologies come with monitoring, networking, and controlling modules; new smart appliances and loads come with the sensing modules for multiple sensing functionalities.

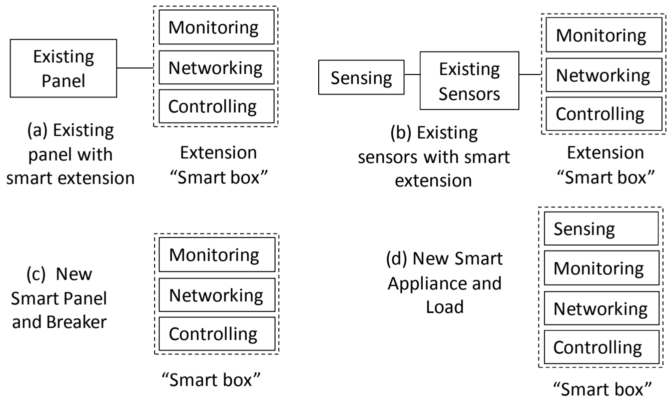

Fig. 3. Integration of existing devices through "smart box" extension

Obviously it will be a long way to go to achieve the above vision. However, we are starting the first step of the experiment and we believe this is an important step towards achieving the goals.

C. Smart Mobile Devices as Remote Controls

In the last several years, smart mobile devices have become very popular. Smart phone is one of the most common such mobile devices which generally have multiple networking interfaces such as 3G, WiFi, WiMAX, Bluetooth, and have multiple sensors including GPS navigation systems. Because of these various connectivity provisions and global accessibility to the Internet, mobile phones are suitable for use in any system that needs humans' online participation or interaction. More and more advanced and delicate sensors are being installed in such smart phones for specific functionalities. The "Internet of Things" [5] trend makes the cost even cheaper and the sensors are connected to the Internet everywhere and at all time.

Smart phones are ideal for monitoring, controlling, and managing the energy control systems remotely from anywhere at any time. After appropriate authentication and authorization, the occupants are permitted to modify and change their energy-saving policies online by interacting with the policy servers of their office and residential buildings. Such design allows dynamic changes to the energy-saving policies and offers better flexibility to the occupants. It can be a good complement to the general policy decision process based on the modeling results. Such an "app" can be easily developed for the smart phone based on web technology.

D. Mobile Device Location-Based Automatic Control

Almost all phones can determine their location by referring to signal strengths from various transmission towers. Newer smart phones can do so much more precisely with the embedded GPS systems in them. We use this location information in designing automatic control policies that can turn on/turn off energy consuming devices at home or office depending upon the location and direction of movement of the user. By doing so, a dynamic and flexible policy can be applied which satisfies the user's preferences for energy saving and comfort. An "App" on the device can automatically enforce these desired policies.

With the help of the location-aware mobile devices, these dynamic adjustment policies could also enable the cooperation and interaction among different buildings. For example, when the location detection daemon on the user's smart phone detects that the user has moved out of a threshold distance range from his home building and is moving into a threshold distance range of his office building, then a message is sent to a centralized server to trigger the policy control process. The office building room owned by the user will start pre-heating/cooling to prepare a user-customized or optimized working environment, while the message also triggers the home building to transit into an energy-saving mode.

E. Multi-source Energy-saving Policies Hierarchy

In a real environment, different parts of an organization, such as campus, building, department, and labs may be in charge of different components of a building. Each of these may have different policies and requirements that need to be taken care of in controlling the energy consumption. Even in a single home building, locations of multiple family members and their preferences need to be taken into account. Therefore, in the location based automatic control discussed above, we add policies coming from these levels of control hierarchy.

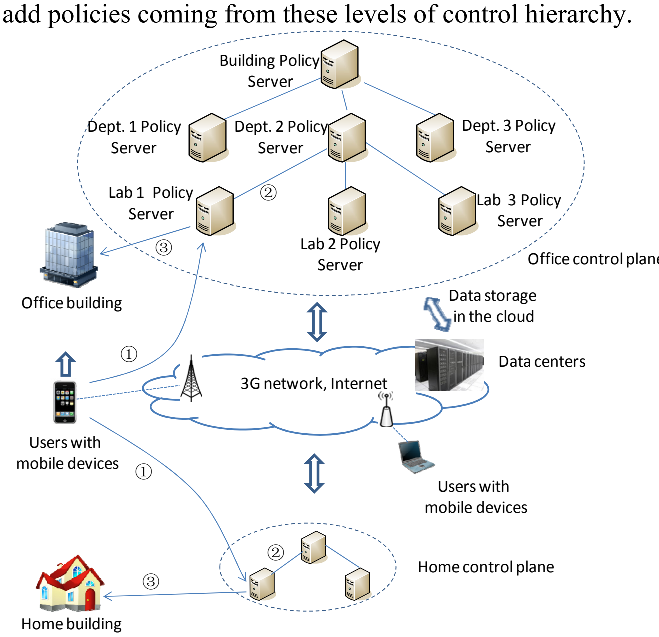

Fig. 4. Example dynamic multi-source energy-saving policy adjustment by the mobile devices

