Nine Lessons Learned From a Green Building Testbed: a Networking and Energy Efficiency Perspective

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Abstract—**Buildings are significant contributors to global energy consumption and their energy efficiency is an important issue for future world sustainability. In our project, we built an energy efficiency research testbed in a USGBC (United States Green Building Council) LEED (Leadership in Energy and Environmental Design) "gold" certificated green building. We monitored the energy consumption and studied the recorded consumption data. In this paper, from a combined networking and energy efficiency perspective, we summarize the major 9 lessons we learned from the testbed and discuss what they mean for the future intelligent building designs and operation. We further broaden the scope to a series of locally inter-connected intelligent buildings with both energy consumption and renewable energy generating capability and study the issues in a microgrid scale.**

Keywords- green buildings; energy efficiency; networking; microgrid; energy proportionality; sustainability

I. Introduction

The problem of energy consumption in building environments has been identified and investigated in many existing research efforts. One of them is described in the report [1] which gives approximate numbers and percentages that the building environments contribute to the total energy consumption in the United States. Specifically, it shows that buildings are responsible for almost 40% of the total energy consumption and 70% of total electricity consumption in the United States. They also contribute a huge part of total carbon emission which is directly related to the global climate and sustainability issues. Given the huge consumption numbers and the close relationship between human activities and building environments, it is very meaningful and necessary to study the energy consumption patterns in the building environments to research and look for potential methods to improve energy efficiency, reduce costs, and introduce effective operation and automation.

Hence, as discussed in our previous papers [2, 3], we built an energy efficiency testbed in a USGBC LEED "gold" certificated green building, which is a typical large office green building. It holds multiple departments and includes offices, labs, classrooms and conference rooms. It has adopted a series of "green" and sustainable designs and measures including more local material usage, advanced insulation design, rainwater collection in cistern, and renewable energy generators such as vertical axis wind turbines and solar panels.

We monitored the energy consumption of the building for a period of more than one year. Some typical data related to electrical, heating, and cooling energy consumption, and some data about renewable energy generated by the in-building generators were recorded. We carried out detailed modeling and analysis of the collected data and tried to find out the underlying energy consuming patterns. After that, we plan to design and implement novel methods and technologies to reduce energy consumption and improve energy efficiency by using networking and computing technologies. Particularly, we plan to design and implement a new smart-phone based location-aware automated energy control system for the green building testbed to optimize energy efficiency. We also envision multiple buildings with such systems can network with each other to create coordination and synergy in a microgrid [4] or even larger scale. More details of the data analysis, our system design, and introduction of the related works can be found in our previous papers [2, 3].

In this article, our primary focus is to summarize the lessons we learned from the testbed and to find potential implications for future designs and implementations of more intelligent and energy-efficient buildings. It is worth mentioning that we are investigating from an energy efficiency perspective, though there can also be others related to building design, construction, material usage, and life-cycle sustainability. We also put the issue in a larger scale, i.e., in consumer-side power grid scale which is beyond a single building's scope. We believe that such perspective is important for a future world of smart grid.

The rest of this article is organized as follows. Section II is the detailed descriptions and discussions on the lessons we learned from the testbed. Section III is the conclusions.

II. Lessons Learned and Discussions

In this section, we discuss the detailed lessons we learned and summarize them as follows:

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A. Lesson #1: Centralized and fixed-pattern control leads to less flexibility and efficiency in conventional buildings

We investigated a series of buildings in our campus including our green building testbed and find that most of them incorporate centralized control designs for the subsystems such as HVAC (Heating, Ventilation, Air-conditioning, and Cooling), lighting, safety and security, and other appliances and subsystems. Multiple buildings share a centralized subsystem. Also, there is almost no interaction or synergy among these subsystems. For example, the running schedule of HVAC system usually does not work together with the safety and security system. It does not make use of recorded occupancy rate and activities information to adjust the running schedule, and the HVAC system almost consumes fixed amount of energy regardless of the real usage at different working hours. In other words, multiple subsystems run individually in a fixed pattern and there are very few or even no efforts to integrate them into a coherent system to gain better energy efficiency and realize real automated operation.

