A Survey of Energy Efficiency in Buildings and Microgrids using Networking Technologies

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***Abstract*—Intelligent buildings and microgrids are important parts of the future smart grid. The adoption and development process of the intelligent buildings has been slow. There are multiple technical and non-technical reasons. However, two recent trends have accelerated the research and application of the technologies related to this area. First, skyrocketing energy price and the global need for reducing fossil oil consumption for environmental sustainability combined with the fact that buildings are a significant source of energy consumption, making buildings intelligent and energy efficient will have huge impacts on the total CO_2 emission and hence global sustainability. Second, rapid popularity and maturation of mobile smart phone technology and Internet technologies like cloud computing enable smart phone holders to be aware of their energy consumption and participate in controlling and running their buildings with seamless Internet connections. Cloud computing enables active interactions between the consumer-side (buildings) and the provider-side (smart grids). Hence, combining energy efficiency and networking perspectives, in this paper, we investigate the key research topics through a broad survey on the latest developments in intelligent buildings and our vision of microgrids formed by such buildings. Our aim is to draw an overall picture of the current research and potential future applications. Moreover, we further summarize and discuss in detail a series of key issues and trends that can potentially motivate and impact the adoption and development of the intelligent building and microgrid technologies in the near future.**

***Index Terms*—Intelligent buildings, energy efficiency, microgrids, building automation, sustainability, smart homes, smart phones, cloud computing, Internet.**

I. INTRODUCTION

THE abundant benefits of applying communications and networking technologies into the future smart grid have been broadly identified. Many interesting new research opportunities, challenges, and research topics emerge, as comprehensively discussed in the book [119].

Intelligent buildings and microgrids are important parts of the future smart grid. Energy efficiency in these buildings and microgrids usually refers to reducing the amount of energy required to provide specific products and services by adopting novel technologies or methods. For example, existing work includes improving the insulation of the building to reduce heating and cooling energy consumption, using fluorescent lights or natural lights to reduce energy usage while maintaining the same level of illumination, designing the buildings and subsystems according to their physical location and climate zones, and improving the energy conversion process to reduce energy waste during the process. Apparently, energy efficiency for buildings and microgrids can be a complex issue and many experts and researchers have been working on it from their own perspectives, and some related work can be found in the reference [114]. For example, a building designer may be concerned about the inner structure that could affect the energy flow; a physicist or HVAC (Heating, Ventilation and Air Conditioning) expert may be interested in the thermal effects due to the physical structure of the buildings; the electrical and computer engineering experts may focus on deploying smart meters and computer networking systems to provide automation and collect data for further analysis and building retrofit.

In this paper, with a networking perspective, we define the energy efficiency for buildings and microgrids [21], [22], [95]–[110] as efforts not only using a specific technology or method, but a series of methods treating the individual building or microgrid as an integrated system, and applying related networking and control technologies to enable it to reduce unnecessary energy usage and to achieve a large-scale energy proportionality. Specifically, we focus on the energy efficiency issue not only in intelligent buildings but also microgrids formed by multiple locally-distributed such buildings.

An intelligent building is generally defined as a building integrated with a building automation system (BAS) [2] which provides functionalities such as computerized, intelligent, and networked distributed control to monitor and control the HVAC, lighting, safety and security, and other appliances while reducing energy consumption and maintenance costs. It also provides its occupants with a flexible, comfortable, secure, and productive environment. The intelligent building concept has a relatively long history since the development and expansion of computer and networking and communication technologies in 1980's [1], [64]. Initially, it attracted a lot of attention from both academia and industry, and a number of researchers expressed their exciting vision about future intelligent buildings. However, the reality fell short and it turned out to be a relatively long and slow process, especially in the area of smart building controls and automation. There are many reasons behind this. First, the key in-building intelligent systems like energy management and control systems (EMCS) for building automation have been underutilized except for some large-sized buildings. Even in the buildings with such systems, only a fraction of the possible EMCS functionality is utilized. Second, it is about the cost. Generally, the initial cost of an intelligent building is higher than a conventional

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building and the benefits are mostly not visible at the stage of construction. Third, individual subsystems inside intelligent buildings are usually provided and maintained by different software or hardware vendors and they are often developed as proprietary products. The lack of standardization of the protocols prevents the necessary interoperability and interactions among the subsystems which are important to create a truly coherent intelligent building. Fourth, many subsystems such as building monitoring and control, elevator monitoring, and security systems are under separate construction contracts and they usually install and use their own communication systems. Better interconnection and integration of these systems without duplication is necessary to realize a fully intelligent building.

Because of all these reasons the deployment rate of intelligent buildings has been slower than initially envisioned. However, two recent developments and trends have reactivated this important and promising topic, and accelerated the research and application of related technologies. These are as follows:

1) **Skyrocketing Energy Prices and the Need for Sustainability:** The energy crisis has made us rethink our previous energy usage of the last several decades. The global warming alarm and huge CO_2 emission have also alerted us to look for a new sustainable energy pathway to the future. **Renewable energy** sources such as solar, wind, and geothermal energy are more and more promising in many situations in terms of global sustainability. Buildings, as a significant source of the total human energy consumption, become a meaningful research and application arena not only for saving energy and reducing operation cost but also for making everyone's life better since we all live and work in various buildings most of our lifetime.
2) **Rapid Popularity and Maturation of Smart Phones Technology and Internet Technologies like Cloud Computing:** In recent years, the world is experiencing a dramatic change from the PC (Personal Computer) to mobile smart phone devices. The broad prevalence of various smart phones and PADs (personal access devices) are changing the users' habit and also creating more possibilities for the future. For example, using appropriate mobile applications on such devices, it is possible to make users aware of the running status of the building energy systems. Also it enables every smart phone holders to participate in the control and operation of intelligent buildings in a real-time distributed manner from anywhere due to the ubiquitous, seamless, and multi-interface mobile Internet connection. Moreover, Internet technologies like cloud computing [85] are making it possible for more advanced interactions between energy consuming buildings (buildings can also be a source of energy using renewable energy generators) and the smart grid or microgrids. By interconnecting multiple intelligent buildings in a local microgrid and by interacting with the external grids, energy efficiency optimization and automation can be achieved beyond a single building.

In this new context, we investigate the key research topics through a broad survey of the latest development status of intelligent buildings and microgrids formed by multiple such buildings. We aim to draw an overall picture of the current research and potential future applications, especially in terms of energy efficiency and the mobile/cloud computing enabled Internet. In our opinion, combining these recent developments of the Internet and applying these to the area of intelligent buildings and microgrids has the potential to accelerate the deployment of intelligent buildings and to have a profound impact on global sustainability.

For the rest of the paper, we investigate the overall intelligent buildings framework and distinguish it from other related building concepts in Section II. In Section III, we review the key subsystems with a focus on the two issues of networking and energy efficiency. As a particular type of intelligent building, the intelligent residential buildings or smart home technologies are discussed in Section IV. In Section V, we give some examples and test cases on using networking technologies for buildings energy efficiency and compare them with other modeling and simulation work. In Section VI, we discuss an important trend towards the convergence of intelligent and green technologies. In Section VII, we study the research issues related to microgrids formed by multiple interconnected intelligent buildings. Other key issues and trends related to the topic of the paper are discussed in Section VIII. Finally, we conclude the paper in Section IX.

II. INTELLIGENT BUILDINGS: OVERALL FRAMEWORK

In this section, we investigate the overall framework for intelligent buildings and related subsystems. Note that in this section and the following Section III, our discussions are mostly based on the general large-sized office buildings. For home and residential buildings with some specific features and concerns, we discuss them in Section IV.

A. *Overall Framework*

To create an intelligent building, multiple stakeholders need to be involved. They include the building constructors, electrical system providers, HVAC providers, security system providers, control and management system software and hardware providers, and others for appliances like lighting and elevator systems, etc. If renewable energy generators are installed in the building, then the generators providers are also involved. The subsystems are usually from different providers with separate contracts. However, to create a truly intelligent building, integration among different systems is necessary to save cost and to create interactions and coordination among them to maximize efficiency.