Fig. 4 shows an example of the policy hierarchy. As shown, there may be a tree-like structure for the building control plane in which there are policy servers enforcing the energy-saving policies covering different levels. This also applies to the residential buildings in which the tree structure may be relatively simple. The mobile users can be connected into the Internet through smart phone, tablet, or even laptop with WiFi connections. In the example shown in Fig. 4, the mobile smart phone holder leaves the home building and walks towards his office building. The movement and location changes will trigger the policy servers to adjust the energy-saving policies for both buildings accordingly. The action steps are denoted as "①②③" in the figure.

As a part of our research on next generation Internet [6]-[9] as well as the policy-oriented Internet architecture [10], we have experimented with several policy based control schemes. Our previous work also includes a lot of contributions to WiMAX [11]-[14] - one of the popular 4G wireless technologies. We plan to apply similar ides to the building and community environments. In particular, each control region can be defined as a "realm" [6][9][15] which is managed by a realm manager (also a policy server in our building testbed). Energy control policies may span multiple realms and sometime conflicts may have to be resolved. Such experiments are currently under way.

F. Cloud Computing and Storage

Cloud computing has become very promising in the last few years. We have two basic kinds of jobs which need the cloud-computing platform: (1) The cloud-based data storage, and (2) the cloud-based modeling and analysis computation. Actually, as part of our current work, we have a "Green Cup" competitions (for student dormitories) [16] in which the electricity consumption in several dormitory buildings were monitored and the logged data were stored into the Google App Engine which allowed the users to view their current usage in real time and how they were doing compared to the others. This successful experience proves the soundness of the idea, and we are expanding the simple application and to build a more powerful and complete application on it.

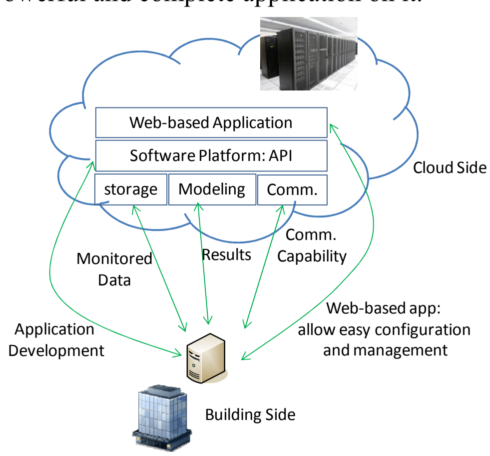

Fig. 5. Cloud computing components and interaction with the building side servers

We have a preliminary design of how to integrate the testbed into the cloud computing platform. As shown in Fig. 5, the cloud provides the basic data storage and retrieval service for the logged building energy consumption data. Computation-intense modeling and analysis jobs will be mostly done in the cloud. The communication layer provides configurability, reliability, and security for the network communication between the cloud and the client. The middle layer in Fig. 5 is for cloud application development by using the open API provided by the cloud provider such as Google App Engine. The reason we incorporate this layer in our design is that it can alleviate the overhead to develop the cloud application and accelerate our application development and deployment process. It also becomes much easier to integrate other services using the same platform (such as authentication services, email services and user interfaces) to the application on demand and make the development of a cloud application a less complicated task.

The top layer is the application layer. We are researching and developing a user-friendly prototype web-based user interface and application for the building environment, which can be easily configured and managed by the remote client.

G. Energy Data Modeling, and Strategies/Policies Formation

The basic idea of modeling in our testbed is to collect the data from various sensors and meters, correlate the data, and work out the correct energy-saving strategies or policies. The modeling will consist of the following steps:

(1) Use multiple data processing and statistical methods to find the correlation among different variables and measure how they can impact the power and energy consumption including seasonality, etc. For example, we use multiple parameter correlation, multiple linear regression, multiple polynomial regression, response surface analysis, principal component analysis, 2^K fractional factorial and full factorial designs and analysis. Occupants' location pattern modeling is also an important item for modeling. Specific intense energy consuming subsystem such as HVAC, lighting, and water provisioning sub-systems maybe studied individually to form better models.