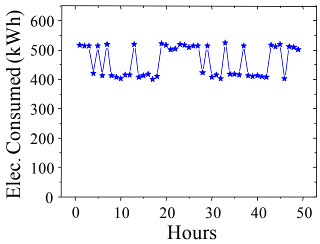

Figure 1. Total electrical energy consumption traces of 48 hours for our testbed building

Particularly, in our testbed, we recorded energy consumption data for almost one year and studied the energy consumption pattern. We studied both short-term and long-term correlations between two groups of parameters [3]: one is the energy consumption parameters such as electrical, heating, and cooling energy consumption; the other group includes environmental factors such as temperature and humidity. The data modeling and analysis results show very low correlations among these two groups of parameters. For example, some simple electricity consumption traces for 2 days are shown in Fig. 1. We can see that for these periods, the consumption toggles between two values and the patterns show little direct and clear correlation with the office and non-office hours. We discussed this with the electricity system maintaining technical staff of the building and found that the electricity provisioning systems offer relatively fixed pattern which includes redundant capacity and introduce little variation among different hours. We also find that this is not a special case, but a common method for most buildings in a campus.

To summarize the lesson we learn in this regard, we find that to enable the electricity consumption to be more correlated to the actual usage for better energy efficiency, we need to change the centralized control and fixed-pattern running mode into distributed control and dynamic switching among multiple running modes. Distributed control enables different building sections and subsystems to run as relatively independent systems and to adjust their own running policies and schedules to save energy based on actual usage or occupancy rate. Multiple running modes and dynamic switching among them make the energy provision match the actual demand actively, and the building system can be more flexible.

The economic potentials of doing this can be huge for several reasons. First, for single building, most of the energy waste in non-office or non-active hours can be avoided. Second, a large number of conventional buildings can benefit from it and the total economic benefits in a larger scale can be very significant. Third, distributed control and interaction bring more opportunities for various software and hardware vendors to work together, which potentially expedite the process of protocol standardization.

B. Lesson #2: Energy Harvesting cannot replace Energy Conservation

Energy harvesting means that the buildings are installed with renewable energy generators to provide alternative energy sources other than from the power grid. Typical energy harvesting facilities include solar panels, wind turbines, geo-thermal generators, biomass generators, etc. Energy conservation means that the building is installed with intelligent energy-saving devices or systems, or applied with specific policies to control the energy consumption and avoid waste. In the efforts of making buildings more efficient and reducing energy dependence to the outside power grid, these two mechanisms can usually collocate in a specific building.

Our testbed office building has solar panels and wind turbine on the roof. We found that the energy generated by the energy harvesting devices contributes less than 0.1% of the total energy consumption in this testbed building. Though the percentage can be a little bit higher for small and medium sized residential buildings, we find that it is not a good or cost-effective idea to just spend a lot of money installing as many solar panels as possible to cover the total energy consumption. Instead, we find that much of the energy in the building is wasted due to a series of reasons. For example, the centrally controlled and fixed running policy of the HVAC system leads to at least 50% of the total energy waste, especially in the non-office hours of weekdays and in the weekends. Also, lighting and other public electrical appliances in the buildings are mostly without intelligent and dynamical control mechanism which contributes to a part of the waste.

Comparing the two sides of energy harvesting and energy conservation, we find that given the current status of the energy efficiency in various buildings, it is reasonable to focus more on the energy conservation than energy harvesting efforts. There is significant room for energy conservation by reducing energy waste by applying some simple energy conservation policies or strategies. It is generally much cheaper than buying energy harvesting renewable energy generators to feed the gigantic demand and to cover the high energy consumption which includes a huge amount of wasted energy. In short, energy harvesting cannot replace energy conservation in our opinion.

C. Lesson #3: Building sections partitioning technology is necessary for building-level energy efficiency optimization

As shown in the data analysis results in our previous modeling and analysis work [3], for the building as a whole, it is difficult to set up strong correlation between its total energy consumption and the environmental factors and occupancy rates. The reason we find is that building is a very complex system, and its separate sections and subsystems may demonstrate very diverse energy consumption patterns and have different correlations with related factors, and hence demonstrate various rooms for potential improvements. If we sum up all the energy consumption data and study them as a total number, we may lose a lot of useful information.