Basically, we summarize the three key modules surrounding the intelligent building concept:

1) **Building Automation System (BAS):** It is responsible for the monitoring and control of multiple building subsystems such as building security and access, fire and life safety, etc.
2) **Building Energy Management and Grid Interaction System:** It is in charge of the energy-related operation and energy efficiency function such as energy generation, storage, metering, and systems monitoring. It

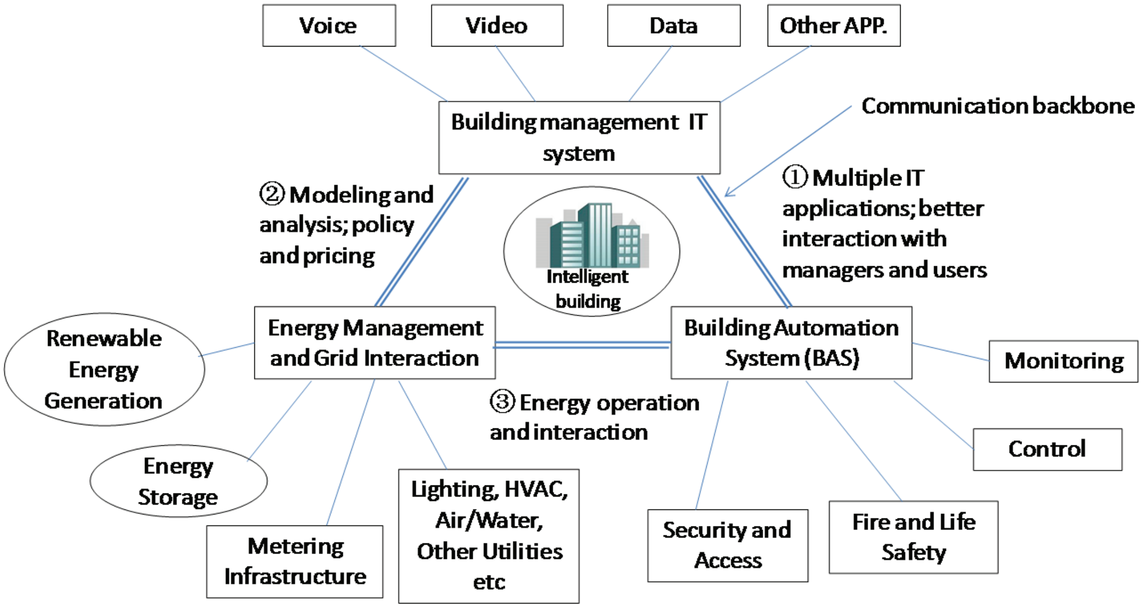


Fig. 1. Intelligent buildings and related subsystems.

is also in charge of the functional relationship to the outside smart power grid.

3) **Building Management Information Technology (IT) System:** It is a high-level management system built with multiple applications based on voice, video or other data services. These applications interact with the above two modules for better intelligent building functionalities and performance.

Note that each of the three key components has different focuses in the overall framework. Specifically, in the outer level of the Fig. 1, we can see that the BAS primarily focuses on the monitoring and control of multiple building subsystems such as fire and life-safety systems, building security and access systems, etc. It aims to optimize the performance of systems and reduce interference among different mechanical subsystems inside the building. The energy management and grid interaction module actually is in charge of the energy-related operation and energy efficiency function. For example, the lighting, HVAC, and various utilities are monitored by a smart metering infrastructure, and also renewable energy generators and energy storage systems which are connected to the grid. Consider a subsystem like HVAC, its operation may be monitored and controlled by the BAS but the energy-related function is fulfilled by the energy management and grid interaction module, hence one subsystem in the building may interact with other modules in the framework for different functionalities. In the top part of the Fig. 1, the building management IT system provides many applications using voice, video, and data services. These applications interact with BAS for better subsystems monitoring and control, and interact with energy management and grid interaction system for better decision and cost optimization.

These three components need to be integrated and need to cooperate well to fully harvest the benefits of an intelligent building, and further nurture interaction among multiple such buildings to form microgrids. To enable a true intelligent building, the three key modules are also needed to connect to each other through in-building integrated communication network backbone (usually using open communication protocols such as Internet Protocol, or IP [10]). The overall framework of these components and their interactions is illustrated in Fig. 1.

As shown in the figure, these components interact with each other to achieve various goals. Specifically, the BAS subsystem [2], denoted as 1 in Fig. 1, needs to connect and interact with the building management IT system to enable multiple voice, video, or data applications over the underlying BAS components. Multiple applications may better engage the building managers and users to be aware of the building current running status, and to control or tune the performance of the BAS. The building management IT system, shown as 2, also interact with the building energy management and grid interaction system to monitor and gather energy consumption data through smart metering system and store them for further modeling and analysis. The results can also be used to interact with the grid for energy pricing, or in-building energy usage policy related decision making processes through a series of algorithms and computation. Also, the energy infrastructure inside the building, such as renewable energy generation and local energy storage, need to interact with the outside smart grid to fulfill dynamic pricing and smart scheduling functionalities through the communication and networking technologies. BAS not only controls the automation of the building, it is also partly responsible for the operation of the energy systems in the building, i.e., the grid inside the building as indicated by 3. The policy and strategies formed by the IT management system are executed by the BAS system by working together with the energy infrastructure.

B. Relationship with Other Building Concepts

Currently, there are multiple types of building concepts depending on the specific design goals. For example, besides

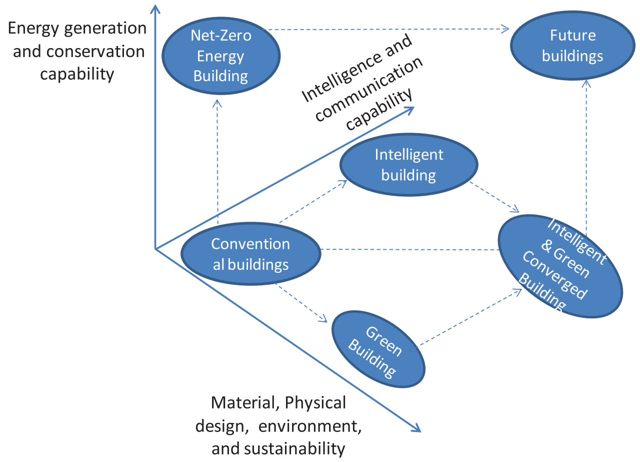


Fig. 2. Intelligent buildings and related building concepts: A 3D illustration.

intelligent buildings, there are “green buildings” [3], [4] and “Net-zero Energy Building” [5], [6]. It is important to distinguish them from each other. We categorize the design goals into three dimensions: (1) intelligence and communication capability; (2) energy generation and conservation capability; (3) material, physical design, environment, and sustainability. Green buildings are generally designed to be environment friendly for the whole building cycle from design, construction, running and operation, and maintenance to building renovation and demolition. Sustainability can be one of the key goals. For Net-zero Energy Buildings, however, the goal is to make the building supply its own energy by conservation and renewable energy generators in the building and achieve net-zero energy consumption and hence carbon emission on an annual basis. Though in some circumstances, there are overlaps among them, these three types of goals are roughly represented by the three types of building concepts. We depict their relationship in Fig. 2 as a 3D graph illustration in which each axis represents a goal. However, it is clear that for future buildings, we need to combine such goals and methods to apply more advanced and intelligent technologies in the whole building life-cycle. We need to maximize the building design and operation in each of these dimensions, and to make them comfortable, safe, healthy, energy-efficient, environment friendly, and smarter to match our multifold demands without sacrificing the environment or our future generations’ benefits.

III. INTELLIGENT BUILDINGS: KEY SUBSYSTEMS

In this section, we investigate and discuss several subsystems and key components in intelligent buildings.

A. *Integrated Communication Network and Building Management IT System*

The communication network inside the building and the building management IT systems are two key components.

1) *Integrated Communication Network*

Currently, building subsystems are usually covered by separate contracts and various vendors deploy their own communication networks separately. Devices of various vendors use different protocols and use translators to communicate with each other. This causes a lot of waste and makes it difficult to integrate. In other words, for a full intelligent building, integration of different subsystems through a consolidated common communication infrastructure is necessary. It can improve synergy and interaction among subsystems. This idea is shown in Fig. 3.

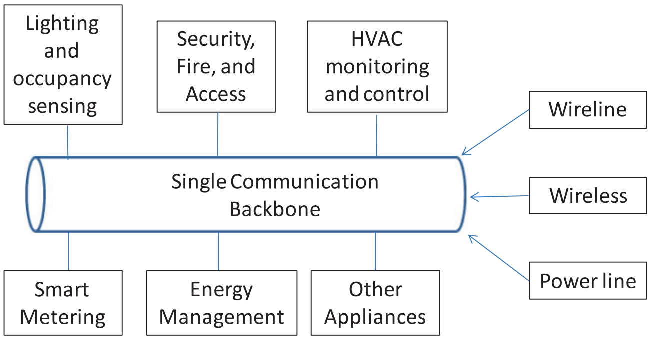


Fig. 3. Integrated communication system of intelligent buildings.

From communication technology perspective, currently there are multiple wireless and wired technologies and protocols. Depending on functions of the subsystems, suitable communication technologies may be used. For example, for security and fire safety systems, elevator and escalators, and health monitoring systems which are required to be very dependable, a highly reliable wired network backbone across the building is needed with backup power supply to ensure working even in unusual and hazardous situations. In comparison, less critical subsystems such as the networked lighting sensing system can use wireless networking technologies [7] with low-cost, easy deployment, and low-reliability but of great resilience to wired network failures and good energy efficiency. Similarly, in some applications where network cables are hard to deploy, power-line communications (PLC) technologies [8] may be used.

We now discuss some details of the communication technologies and their applications in the building environment.

- **Wireline Networking Technologies:** Wireline technologies constitute the backbone of the global Internet. From global scale to local scale, a lot of networking hardware such as routers, switches, and bridges, and software protocols across the whole OSI (Open Systems Interconnection) protocol stack [9] have been deployed. For buildings, it is reasonable and convenient to use LAN (Local Area Network) [10] technologies to build a high-speed consolidated backbone network infrastructure for integration of different subsystems. Multiple protocols across the whole OSI stack can run on such infrastructures. Specifically, widely-accepted TCP/IP protocols (Transmission Control Protocol/Internet Protocol) [10] can be deployed to transmit multiple types of data units defined by previous proprietary subsystems over a consolidated and common networking infrastructure. Multiple building-related applications can be further developed and built on top of TCP/IP to realize new features for intelligent buildings.