(2) Try the above modeling methods for different types of buildings such as small office buildings, dormitory buildings, residential houses, and apartment buildings. In our preliminary work, we noticed that these building types have different control strategies. For example, office buildings (at least in the university) are never completely empty and so turning off air-conditioning is not viable.

(3) According to the modeling results, develop complete algorithms and processes to find the principal factors that affect the energy consumption most and the factors that can be changed according to a set of policies. The final end results of this step will be a workable goal and suggested energy-saving principles and rules for multiple granularities. Note that the human comfort and health factors measured by the qualitative and quantitative metrics will also be included as a part of the factors that can be used in deciding the energy-saving policies.

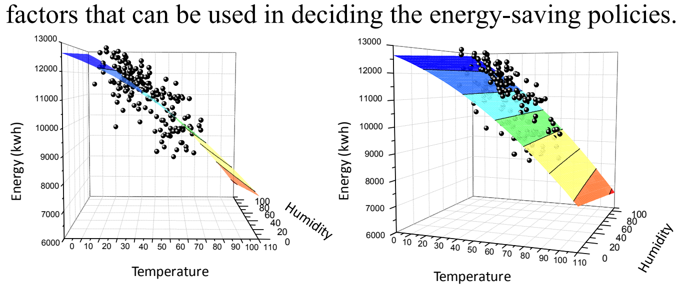

Fig. 6. Multiple polynomial regression results of daily energy consumption as a function of outdoor temperature and humidity in Brauer Hall (two views in different angles)

We have done some preliminary modeling and analysis based on the energy consumption and the outdoor weather data we collected during a six-month period for the Brauer Hall. As a first step, for the office building Brauer Hall specifically, we tried to find the underlying correlation among several simple involved factors such as energy consumption, and outdoor temperature and humidity for the building. Some of the results are shown in Fig. 6.

Preliminary data analysis showed little correlation between total electricity consumption and weather conditions when we do an hourly sampling rate analysis. But when we do monthly average over a longer period of time, the results do show some seasonality among the different months. Such results are reflected in Fig. 6 in which the multiple polynomial regression model approximately matches the overall energy consumption trend. We expect higher correlation and more conspicuous seasonality for small-sized office buildings and residential buildings. We need different regression models for different types due to the significant difference between buildings regarding the factors that contribute to the total daily energy consumption. More evaluation and modeling work are undergoing, and we will carry out systematic modeling for different types of buildings.

IV. Related Work

Due to the multi-disciplinary essence of the research topic, the related work covers a range of different areas. We discuss a few of them briefly in this section.

First related area is the building energy simulation tools. Actually a lot of them are available and broadly used in the building construction process. One of the representative tools is EnergyPlus [18] which is very widely used in many countries. A complete list of such tools can be found from the website [19].

Second area is the climate effect models research in which a lot of existing work is about the relationship between energy and climate factors [20]-[27]. However, most of these are based on theoretical thermal calculations and simulations and very few of them are using the actual building energy data and research on how to reduce the energy consumption by incorporating occupants' participation.

Third area is the application of Wireless Sensor Network technologies into the building environment and experiments on a specific subsystem like lighting and thermostat [28]-[39]. Wireless Sensor Networks were designed for other purposes but they are able to provide a good complement to other sensing and metering technologies in building environment.

Last related category lies in the information and computer science technologies. The iPhone, Android, and Windows Phones provide similar open platforms for smart phone developers to develop versatile smart phone applications. Multiple sensors including GPS sensor can be used by the applications. However, so far there are not many wide-scale applications on building environment energy auditing and control. Cloud computing [40] certainly is a very hot topic which is one of the key aspects related to our research.

Washington University also has a dedicated sustainability office [41] administrating university-wide green and energy efficiency efforts. Multiple competitions were organized on campus to bring the issue to the public concern. Typical examples are the "Green Cup" [16] competitions among several undergraduate student dormitory buildings, and the "Green Lab Initiative" [17] in reducing energy consumption in research labs. These efforts also offer a good experimental platform for our project in the future.

V. Conclusions and Future Work

In this paper, we presented a novel framework to incorporate the occupants' awareness and participation into the efforts of reducing energy consumption in a green and smart building testbed. Multiple advanced information and networking technologies can be used and applied to the topic. By these advanced technologies, we aim to change the current centrally controlled energy systems in large office buildings and create a distributed control paradigm to enable all the occupants to monitor and change their energy-saving policy in real time. The current project is still in its starting process. We've already done a series of data analysis over our testbed. Our next step is to use the modeling results and our new design ideas to implement and test it in our testbed. By cooperating with the university-wide sustainability office, we hope to apply our idea in a broad range and involve the whole community into the building energy-efficiency efforts.

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VII. Biographies

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