Thus, we coin a term of "deep building partitioning" technology to reflect our idea that we may study building's subsections and subsystems separately. We can study the energy consumption of these systems and model their correlation patterns individually. It will enable us to know which sections or subsystems can be adjusted according to the actual weather condition and which sections or subsystems can be adjusted based on the real occupancy rates. Then we can apply networking and computing technologies to these subsystems to gain best results out of limited resources. For example, for the lighting subsystem, its real electricity consumption will be highly correlated with the occupancy rates in the building. Thus, we may apply related technologies to automatically turn off some or most of the devices during non-office hours or week-ends. Similarly, for HVAC systems, especially the small-sized HVAC systems for small and median resident buildings, their running schedules and strategies can be formed considering the weather conditions to achieve optimized energy consumption. Such ideas can be generalized to multiple types of buildings. Due to the diversity of buildings and various appliances in them, it is necessary to do such deep building partitioning based on each actual building before achieving optimized energy results for it. Generally, we divide this deep building partitioning technology into three key steps:

(1) **Partitioned energy monitoring**. Building subsystems and subsections are monitored separately and their energy consumption is logged for offline modeling to find their correlation patterns for further consideration.

(2) **Separate energy modeling and analysis**. The goal of this step is to find energy pattern for each subsystems and subsections that can potentially be adjusted to save energy.

(3) **Applying changes using networking and other technologies**. Based on the modeling and analysis results of the step (2), we will know which subsystems and subsections can achieve best energy saving if we apply limited networking devices. Then we can devise the strategies for each subsystem or subsection to achieve optimization for a whole building.

D. Lesson #4: Buildings should be designed and operated to be energy proportional

We know that buildings are complex systems, and it may be difficult to enable them to have simple and straightforward correlation with specific parameters. However, built upon the deep building partitioning technology, it is possible to enable the buildings to achieve best energy saving with limited resources. In other words, we may achieve "energy proportionality" to the actual usage or occupancy.

There are two incentives to achieve this goal. First, energy consumption in buildings is a billion-dollar problem and making them more energy efficient is of significant economic meaning as well as social implications in terms of promoting global sustainability. Second, by implementing the idea using networking and computing technologies, the buildings can be turned smarter, and will serve people better and provide more advanced features that are not possible before.

To achieve such energy proportionality, we propose to learn from the history of computer development. The original computers were designed consuming constant amount of energy regardless of whether they were busy or idle, which caused significant waste of energy. Nowadays, the computers, especially the CPUs inside are designed to be energy proportional and consume significantly less energy when they are not busy. Thus, we propose to import this concept to the building environment. Given the significant amount of energy consumed in the building environment, if we are able to create such energy proportional buildings and apply the related ideas to a wide range, then we can potentially save billions of dollars. Thus, such technologies can be of both technical merits and economic impacts to the society.

We study the key methods and technologies in energy proportional computers. Particularly, we find that the following two features of energy proportional computers [6] can be imitated in buildings to enable an energy proportional building.

(1) **Identifying the major energy-consuming components in buildings**. In computers, the major energy-consuming components are CPUs, memory units, etc. Making them energy proportional is an important step to enable an energy proportional computer. Similarly, for energy-proportional buildings, we need to identify the major energy-consuming subsystems and subsections, and adjust and change their running policies or strategies to make it energy proportional.

(2) **Enabling the key components to work in multiple active running modes with different energy-consuming rates**. One of the key technologies of the CPUs in energy proportional computers is that it allows the CPUs to be active but working in different intensity and hence consuming less energy than conventional CPUs. Similarly in the building environment, after we identify the key components, we can apply networking and other computing technologies to allow the key components to work in a smarter way and to be able to switch between multiple active running modes according to the real occupancy rates or usage conditions.

E. Lesson #5: Enabling multi-scale (organization or user-level) energy proportionality using networking and computing technologies

A more aggressive goal than creating energy proportional buildings is to create multi-scale energy proportionality. It means that the energy proportional perspective can be realized at multiple granularities. In other words, by applying a series of networking and computing technologies, we may be able to allow not only building level energy proportionality, but energy proportionality for any scale, for example, a single user or a specific organization.