- **Wireless Networking Technologies:** Wireless technology has become popular in recent years. Examples include 3G/4G smart phones [11] based on iOS and Android, wireless sensor networks (WSN) [7], and the widely used WiFi (IEEE 802.11 standard [12]) technology which is a good complement to the in-building wireline communications. Other wireless technologies like Bluetooth [13], Ultra-Wide band (UWB) [14], etc. can also be deployed in some applications. High resilience and reconfigurability are the major features of the wireless networks. Typical examples include the intrusion alarm systems, patient movement detection and monitoring systems in hospital, some in-building voice and data communication systems, and some convenient wireless control function of HVAC systems.
- **Power Line Networking Technologies:** Power line communication (PLC) [8] is a low-cost technology that allows the communication signals to be transmitted over the conventional power cables without deploying dedicated networking cables. It is currently being used for multiple applications such as Internet access and home automation. Some PLC technologies are restricted in specific wire ranges and the normal transformers may prevent the signal propagation. Thus, it has a relatively limited applicability for a large-scale application. For intelligent buildings, especially for home area networks, however, PLC can be a good alternative for wireline and wireless networks. Home automation can be expedited by the PLC technologies in applications like remote controlled in-home utilities and lighting without using special networking cables or extra wireless transmission devices. Currently, popular PLC protocols and standardization organizations include: HomePlug Powerline Alliance [15] (HomePlug AV protocol [16]), G.hn protocols [17] by ITU-T (International Telecommunication Union's Telecommunication Standardization sector), HD-PLC (High-Definition Power Line Communication) Alliance [18], and Universal Powerline Association [19].

Table I summarizes the major communication media that could be used in the building environment, and compares their advantages and disadvantages, their major usage, technology names, and industry standards. It also demonstrates the main problems of various communication media and technologies in the building environment.

2. *Building Management IT System*

The building management IT system shown in Fig. 1 could potentially include a series of value-added business-related voice, video, and data applications. Examples of such applications include those related to energy market modeling and monitoring, real-time energy pricing by interacting with the smart grid, energy demand/response, and billing systems. These systems guarantee how an intelligent building can be operated and managed profitably as well as efficiently. Note that some tasks of the building management IT system related to energy overlap with the energy management and grid interaction system shown in Fig. 1. The difference is that the building management IT system is more about high-level business applications, while the energy management and grid interaction system is more about the interior operation and interaction with the outside smart grids.

B. *Energy Management and Grid Interaction*

1) *Brief Introduction*

This subsystem consists of energy management and building-grid interaction. The major functions of the energy management generally include: (1) in-building metering infrastructure, and data collection and analysis; (2) management subsystem for HVAC, lighting, and other utilities; (3) renewable energy generation and energy storage. A typical example method of the building-grid interaction is "demand response." We further envision and discuss a future building-grid interaction scenario in this subsection.

This management subsystem analyzes the resource usage data obtained through the in-building metering subsystem and passes the results to the business applications of the building management IT system. It actually serves as a mediator between the metering infrastructure and the building automation system in the sense that the metered data are passed and processed by it and the results are fed back to the high-level applications to initiate the building automation process as a response. The energy management subsystem also performs the management functions for individual utility systems in the building. Finally, the energy management and grid interaction subsystem also manages the in-building renewable energy generation and energy storage subsystems, and enables better integration of renewable energy resources to the traditional power grid in buildings.

2. *Smart Metering Platform*

Smart metering [23] infrastructure monitors the consumption of multiple resources such as electricity, water, gas, heat, etc. It also enables us to know not only how much energy is consumed but also how and when they are consumed. It is the foundation of the smart grids and also the fundamental component of intelligent buildings. It usually comprises of multiple networked sensors of different granularities that monitor various building loads and send information back to control systems through a network backbone. The metering infrastructure is separate and different from the building automation system (BAS) in that it has built-in storage facilities and needs to be more open and available to the stakeholders such as building owners, tenants, and managers.

It is also different from the conventional metering facilities in the sense that it allows a two-way communication capability. The reading instructions and data can be sent remotely to the central servers. There is also a trend for it to use TCP/IP protocol suite as a common platform. Some also suggest the separation of the grid meter function from the communication modules to enable a universal metering interface without using specialized communication standards and lowering the investment risks.

Smart metering can be used to work closely with demand response (DR) by interacting with the smart grids. Such interaction provides real-time pricing information and helps the building managers run specific policies to reduce energy usage during the peak periods and thus reduce costs and lead to a better energy usage. It also allows the utility companies

TABLE I
COMMUNICATION MEDIA, TECHNOLOGIES, STANDARDS, AND COMPARISONS

Media	Advantages	Disadvantages	Major usage in building	Technologies	Standards
Wireline	1. Reliable and stable 2. Secure 3. Technologies mature	1. Expensive 2. Hard for wiring 3. Inflexible	1. Network backbone 2. Connect systems need high security and reliability	Ethernet (LAN)	IEEE 802.3 series, 802.1 series
				HomePNA	HomePNA 2.0: ITU-T G.9951-3; HomePNA 3.x: ITU-T G.9954
				G.hn/HomeGrid	ITU-T G.9960, 9961,9963, 9970,
Wireless	1. Reduced wiring and cost 2. Wide coverage 3. Support broadcast 4. Flexible deployment and high reconfigurability	1. Possible security leak 2. Instable and lossy link 3. Limited signal propagation range in built environment	1. Complementary to the wireline 2. Resilient and reconfigurable monitoring 3. Data and voice communications	WiFi	IEEE 802.11 series including (a, b, g, n)
				Bluetooth	IEEE 802.15.1
				ZigBee, 6LoWPAN, Wireless HART, etc.	IEEE 802.15.4 series
				Ultra-Wideband (UWB)	IEEE 802.15.3 series
				RFID (Radio Frequency Identification)	ISO 14223, 18185; ISO/IEC 14443, 15693, 18000, 18092, 18185, etc.
Optical	1. Reliable and stable 2. High speed and bandwidth	1. Expensive 2. Difficult to wire 3. Inflexible	1. Access network 2. High speed data transfer	IrDA	Specifications across the OSI stack (include IrPHY, IrLAP, IrLMP, Tiny TP, IrCOMM, IrLAN, IrSimple, etc.)
Powerline	1. Low cost 2. No special wiring 3. Flexible modification 4. Easy installation	1. Not suitable for large-scale deployment limited by some transformer 2. Instable signal and link	1. Smart home appliances 2. Home automation 3. Internet access	HomePlug	IEEE 1901
				UPA: Universal Powerline Association	UPA Digital Home Specification v1.0, and other 2 related specifications
				G.hn/HomeGrid	ITU-T G.9960, 9972

to manage the demand and supply in a balanced and effective way which is good for running and operation of the whole grid.

3. *Renewable Energy Generation and Energy Storage*

Conventional power generation involves usage of scarce fossil fuel and coal which are expensive and have impact on the global climate. Long distance transmission of electrical power also introduces high power loss and high initial infrastructure construction costs. Thus, the integration of green and renewable energy resources (solar, wind, geothermal, etc.) has become a promising trend for global climate control and sustainability. "Local generation, local consumption" notion can significantly reduce the waste and enable energy efficiency and sustainability.

However, renewable energy sources, such as solar and wind, have intermittent and variable availability and may not be able to provide energy when users need them most but provide it when the users may not need it. To solve such mismatch, it is necessary to use energy storage systems to temporarily store the energy for future demand and to share the excess energy with neighboring buildings that may be able to use it, i.e., by forming a microgrid.

At the microgrid level, the renewable energy generation and energy storage subsystems in intelligent buildings can further interact with the external grid and form a certain level of interaction and synergy to achieve a specific set of goals such as minimum energy import from the external grid, lowest overall energy cost, and lowest peak-time energy consumption, etc. The relationship among these subsystems and their interactions are shown in Fig. 4. We can see that the three components in individual building domain interact with each other as well as with other buildings in the microgrid. The buildings and/or microgrids can import/export their energy from/to the external grid depending on the real demands and strategies. In Section VII, we will present more details of our vision about these aspects.

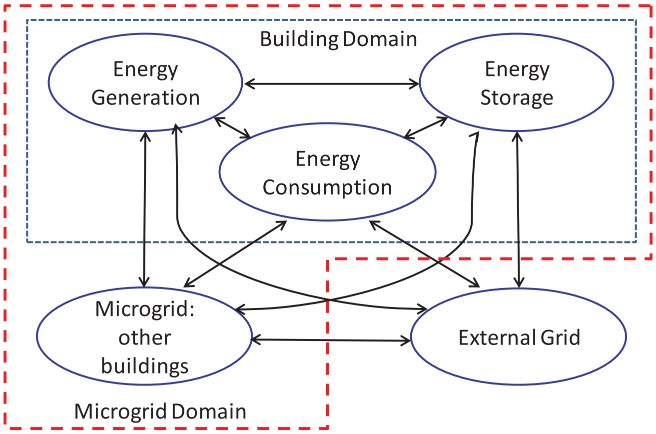


Fig. 4. The relationship among energy generation, storage, consumption, and external grid in intelligent buildings and microgrid level.

4. *Demand Response and Demand Side Management*

The energy management and grid interaction subsystem is also responsible for the automated demand response (DR) [20] function and demand side management [120], [121]. DR is one of the types of building-grid interaction. It is now very broadly used in not only large office buildings but also residential buildings and smart homes.

It is linked to the smart grid for demand-provider mutual negotiation and dynamic utility pricing. It means that the building-side energy consumers actively monitor the grid-side power supply conditions and prices, and shut off some loads to reduce part of the energy consumption to avoid expensive energy usage during the peak times, or, start their own energy generators to meet the actual demands. This method is a little different from those trying to improve the energy efficiency in the building which basically tries to reduce the energy consumption without changing the tasks. DR means that the demands are restricted as a reaction to the energy prices in the utility market. DR provides multiple financial and operational benefits for users, grid operators, and utilities services. Typical benefits include reduced energy usage for end-users, lower wholesale energy market prices, and grid operational security benefits. Most of such functionalities and features are missing in conventional buildings. In more advanced cases, automated demand response can be developed over multiple suppliers to enable an automated strategy for different devices related to lighting or HVAC.

5. *Future Building-Grid Interaction for Energy Efficiency*

Building-side grids (microgrids) are important parts of the smart grids. It is an important and challenging task to make them smarter and enable them to collaborate with the external grids to achieve better efficiency and cost-effectiveness. Especially, in the future, renewable energy generators may become available in local interconnected buildings, and they are also connected to the smart grids. If the generators' capability exceeds the microgrid's own demands, it will export the remaining energy to the external smart grid. Dynamic and optimized scheduling of these distributed generators located in multiple buildings can feed the demands better and reduce the overall cost. It can also achieve better energy efficiency in not only building scale but also in community, city, state, and even country scales. Also, through dynamic interaction between the intelligent buildings and the smart grid, not only the building-side users can reduce their energy consumption and use energy more efficiently by avoiding high peak-time energy usage, the utility-side energy providers can reduce the peak-time load, allocate the power generation capacity more efficiently, and avoid constructing expensive new power plants for peak time demands.

C. Building Automation System (BAS)

BAS is a computerized distributed control system which automates the monitoring and control of various mechanical and electronic systems in intelligent buildings.

1) *Major Functions*

BAS provides the most basic control functions for the major subsystems such as lighting, HVAC, water, gas, occupancy sensing, building access, and fire and safety systems. Using principles of control theory, BAS controls the operation of multiple feedback loops to keep a series of parameters under the set ranges without manual intervention. BAS system is one of the key differences between intelligent buildings and conventional dumb buildings. According to recent research [24], the market for BAS is expanding fast and there is potentially a great opportunity for research, standardization, and application in the near future.

BAS generally consists of multiple hardware and software entities including various sensors, actuators, controllers, and corresponding software. Multiple algorithms are embedded into the scheduling, controlling, and decision-making processes of the systems. BAS builds on top of the integrated communication backbone on which multiple types of data packets for different subsystems can be sent. The protocols for BAS are supposed to support the intercommunication among different subsystems. It integrates multiple subsystems and optimizes the performance by increasing interactions among them. The integration of multiple subsystems through open standards and protocols is critical for an effective and efficient BAS. The integration of BAS with other components in Fig. 1 also affects the overall effectiveness of the intelligent buildings. As a summary, the BAS has the following key functions: (1) *improved automated operation and monitoring of the subsystems;* (2) *optimized start (restart) and stop of subsystems like HVAC;* (3) *automated system diagnosis, abnormal event alarming and logging;* (4) *modeling and predicting potential problems and preventing them through extra intervention;* (5) *optimized maintenance scheduling and decision making.*

2. *Standards and Protocols*

The protocols, as the outcome of standardization process, are always bound to huge commercial market interests. The standardization makes the process very competitive among multiple stakeholders. The development of the Internet and computing benefited a lot from the openness of the standardization process. Such lessons also apply to the intelligent building industry. Just as the integration of multiple systems is a key for an intelligent building, ***open and widely-accepted standards and protocols are the keys for the effective integration***. The standardization will help create interoperability and synergy among various participants of the markets. Compared with the private protocols, open standards allow all interested parties to join in and contribute. The process also potentially reduces the risk since the protocols usually have to be reviewed and evaluated by all parties, and any potential bug and issue can be found out and addressed. Specifically, it helps create a virtuous cycle among the three factors of ***innovation, standardization, and investment***. Such cycle is valuable in promoting new advanced technologies into real applications and nurturing market's acceptance of new technologies related to the intelligent buildings.

We now discuss two popular and leading standards for BAS in the intelligent buildings:

- **BACnet:** Building Automation and Control Networks (BACnet) [25] is a building communication standard protocol developed and supported by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [26], American National Standards Institute (ANSI) [27], and International Organization for Standardization (ISO) [28]. It is now widely used to communicate among many building applications including HVAC, lighting, fire detection, safety and access control, and other utility systems. The protocol allows the devices made by different manufacturers to interoperate and exchange information with each other and create interaction and synergy to enable an automated intelligent building system. It is designed to run on many different data links and protocols including Ethernet [10], ARCnet [29], Point-To-Point over RS-232 [30], BACnet/IP, and LonTalk [31].
- **LonWorks:** LonWorks [32] stands for "Local Opera-

tion Network." It is developed by Echelon Corporation using ANSI/EIA 709.1 (called LonTalk [31]) standard as the communication protocol. It is also designed to work on multiple kinds of networking media such as optical fiber, power line, twisted pair, and wireless radio frequency. Similar to BACnet, it is used for building automation and interoperability across multiple systems like HVAC, lighting, etc. In 2008, ISO and International Electrotechnical Commission (IEC) [33] approved the protocols and numbered them as ISO/IEC 14908-1 to -4. LonWorks is widely accepted by the industry and it is being implemented with IP and web services and applied into the areas like intelligent buildings, homes, utilities, and transportation industries. However, LonWorks is not natively compatible with BACnet. Some of the currently available intelligent building automation and control protocols including the above two are listed in Table II. Their scopes and major features are also briefly discussed. The table includes not only the automation and control protocols for general intelligent buildings but also those for residential home buildings. Note that there are many different types of standard protocols for different applications and hence with different scopes and features. Other such protocols include KNX, S-Bus, Dynalite, EnOcean, Insteon, MyriaNed, X10, etc. They have various scopes and features. We will not enumerate all of the protocols available in the market. A relatively longer list of them can be found at [34], [35]. As a quick comparison, LonWorks and KNX are usually more like field-level solutions which connect a series of sensors and devices in a floor or room level. In comparison, BACnet is more like a controller-centric protocol which offers more upper-level functionality. Thus, in some cases, BACnet is usually deployed in combination with other field-level control networks. These control networks are connected through a gateway and become recognizable by the BACnet controller. Currently, BACnet and LonWorks have achieved considerable deployment in the global market, while KNX does well in European market.

3. *Lessons Learned for the Protocols and Standards*

Given the long list of the various building automation tools and relatively long history of the development of these tools, we discuss briefly the lessons [118] we learned from the protocol development and standardization process.

- **Compatibility and Interoperability Issues:** Two major BAS protocols of BACnet and LonWorks are not compatible with each other. For the devices supporting one of these two protocols to talk to each other, a proxy device is needed. In the future, for a specific protocol to be more widely recognized and accepted, or for it to gain consensus in the research and industry community, multiple options and choices should be provided and included. **Interoperability** is needed and provided by default. In other words, it should be compatible or interoperable with other protocols. This is the case for all the current BAS protocols.
- **Security and Privacy Concerns:** As the application of smart technologies in the building environments becomes more and more popular, significant concerns on the security and privacy issues arise. This calls for appropriate security models to cover these concerns. For example, when integrating multiple subsystems provided by various vendors into a truly smart building, it is important to design, implement, and enforce a set of unified security and privacy rules or policies to avoid potential security and privacy leaks.
- **Systematic Design and Evaluation:** Generally the current subsystems in the buildings are installed separately without systematic formal designs. But formal specification of designs and the corresponding automated tools for evaluation are necessary to ensure a valid and effective implementation and deployment of building automation system. Thus, in the long term, it is required to have such protocols and methods standardized to evaluate and guarantee the system reliability, dependability, and performance. More studies and standardization efforts in this aspect are needed in the future.

In summary, the development of the standards will speed up the maturity of the markets related to intelligent buildings and enable multiple vendors to provide interoperable devices with various features and prices. Open and competing markets will potentially nurture new intelligent building technologies. In the future, a limited number of well-accepted and open protocols may be desirable for the development of the intelligent buildings.

IV. SMALL RESIDENTIAL BUILDINGS: SMART HOME

So far, most of our discussions are about the general issues in mostly large-sized commercial office buildings. However, for general residential buildings, or home buildings, there are a series of specific issues and we discuss them in this section.

A. *Large Office Buildings vs. Residential Buildings*

Buildings are complex systems and various types of buildings may demonstrate significantly different energy consumption patterns. Compared to large-sized office buildings, small or medium sized residential buildings usually have smaller numbers and types of appliances, and the scales of the appliances can also be different. For example, the HVAC system in smart homes can be much simpler and much easier to control according to the occupants' dynamic schedules. Compared with the general fixed pattern and centralized control of large-size office buildings, the smart phone based location-aware automated energy control system (we will discuss in details in Section V) is relatively more suitable for the small or medium sized residential buildings. It is relatively easier and more realistic to apply finer-grained and dynamic energy control in these buildings without the involvement of multi-level policies from different levels of organizations.