A typical example to achieve energy proportionality for a single user is applying networking technology based on smart phone with location-sensor to create a platform allowing users to automatically and dynamically control or adjust their own energy usage policy and profile across multiple buildings [2] in real time or according to their current locations. By doing this, users will be able to consume optimized amount of energy according to their real demand and usage. The individual user may have to follow the energy policies enforced or required by a larger affiliated organization such as a company or department in university. Hence, as long as individual users in a specific organization use applications like this, the energy proportionality for this organization can be achieved. Similar policy structure and policy enforcement can be applied to many other scales to achieve multi-level energy efficiency optimization goals. The details of how such energy saving policies can be negotiated and formed can be found in our previous system framework design paper [2]. A simple comparison of the concepts of energy proportionality in multiple granularities can be found in Table I.

Table I: Comparison of energy proportionality concepts in multiple granularities.

	Computer	Building	User	Organization
Identifying Major components	CPU, RAM, etc.	Key subsystems such as HVAC or electrical appliances	All components under the user's control	All components under the organization's automatic control
Key idea	Dynamic running mode changes	Networked monitoring and control; Real time dynamic energy policy adjustment; Location based mode switching and control		
Key enabling technologies	1. Multiple active running modes for CPU	1. Apply active running modes to key appliances	1. Direct monitoring and control	1. Multi-scale energy policies enforcement under its realm
	2. Wide energy adjustment range	2. Allow dynamic control based on real usage	2. Dynamical adjustment based on location	2. Aggregate the building and user energy proportionality

There are several major benefits of realizing such multi-scale energy proportionality. The first one is the economic benefit. Apparently, a huge amount of energy waste can be avoided in multiple scales, and the total effects can be accumulated to a significantly large amount of energy savings for a specific region or country. The second benefit is that we can achieve better organization-based control and better representation of their existence. In other words, these organizations can design and enforce their own group energy-consuming policies and achieve optimized energy usage in their own territories. They can also play more important roles as high-level energy policy related strategy makers.

F. Lesson #6: Actively involving occupants and stakeholders' awareness and participation can make a huge difference

With the proposed idea of involving smart mobile location based network control, we can greatly promote the broad awareness and participation in the energy efficiency efforts. People's awareness of the energy consumption issue and their behavior inside the buildings has huge impacts on the energy efficiency of the whole building. All the automated systems using advanced technologies work around and for the people or occupants. Neglect or unfamiliarity to the systems may lead to low effectiveness and efficiency of the advanced intelligent systems in the buildings. For example, most of people may not care too much about the energy consumption in their work places while on the contrary they may care more at their own homes. If the intelligent technology is too complicated for them to use, there will be a high possibility that the systems will be under- or unutilized. We summarize the following key factors that can influence the adoption of intelligent systems and hence energy efficiency inside buildings.

- **Awareness**. The occupants or the building owners may not know in detail how much energy they consume and how it is consumed. Hence, creating real-time data display applications for online access can make the stakeholders aware of the energy consumption before improvement measures are taken. A study by Oregon Sustainability Center shows that the commercial buildings' energy consumption can generally be reduced by 10% if occupants are provided the energy usage information.

- **Sensitiveness**. Building stakeholders may have different degrees of sensitivity to the energy consumption issues. Methods associating such sensitiveness with the economic benefits may motivate them to take measures to actively interact with the intelligent systems in the buildings to improve the energy efficiency and save costs. Another study shows that providing users with in-home display of their real-time energy usage helps reduce the energy consumption by 15%. It demonstrates that combining the awareness and sensitiveness has a great potential in saving energy.

- **Participation**. Conventional buildings involve very little participation from the general population hence the energy policy and decision are out of the control of most of them. Intelligent systems with convenient methods encouraging the stakeholders' active participation in the energy saving process can be very effective and fruitful. For example, smart phone applications [2] can be used to encourage such participation. Two green efforts of "Green Cup" energy-saving competition and "Green Lab Initiative" in Washington University have confirmed this.

To summarize, if we can actively involve occupants and stakeholders' awareness, sensitiveness, and participation for the energy saving efforts through multiple policies, facilities, and activities, we can make huge difference in terms of reducing energy waste and improving energy efficiency for both individuals and organizational groups in multiple scales. It also means a lot for social sustainability.

G. Lesson#7: Integrating social behavior and activities in sustainable education tools may have a huge impact

Energy consumption is an issue not only about cost but also about environmental sustainability. Hence, saving energy and introducing intelligence into buildings also have social implications. Besides the long-term cost benefits, introducing intelligent building designs and certificates may help the stakeholders improve their public images in term of social roles and responsibilities. Future social network based applications involving energy saving profiles may help the energy efficiency efforts in a much larger scale and potentially have profound impacts.