B. *Home Automation*

Smart home has appeared in all kinds of science fictions or movies for a long time. However, though it has been developing fast in recent years, it has not gone into everyone's life yet due to many reasons including the lack of standardization,

TABLE II
A FEW EXAMPLES OF BUILDING AUTOMATION CONTROL STANDARDS AND PROTOCOLS FOR INTELLIGENT BUILDINGS.

Protocols	Scope	Features
BACnet	For building automation, integrating multiple data link and physical link	Over multiple types of media and support many systems; broadly accepted by standard organizations like ASHRAE, ANSI, and ISO.
LonWorks	For building automation; by Echelon Corp.; wide variety of industry participants	Over multiple types of media and support many systems; initially based on "Neuron chips" but now support general purpose chips too.
S-Bus	Based on RS485 for twist pair; for intelligent building communication; also known as Smart-BUS, and SmartHome-BUS	Can install up to 250 devices in each bus linked with network bridge; flexible topology; ASCII protocol format; full range of products with little wiring
Dynalite	Lighting and building automation; built by an Australian company; Network protocol is named DyNet as an open source protocol that use 100-BT an run TCP/IP	Device contains programmable logic controller with P2P model in distributed manner; open protocol for integration; but with no error correction or transmission control
EnOcean	Wireless energy harvesting in building automation and other areas like smart home and transportation.	Combine micro energy converter and enable wireless communication between wireless sensors and control devices without batteries; ratified as ISO/IEC international standards; standard covers OSI layer 1-3.
Insteon	Powerline and RF based home automation networking technology by SmartLabs, Inc. ;	Enable all devices to network with power line and RF, or both; devices are peers, no need a master controller or routing software; with error detection and correction; every devices act as repeater.
MyriaNed	Wireless Sensor Network (WSN) platform based; for building automation, transportation, agriculture, etc.	Highly resilient and scalable; robust and energy-efficient protocol; small stack, low cost; no conventional master-slave mode, but radio broadcasting principles and mimic human gossiping
KNX	OSI-based communication protocol for intelligent buildings; converged three previous protocols; administrated by KNX association	Designed to support different media including twist pair wiring, powerline, radio, infrared, and Ethernet; approved as international standards and countries like Canada, Europe, and china.
X10	Mostly for home automation; using power line wiring, also wireless; different high bandwidth choices	Popular in home environment and relatively inexpensive for the components; limitations include interference, low speed, limit functionalities, and compatibility issues.

technical complexity, relatively high expense, and the lack of inexpensive and feasible commercial models. Hence, many existing researches [39]–[42] were carried out in smart home laboratories instead of real living homes.

Home automation is a specific case in residential buildings for the general concept of *building* automation. Due to the different scopes, home automation has a different focus. Specifically, the types of appliances in the residential buildings are relatively limited, and the total energy capacities are also not as large as those in commercial buildings. The central goal of the home automation is to meet the occupants' demands in terms of security, comfort, convenience, and energy efficiency. Generally, it consists of a light-weight HVAC, lighting system, and life safety and convenience appliances. Smart homes can also include smart health related appliances and services to improve the in-home life quality for the elderly and/or disabled populations. Typical home automation related appliances that the general intelligent office buildings do not have include the home entertainment systems such as home theatre and home gaming systems, real-time household monitoring and controlling equipments for air-conditioners, washers and driers, backyard watering, pet feeding, floor cleaning robots, security and access control, etc. These systems can be connected through computer networks to a central system and potentially allow remote control from Internet after appropriate authentication. Overall, the home building automation system structure is simpler than the structure shown in Fig.1.

The home BAS is prone to be more specialized according to the occupant's own preferences or interests. Many interesting automated applications and scenarios may be deployed in the home area. For example, besides new functions, the home owners may be interested in **energy efficiency** and install smart thermostat systems to dynamically adjust and predict the running of the HVAC system according to his/her own working or resting schedules. Some typical such smart applications include:

- **Lighting:** Turn lights on or off if they are not used or under-utilized; based on the ambient light, adjust the indoor brightness of the lights to save energy. Windows' shading can also be used to adjust the indoor brightness to maintain comfort while saving energy.
- **HVAC:** Internet-connected smart thermostat systems allow the building owners or users to monitor, predict, and control the HVAC running policies remotely and wirelessly in real time. Such systems can improve home comfort and provide better energy efficiency by setting the parameters such as temperature and humidity dynamically, or shutting off or changing to low-active modes to save energy when it is not used or under-utilized.
- **Security and Building Access:** Automated systems can monitor buildings all the time and report any suspicious movement around the buildings to the owners or occupants through Internet when they are not at home. They also provide necessary authentication and access control for anyone who wants to enter the buildings. Fire, gas, and water leaking events can also be part of the system.
- **Entertainment Systems:** Audio and video systems like home theatre, wireless telephone, cable TV, HiFi, home gaming systems can be integrated and put under a centrally controlled and dynamically adjustable system to provide the owners with customizable usage experience for different rooms and scenarios.
- **Home Robots:** Home robots can be used to accomplish many tasks in home buildings. They range from household appliances to life quality enhancing products in multimedia, communication, audio and video systems, e-commerce systems, etc. A typical example is the floor mat cleaning robot (like iRobot [36]) which has been widely used in recent years.
- **Others:** Other systems can cover other aspect of the users' demands in daily living. In fact, all the entities and in-house appliances that we use in everyday life can potentially be made smart and networked if necessary. Potentially there will be a significant amount of new applications related to them. A typical example of home specific appliances management project is the HomeOS from Microsoft [37, 38] which aims to develop a dedicated operating system and allow a centralized control of devices for homes. Load monitoring and metering in smart building using home automation protocols is the topic of research at many universities, e.g., [90]. With technological developments, advance and maturity of standardization process, and popularity of the smart phone and Internet technologies, the cost of making home smarter is consistently decreasing. Specifically, more products are using iPhone or Android mobile applications to enable users to monitor and control in-home devices and systems in real-time. This trend makes common people be more acquainted to the smart home applications and begin accepting these low-cost systems. Moreover, the automated systems help enhance and improve the users' everyday life quality. They also help **reduce energy consumption**, save costs in the long run and promote global sustainability. More detailed discussions on this aspect are in Section VIII.

C. Home Area Network (HAN)

In home buildings, given their smaller size compared with the general commercial intelligent buildings, their consolidated communication network can be relatively simpler. A new term "Home Area Networking" (HAN) is used to describe the networking technologies that connect all the smart or computerized devices inside the homes for automation or Internet-based access and control.

There are a series of specific research projects focusing on home area networks [43]–[46], access control for data and devices inside home buildings [47], [48], and home network management issues [49], [50]. In this paper, as one of the key perspectives discussed in Section I, we focus on the networking aspect, particularly the communication technologies and protocols that can be used in home buildings.

Multiple communication media can be used in a home building: wireless radio, UTP (Unshielded Twisted Pair) cable, telephone line, coaxial cable, and power line. Specifically, wireless networking technologies are very cost-effective for deployment in the residential buildings to interconnect various smart devices. Power line communication can also be used since normally all the power appliances in a single residential building are under one power transformer's territory. One of the typical scenarios is that the devices use TCP/IP protocol over multiple types of physical media and they connect to a central router running Network Address Translation (NAT) [51] acting as a proxy server with firewall between the intra-home network and the Internet. The router can also be a WiFi access point for wireless devices in the building. Such scenarios enable the global accessibility and security of the home networks.

However, for home area network, some typical challenges that need to be addressed include: (1) How to make sure that the wireless signals inside the home building can cover the entire building without loss of any possible communications; (2) How to guarantee the security of the wired and wireless communication in the home building since signal is relatively easily accessible to potential attackers; appropriate authentication and encryption are necessary in such cases; (3) How to tackle the interference of the signals and specifically overcome the background noise in case of power line communication.

There are several smart-home specific communication standards which were included in Table I. Generally speaking, two biggest standardization organizations are IEEE and ITU-T. The IEEE standards include the "HomePlug" presented in IEEE 1901 and WiFi which is presented in IEEE 802.11 protocol series. The ITU-T recommendations include HomePNA series from HomePNA alliance [56] and G.hn [17] series promoted by HomeGrid Forum [57]. These are important standards for home area network.

D. Net-zero Energy Building and Energy Efficiency at Home

The term "Net Zero-Energy Building (NZEB)" [5], [52] refers to the buildings that have their own energy generators to feed their energy demands. They are approximately with net zero energy dependence to the outside power grid on an annual basis. Limited by the availability of renewable energy sources and seasonality, most of these buildings are also connected to the grid and import energy from outside when the self-generated capacity is below the actual usage. In reverse direction, they can also export excessive power to the grid through a "buy-back" policy between the building owners and utility companies. But overall, the energy they generate and consume is even and contributes zero carbon emission to the environment on an annual basis.

The term "Net Zero-Energy Building" (NZEB) is defined and used differently in North America and Europe [53]. But they are all based on a similar concept that the buildings can generate enough clean energy equal to their own demands and thus not consume excess energy from the outside supply. It is different from the concept of "Green Building" [3], [4] in the sense that the key goal of NZEB is sustainability and they tend to have much lower ecological impacts compared with other buildings.

Due to the current limitations of the renewable energy generation, net zero-energy goal is primarily feasible in small and medium size residential buildings where the energy demands are relatively low compared with large office buildings. For example, in Washington University, we have a Tyson Research Center net zero-energy building [54] which won the "Living Building Challenge" [6] award. It successfully realizes the annual net zero-energy goal by generating energy through solar panels and with conservative energy designs and operations. It also has cooperation with utility company to balance the generation and consumption on an annual basis.

Residential NZEBs require installing clean and renewable energy harvesting devices using biofuel, solar panel, wind turbine, etc. They also try to minimize water consumption by appropriate recycle or conservation methods. Local and sustainable materials are used and the whole construction process also considers minimizing the environmental impacts.

A net-zero energy building certificate system has been developed by the International Living Future Institute [55] in November 2011, which may potentially encourage further developments in this area. For example, researchers at University of Massachusetts have published several papers in areas related to energy consumption and generation. The topics include open data sets for both smart home data and microgrid data [91], renewable energy management [92], reducing energy consumption by using energy storage made by batteries [93], and methods to schedule electricity loads to flatten peak electricity demand in smart home [94].

E. In-home Smart Health

Residential and home buildings are also a hot research area for smart-health applications. They are especially useful and valuable for those disabled and elderly people living alone. There are two major drivers for the development of such applications: (1) the medical economy growth and the patients' increasing interests in such applications; (2) the advances in information and networking technologies.

Due to these factors, a series of smart in-home health applications have emerged. They can be divided into two categories: patient-centered and the healthcare-centered. The first category focuses on applying advanced technology to patients to improve their life by providing new methods and devices for them to fulfill functions that they usually have difficulty performing. Typical examples include elderly fall detection and alarming systems via wearable accelerometer sensors [58], [59]. The second category tries to improve the efficiency of the normal healthcare services by new technologies. A typical example is the remote patients' vital monitoring system installed in patients' home which provides the doctors with fast and effective ways of knowing the patients' health conditions. Such applications actually have been developed for decades for a variety of medical purposes like elderly care, patients' related emergency response, and continuous disease monitoring [60].

F. Smart Thermostat at Home

Smart thermostat or HVAC is another in-home application area that potentially can simultaneously improve users' comfort and energy efficiency. The conventional thermostat is manually controlled and cannot be tuned automatically according to the weather conditions, occupancy, and owner's comfort. For residential buildings specifically, the HVAC system is light-weight compared with the large-sized commercial office buildings. Hence, applying more intelligent and human-based control to tune the indoor conditions to match the occupants' actual demands is easier. Currently, there are several such control systems available both in academic research [61], [62] and in real commercial products [63], [64] that are built on top of the existing home based HVAC with relatively low cost. Internet-controlled capability allows the users to monitor the HVAC conditions from anywhere at any time through remote PCs or smart phone applications based on iPhone or Android platforms [63]. The HVAC running policies and schedules can also be reconfigured and controlled on air in real time. Moreover, some systems offer learning capability which analyzes the usage patterns of the owners, predicts their behavior, and develops an optimal running schedule for the thermostat. According to different goals, there can potentially be different modes like aggressive scheduling strategies best for energy efficiency or mild scheduling strategies best for human comfort.

V. EXAMPLES OF USING NETWORKING TECHNOLOGIES FOR ENERGY EFFICIENCY IN BUILDINGS AND RELATED RESEARCH

In this section, we first discuss some examples and test cases demonstrating how networking technologies can be applied in the building environments for energy efficiency benefits. Then we compare them with some related research on building modeling and analysis for energy efficiency purposes.

A. Example and Test Cases

Here, the two examples and test cases are: (1) location-based automated and networked energy control, and (2) wireless sensor network based energy saving solutions.

1) *Location-based Automated and Networked Energy Control*

The first typical example and test case is using smartphone platform and the location sensor to enable inter-building

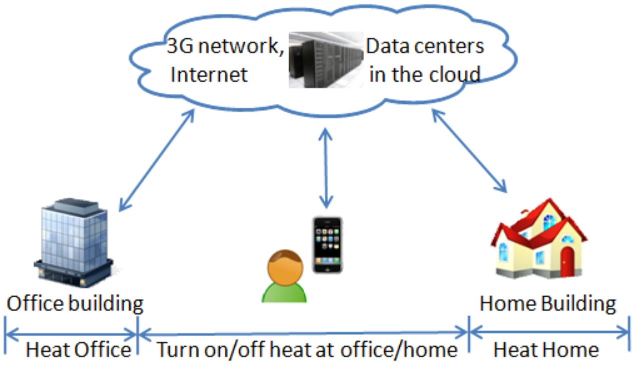


Fig. 5. A simple example of location-based dynamic heating policies control.

cooperation and to improve energy efficiency in intelligent building environments. In our previous research [79], [115], we designed a network framework for smart location-based automated energy controls in a green building testbed. The location information provided by the occupants' handheld smart phones can be used to dynamically adjust the energy consumption policies in multiple cooperative buildings which virtually enable distributed and dynamic energy control in the building environment. A typical example of such scenario is shown in Fig. 5. The scenario is assisted by the central cloud-based data center.

In this example system, we considered two groups of electrical appliances associate with the user in two buildings: his/her office building and his/her home building. We aim to enable the central controller to detect the user's location changes and trigger the heating energy policy changes of the electrical appliances in both office and home buildings. Because of this, the user can control and enforce their energy policies in real time and their energy consumption will be approximately proportional to their actual usage.

We implemented the prototype system and did multiple experiments to validate and prove the effectiveness of our system. During a typical 24-hour period, we applied dynamic control policies and changes to both buildings (home and office buildings). We compared the real energy consumption with the baseline estimation of three energy using modes: **luxury mode**, **moderate mode**, and **frugal mode**. We found that the real energy consumption after applying our location based idea is **very close to the energy consumption of the frugal mode**. It means that with our idea and system, users can continue a luxury living style but only need to pay for the cost of a frugal mode's living style. Such effects can be more conspicuous for home and residential buildings and can be applied to existing conventional buildings without significant renovation costs.

After each user's energy proportionality is achieved, it will be aggregated to achieve any organization-level and then building-level energy proportionality. In the future, if the proposed idea gets a wide deployment, we expect that it will generate not only huge economic benefits in terms of energy savings, but also significant social benefits in terms of global sustainability by involving the general public in these efforts.

1) *Wireless Sensor Network (WSN) Based Energy Saving Solution*

The other typical example and test case is that of using Wireless Sensor Networks (WSN) in intelligent buildings as the central method to enable energy efficiency improvements. It has been a research and experimental topic for some time. Compared to other networking technologies, WSN has its advantages such as low cost, highly resiliency, and dynamic reconfigurability. It has been used for specific subsystems in buildings such as thermostat, lighting, and electrical device energy metering. Typical examples include: sensing and control of indoor lights based on the sunlight intensity or based on human activities; using the logged indoor human activities data to adjust the thermostat working schedule to provide better comfort or energy saving, etc. There is already a lot of research and experimentation about these topics. Two examples are in [88], [116] and more similar research can be found from the list at [114].

Compared with example and test case discussed in Section V.A, the WSN based experimental research efforts mostly try to apply the technology to a small area (a lab or a floor) energy monitoring, light monitoring, or HVAC monitoring to see the energy consumption status and to improve the efficiency accordingly by applying some remote control mechanism.

However, there are several limitations of such research. Firstly, the WSN technologies were not initially designed for building environments. The low-power design of WSN is mostly suitable for remote rural area (such as smart dust, bridge defect monitoring, natural environment and habitat monitoring, etc) without energy power supply which requires low-battery and work-and-hibernation working style. These design considerations are not important factors in the building environments where usually there is enough power supply. Wireless may also not be the only and effective option for communication inside a building since the communication can also be wired using networking cables or power-lines. However, regardless of these limitations, WSN still could provide a good complement to other sensing and metering technologies in the building environment, by using the wireless communication technologies, for energy efficiency and other related improvements.

B. *Other Research Examples and Comparisons*

There are a few other types of related research, though they are not directly related to applying networking technologies to improve the building energy efficiency, their research results are useful in term of achieving better energy efficiency from different aspects including better architecture designs, better insulation and thermal designs, or better operation. Specifically, some are about energy efficiency modeling or simulation. Typically, they include: (1) building climate effect modeling and evaluation, and (2) building energy efficiency simulation using specialized tools or software. For the first category, the major research topic mostly is to find the relationship between building energy consumption and climate or weather conditions through extensive modeling [114]. This category of research consists of two major directions: one is to simulate the heat transfer process and building structure (roof, envelope, tree shelter, etc), and find how the thermal law can affect that and hence the building energy efficiency;

the other direction is about the modeling of the solar effects on heat and mass transfer and hence their impacts on the energy efficiency of the buildings. However, generally such studies are of limited use in controlling energy consumption which requires knowledge of human presence and human preferences along with the weather. Also, there is a shortage of studies relating actual usage data (rather than simulated usage data) to the climate.