To be more specific, we propose to take advantage of the smart phone and location service based idea [2] by designing and implementing a sustainability education tool with social network plugin (such as Facebook, Twitter, and Google plus) on the top of the smart-phone based energy monitoring and control application. A simple illustration of the concept is in Fig. 2. By creating a bridge between the energy monitoring/control modules and the social network module on the smart phone platform, and facilitating their interaction, we may be able to create extra incentives and motivations for every common energy user to know the energy consumption issue and participate in the global sustainability efforts, taking advantage of the fast and effective information propagation of the social networking applications. For example, a specific smart phone holder may post their energy profiles and energy-saving data through social network applications, influence other people's energy consumption habits, propagate good energy and sustainability concepts, and encourage everyone to participate in this global effort. Online social sustainability related activities may also benefit from such platform.

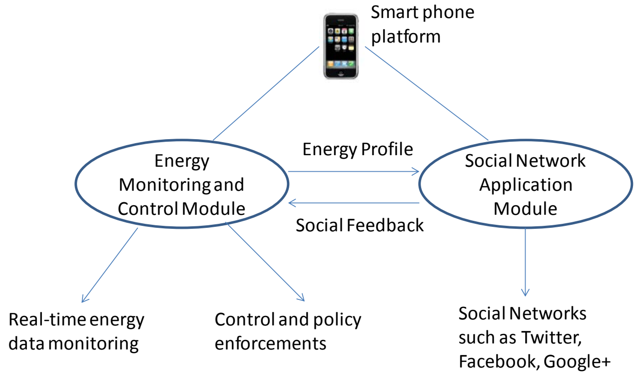

Figure 2. Bridging energy monitoring and control with social network applications

There are two major forms that we can use the tool for wide-scale sustainability education. The first is through online social network dissemination and propagation as discussed above. By doing this, sustainability education can be carried out in every occupant's real everyday life and their social behavior can affect those who are in their social network connections. The second form is through online or offline sustainability related competitions or social activities. The effects of competitions can be magnified by social media and everyone's social behavior. The proposed idea builds upon our previous successful experience, and the new socialized idea may achieve even broader impacts. The potential for commercial applications is expected to be big if the proposed goals are realized and turned into real commercial products.

H. Lesson #8: Create synergy among multiple intelligent buildings to enable optimization in a larger (microgrid) scale

The importance of energy independence at multiple scales has been proven in the history of massive electricity blackouts internationally and their corresponding costs. The concept of microgrid [4] is to promote such energy independence. It promotes generating energy especially renewable energy (such as solar, wind, fuel cells, etc.) as near consumers as possible in a small-scale geographic area. The distributed energy generators provide a reliable and inexpensive alternative to the local consumers especially during peak time or even in the case of electricity blackout. The costs and risks of long-distance energy transmission and delivery are also reduced. Microgrids are very friendly to environmental sustainability due to the savings they introduce and the renewable energy generation they promote. Currently, microgrid concept is still in its incubation stage, and it is mostly restricted to the energy backup sources in small scale and lacks mechanisms and designs for smart dynamic allocation and scheduling among multiple sources.

For sustainability, we envision that in the future, buildings will not only act as sole consumers of the power grid, they will also become sources of energy, given the fact that more and more new buildings are now being installed with renewable energy generators such as solar panels, wind turbines, and biofuel-based energy generators. "Local generation, local consumption" policies can significantly reduce the energy dependence of the grids from different scales. By using smart-phones and cloud computing technologies to allow microgrids to dynamically monitor, schedule, and allocate generation and consumption capacities, significant amounts of power transmission loss can be saved. With such optimization, peak energy demands can be reduced, potentially saving a lot of infrastructure investment in the construction of power plants. In short, it is of high significance in terms of sustainability to enable innovations at microgrid scale.