The second category is about the energy simulation using specialized software or tools. These software packages usually take building characteristics or parameters as inputs and output estimated energy usage for heating, cooling, lighting, ventilating, water usage, and carbon emission, etc. One example is "EnergyPlus" [117], which is provided by the U.S. Department of Energy. It is widely used in more than 120 countries by architects to predict energy flow in commercial and residential buildings. However, simulation tools and their results are relatively limited to some extents. These tools are useful in the building construction process but not after the buildings have been successfully constructed. Reducing energy consumption in a building during its operation is important for both new buildings and existing buildings. Also, the existing simulation software does not generally consider the occupants' preferences. Therefore, controlling energy consumption using a policy that includes human interaction has not been handled by these simulation tools.

We briefly compare these examples, test cases, and the other related work in Table III. Specifically, we illustrate the pros and cons of each of the method and compare them in a single table.

VI. CONVERGENCE OF INTELLIGENT AND GREEN TECHNOLOGIES IN THE BUILDING ENVIRONMENT

In this section, we discuss an important trend of combining the key concepts of green and intelligent buildings in creating "intelligent green buildings." Intelligent green buildings are also called "bright" green buildings in some research literature [65].

A. Definition

An intelligent green building is usually defined as better building designs and operation using both intelligent and green technologies. Specifically, on one hand, its design, construction, and operation are supposed to create minimum impact on the environment, to use resources efficiently and conservatively, and to create healthy and comfortable living and working conditions for the occupants. On the other hand, with intelligent technologies and integrated systems, intelligent green buildings provide monitoring and control functions to automate the running and maintenance processes and ensure efficient and fast operation. These functions can help the building owners and operators make better decisions in offering safe, healthy, and comfortable environments to the occupants.

The green building concept is combined with the intelligent building concept to advocate the prospect of sustainability with modern advanced information and communication technologies. Intelligent technologies integrate the whole building into a coherent structure and create interoperability and interaction among subsystems to make the building run cost-effectively and even profitably while providing a healthy living environment for the owners in the long run. More discussions on the benefits will be in the next subsection.

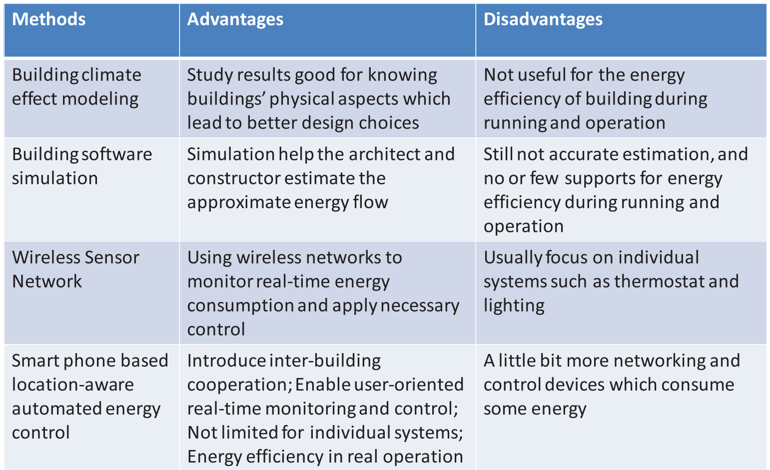
Moreover, another motivation of combining the "green" and "intelligent" aspects is to promote not only good building design but also efficient operation of the buildings. As indicated in our previous research results on the energy efficiency of the green building testbed [78], [79], [115], [118], "green buildings" that are "green" by design do not always lead to energy efficiency in operation. Thus, one of the major motivations for the "intelligent green building" is to connect these two aspects and try to use intelligent computing and networking technologies to enable energy efficiency and saving during running and operation of the buildings.

B. Energy-efficiency and Sustainability Benefits

To be more specific, intelligent green buildings have the following features or design goals. These features are also the major motivating and driving factors for the convergence of green and intelligent technologies.

- **Automated Control and Running:** Latest control protocols and technologies can be applied in the new context to facilitate the initial "green" design goals.
- **Efficient Energy Utilization:** Empowered by the integrated networks with multiple devices and sensors connected to it, energy is utilized in the building more efficiently.
- **Healthy and Comfortable Environment:** Using intelligent and green technologies, buildings can provide occupants with healthier and more comfortable environment without negatively impacting the environment. Better in-building environment can also improve the occupants' life quality and productivity.
- **Renewable Energy Generation:** Green buildings can be installed with renewable energy generators like solar panels and wind turbines to supply their own energy usage as much as possible. Such methods can reduce energy dependence on the grid to some extent.
- **Easily Adaptable to Future Needs:** The intelligent system inside the buildings can be easily tuned to accommodate the new demands from the owners and occupants without significant renovation to the buildings.
- **Long-term Profitability:** Compared with conventional buildings, the initial costs of green and intelligent designs can be relatively high. However, in the long run, the intelligent green buildings should cost less ultimately. It may also result in economic gains (like better resale values for building owners) and help the facilities and organizations to realize their social responsibilities and sustainability goals. These benefits can be better evaluated by a Life-Cycle Cost Analysis (LCCA) [66].
- **Low Green-House Gas Emission and Sustainability:** There is a trend and possibility that in the future the legislative and regulatory responsibility of the climate change will be transferred to the energy producers and consumers directly [65]. Hence, building owners are also

TABLE III
COMPARISON OF DIFFERENT METHODS: ADVANTAGES AND DISADVANTAGES.



Methods	Advantages	Disadvantages
Building climate effect modeling	Study results good for knowing buildings' physical aspects which lead to better design choices	Not useful for the energy efficiency of building during running and operation
Building software simulation	Simulation help the architect and constructor estimate the approximate energy flow	Still not accurate estimation, and no or few supports for energy efficiency during running and operation
Wireless Sensor Network	Using wireless networks to monitor real-time energy consumption and apply necessary control	Usually focus on individual systems such as thermostat and lighting
Smart phone based location-aware automated energy control	Introduce inter-building cooperation; Enable user-oriented real-time monitoring and control; Not limited for individual systems; Energy efficiency in real operation	A little bit more networking and control devices which consume some energy

increasingly requested to bear the social and economic responsibilities to improve the business efficiency and energy efficiency. It is also an indispensible part of global sustainability efforts.

In short, combining green and intelligent building technologies and processes can bring a lot of benefits for owners and occupants not only in terms of convenience and efficiency, but also in terms of cost-effectiveness, long-term profitability, and maintaining the social responsibilities in sustainability.

C. Factors for the Adoption of Intelligent Green Buildings

Related work in [65] presents a qualitative and subjective rating system evaluating the major factors that motivate the adoption of the convergence of the green and intelligent buildings. Based on this rating system, the major factors include energy saving, greenhouse gas emission, operation and maintenance, water conservation, and productivity. Each of these factors is associated to benefits such as return on investment (ROI), life cycle cost (LCC), image and corporate social responsibility (CSR).

- **Energy Consumption Saving:** Given the huge amount of energy consumption in the building environment, reducing these costs and gaining energy saving becomes a significant incentive. Thus, for this factor of energy saving, its impact on ROI is the major benefit, while in comparison the impact on LCC and CSR are less significant. Due to rising energy prices, energy saving is expected to become an important incentive for the future intelligent green buildings.
- **Greenhouse Gas Emission Reduction:** The need for reducing greenhouse gas emission and protecting our planet from climate change has attracted more and more attention from the global society. Many policy makers and property owners are under increasing pressure to reduce carbon emission. The stakeholders are required to demonstrate their awareness of social responsibility and take action to improve their public image by reducing greenhouse gas emission and disclose related information to the public. Compared with the factor of energy saving, the factor of greenhouse gas emission reduction has less direct benefits and impacts on ROI and LCC, while it apparently has the more benefits in terms of public image and CSR.
- **Operation and Maintenance Cost:** Considering the building's total costs in its lifecycle, operation and maintenance costs contribute about 50% to 80% of the total amount. Thus, this factor of operation and maintenance is much more significant in terms of gaining benefits in ROI and reducing LCC, than the impacts and benefits coming from the public image and CSR.
- **Water Conservation:** Water conservation issue is important and can be closely related to the global climate changes. The related incentives are on the rise. Thus, water conservation has become a factor in motivating the green and intelligent converged building perspective. For example, appropriate intelligent monitoring system using multiple distributed sensors can be used for this purpose. This factor has relatively low or average impacts and benefits in terms of ROI, LCC, and CSR.
- **Comfort and Productivity:** Studies by U.S. Green Building Council (USGBC) show that workers' productivity in green buildings in usually higher than in those conventional buildings. This effect is easily noticeable in the commercial and industrial building environments. The ROI benefit can be high for this "comfort and productivity" factor, followed by the CSR benefit.

D. Key Supporting Technologies for Intelligent and Green Converged Buildings

Some of the latest key supporting technologies include the following:

- **Integrated Communication Backbone:** As we discussed in Section III.A.1, integrated in-building communication backbone is a key component of the green and intelligent convergence. It allows the building owners and occupants to effectively monitor and control their energy and resource usage, and apply instant changes and adjustments to see the improvements. Integrated communication backbone also saves duplicated infrastructure costs and is very cost-effective compared with multiple independent and proprietary communication networks. The other one that is related to this aspect is the Fiber-to-the-Telecom-Enclosure (FTTE) technology which encloses multiple telecom media and introduces comprehensive saving and reduction in multiple costs.