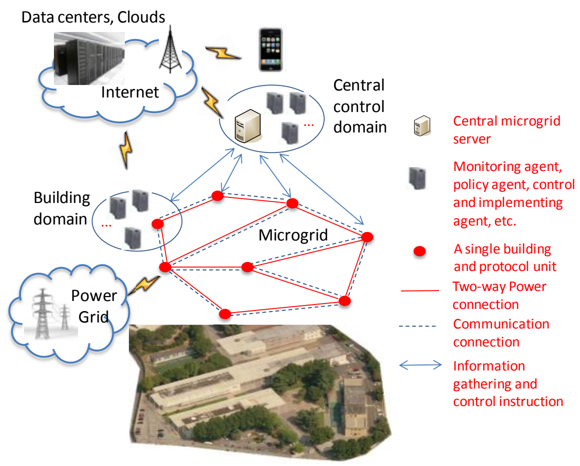

Figure 3. A simple illustration of the multiple building microgrid networking and control structure.

Hence, from a technical perspective, we identify several key components for possible innovations in this theme:

(1) Network the buildings and create a central knowledge plane;

(2) Optimized allocation and distribution of generated energy;

(3) Smart prediction and balanced energy delivery.

A conceptual illustration of this scenario is shown in Fig. 3. We propose to network neighboring buildings in a microgrid such that each building becomes an "Autonomous System" (AS) monitoring its own energy and interchanging real-time consumption and generation capacity information with neighboring buildings as well as a central knowledge server. Each building has a monitoring agent, a policy agent, an interaction agent, and a control system implementing agents that network together to achieve multiple functional optimizations. It virtually creates a central "knowledge plane" in a central server for the microgrid which is in charge of communicating with the agents of multiple buildings to collect real time information through distributed networking and dynamic scheduling of the energy capacity of the microgrid. Individual buildings work in a distributed manner as well as interact with the central server without creating "single-point-of-failure" even when the central server is down. In Fig. 3, the top part is a network topology corresponding to the bottom physical building distribution. We can see that each building actually is a networked domain or an "autonomous system" which hides the inside networking structure to the outside. Every building is actually connected to the grid so even in case of faults or networking failure the building can continue functioning without any interruption. The central microgrid server and the agents in all the buildings can interactively work with cloud computing services for storage and application without introducing significant initial construction and maintenance costs.

On top of the networking topology and protocol problems, the energy efficiency optimization problem can be formalized and modeled as a computing optimization problem. Given all the constraints, we can use ***linear programming*** to solve such optimization problems ***in polynomial time***.

I. Lesson #9: Synthesizing three dimensions related to the building concepts for future buildings

There are multiple dimensions of features relating to the concept of intelligent buildings depending on the major design goals. The three most important ones are:

(1) Communication capability and intelligence;

(2) Energy generation and conservation capability;

(3) Material, physical design, environment friendliness, and sustainability.

These are shown in Fig. 4. If a building is designed and equipped with multiple intelligent technologies, then it is good in the first dimension. The general "intelligent building" concept falls in this category. Similarly, "net-zero energy buildings" [5] mostly focus more on the second dimension which is energy generation and conservation capability for the building to provide relatively stricter and more aggressive energy performance on an annual basis. Lastly, "green buildings" focus on the third dimension using more environment friendly materials and designs to support the global sustainability and environment-protection call.

In our opinion, in terms of global sustainability and energy efficiency, future building designs should do better jobs in all three dimensions. In other words, all three dimensions should be synthesized in a single building, not only by design and construction, but also by the real operation of energy-conservation and generation functional facilities, or the intelligent and networking systems installed and run in the building. For example, an intermediate design combining some of the three individual dimensions mentioned above is called "intelligent or bright and green converged buildings" which integrate features of dimensions (1) and (3).

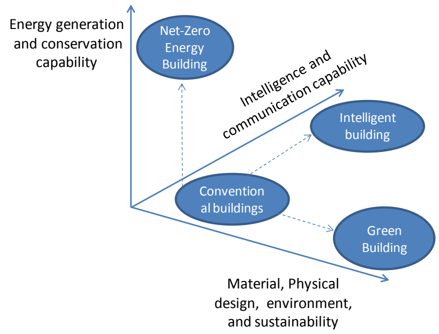

Figure 4. Three dimensions of features related to building concept

III. Conclusions

Buildings are significant global energy consumption sources and their energy efficiency is important for future sustainability. In this paper, we presented our findings in analyzing a green building testbed in a LEED (Leadership in Energy and Environmental Design) "gold" certificate building for energy efficiency research. In a combined networking and energy efficiency perspective, we summarize the major 9 lessons we learned from the testbed and discussed what they mean for the future intelligent building designs and operation.

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