- **Networked Electrical Architecture:** As with the integrated communication networking infrastructure, the electrical infrastructure can also act as an integrated center for multiple electrical appliances such as lighting, energy, and control systems. For example, instead of the traditional pipe and wireline based lighting system, nowadays such lighting system is with embedded control capability and is connected with networks. Such perspective helps create a building environment more closely around the people, and preserve and improve the ROI for the owner and managers.
- **Water Conservation Technologies:** Water shortage is a significant global challenge and water monitoring and control technologies can make a huge difference in attacking such challenge. By connecting the water meters and sensors and delivering data and control messages through communication and networking technologies, the building owners and managers are able to get a real-time and complete picture of the water usage and help end-users achieve better experience while harvesting benefits in sustainability.
- **Integrated AV System:** Integrated audiovisual (AV) technology in the green and intelligent buildings helps link multiple organizations and their devices together, which promotes the usability and the value of the green and intelligent buildings. It also helps provide better comfort for occupants and better facilities management for the building owners and managers. Conference rooms with AV features embedded can also connect many intelligent devices such as smart lighting sensors and windows shading systems, remote digital control systems, and video conferencing systems, etc.

E. Green Measurement Ratings Promoting Intelligent Building Perspective

Building certifying organizations play a very important role in the process of creating green and intelligent buildings. With a large amount of new intelligent building products and vendors on the market, it is necessary and important to create "labeling and rating" systems to promote the proliferation of the new compatible technologies and products and ensure that such systems can reflect and impact the dynamics in these buildings in the long run. We, therefore, briefly introduce two certifying organizations and discuss their status in promoting the trend of the intelligent and green convergence.

1) *LEED by USGBC*

LEED (Leadership in Energy and Environmental Design) [67] has been developed by USGBC (United States Green Building Council) [68]. Since 1998, it has been broadly accepted by over 135 countries with a huge number of projects. The rating system is still evolving and by 2012 it has reached Version 4. It covers the design, construction, and maintenance and operation of commercial buildings, homes, and neighbors. The goal is to advance better practices in the design and construction so that better building designs will emerge and new materials, products, and methods can be used for environmental friendliness and global sustainability. The LEED rating system framework is described in Fig. 6. It basically covers different building types, specific portions of the building, and running and maintenance of the buildings.

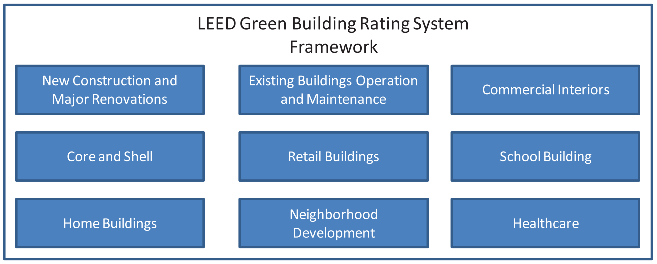


Fig. 6. LEED green building rating system framework [67].

Depending on the points allocated to different categories such as water efficiency, energy and atmosphere, sustainable sites, indoor environmental quality, materials and resource used, and innovation in design, green buildings can fall into four classes of certificates: ***certified*** (40–49 points), ***silver*** (50–59 points), ***gold*** (60–79 point), and ***platinum*** (80 points and above). Moreover, LEED provides professional credentials and honors to those with outstanding expertise in green building related disciplines. Specifically, it includes LEED Green Associates, LEED AP, and LEED Fellow.

LEED effectively promotes the environmental sustainability and human health and productivity in the building environments. It also advocates building energy-efficiency improvements by reducing the greenhouse gas emission, water consumption, materials energy footprints, and other waste of the buildings. The initial costs for design and construction for such buildings can be high. However, such costs can be gradually mitigated by the economical saving and social gains over time.

2. *Energy Star*

Energy Star [69] is a standard created by the Environmental Protection Agency (EPA) [70] and the Department of Energy (DOE) [71] of United States. The Energy Star marks are used by computer products, electrical appliances, home electronics, heating and cooling systems, lighting systems, and commercial and industrial buildings. By 2007, Energy Star had led to energy and cost saving of 16 billion dollars. For building rating, the core part of Energy Star is the “Portfolio Manager” which is used by building owners to track the key information related to building running, performance, and resource consumption regardless of its actual facility types. The Energy Star rating system for the building energy efficiency scales from 1 to 100. Buildings with scores higher than 75 points can qualify the Energy Star marks. The scores are generated by the Portfolio Manger after inputting all the ratable attributes of the buildings. The Energy Star energy performance rating is also included in LEED-EB (Existing Buildings) standard.

Other popular certifying organizations include (1) Green Globe [72] promoted by Green Building Initiative (GBI) [73], (2) SBTool (Sustainable Building Tool) [74] developed by the iiSBE (International Initiative for a Sustainable Built Environment) [75], and (3) BIQ Tool (Building Intelligence Quotient) [76] supported by the CABA (Continental Automated Buildings Association) [77] and BIQC (Building Intelligence Quotient Consortium).

In summary, building certifying organizations have grown significantly over the last several years. The numbers of projects with such certificates have also increased dramatically. There are multiple benefits: energy efficiency improvements and energy savings, automated and convenient building operation, lower impacts to the environment, healthier indoor conditions, and smart renewable energy generation and usage. The certifying organizations and activities also (1) promote the convergence of green and bright technologies for buildings, and (2) motivate the surging trend of growing certified building projects.

VII. MICROGRID FORMED BY MULTIPLE DISTRIBUTED INTELLIGENT BUILDINGS

In this section, we study the microgrid concept, particularly, in the context of microgrids formed by multiple distributed intelligent buildings with renewable energy generators.

A. *Microgrid Concept and Components*

The conventional electrical energy generating and delivering patterns are experiencing significant changes due to the emergence of small-scale microturbines located closer to the users. It has become a promising option to generate electricity using distributed renewable energy sources to meet the customers' demands in energy reliability and security.

Microgrids are deemed as a very important part of the future smart grids to provide reliability and power quality to the customers. A general microgrid consists of energy generators, energy storage, electrical loads, interfaces between the distributed energy generators and the outside power grid, and interconnection and control mechanisms. We briefly discuss them as follows:

- **Energy Generators:** Typical renewable energy generators are based on solar power (PV, Photo-voltaic), fuel cells, wind power, geothermal, water power, tidal power, etc. Different from the conventional centralized power generators based on large-scale hydro, natural gas, coal, and nuclear power, microgrid is usually formed by small-scale renewable distributed generators that are close to the customers.
- **Energy Storage:** Typical microgrid storage can use batteries, fly-wheel, and ultra-capacitors [111]–[113]. Using energy storage can achieve several functionalities: (1) balance the power generation and power demand in spite of loads fluctuation and transients; (2) allow fluent initial transition when microgrids connect to or isolate from the outside power grid; (3) provide enough capability in case of variation for intermittent energy sources such as wind generators.
- **Electrical Loads:** Loads can come from very diverse sources including residential users as well as commercial and industrial users. Depending on their importance, loads can be further prioritized as critical loads and less critical or non-critical loads. Different categories need different strategies to fulfill their functionalities.
- **Interfaces Between Generators and the Bulk Grid:** These interfaces need to handle the connection between the microgrid and outside grid. The conventional protective equipments like circuit breakers are generally not capable of handling isolation and switching fast enough. Thus, the latest research is on using Digital Signal Processor (DSP) technology for the switches to achieve a fast response.
- **Interconnection and Control Mechanisms:** Microgrids are different from the bulk power grid due to their limited scale and hence have specific requirements when connecting to the grid. They have their own control requirements among dynamic energy generators and consumers. The control methods used inside the microgrids can be centralized or distributed, or hierarchical based methods that combine the two types. The control mechanism should allow flexible addition or removal of distributed generators in a "plug-and-play" style without disturbing the rest of the system or re-engineering or reconfiguring the whole system.

B. *Research Status and Our Vision*

Microgrids have been a very hot research area for some time and generate huge amounts of publications each year, especially in the electrical control aspects. Regarding the microgrid concept [21], [22], [95]–[110], there is a significant amount of research on the electrical engineering and control theory and practice aspects of the microgrids. In this section, we do not intend to enumerate all such efforts. Instead, we focus on our vision of microgrids formed by multiple distributed intelligent buildings that act both as electrical energy consumers and providers. We aim at studying the microgrids in "computing" perspective instead of "electrical engineering" perspective. In other words, we primarily focus on the communication and networking aspects, and in an energy efficiency research context. Particularly, we study how multiple intelligent buildings can work together and create a synergy by applying networking and Internet technologies in such distributed environments. We know that smart grid includes not only the parts for energy generation, transmission, and delivery, but also energy consumption. It is important and challenging to make the consumer-side buildings and grids smarter, more efficient, and cost-effective. Especially, in the future, distributed generation (DG) and microgrids will be common when renewable energy is generated by facilities located in distributed buildings near solar, wind, and biofuel sources. If the generators' capability exceeds the building's own demand, it is good to export the rest of the generated energy to the microgrid. Dynamic and optimized scheduling of these distributed generators can feed the demands better and reduce the overall cost and achieve better energy efficiency at not only building scale but also at community, city, state, and even country scale grids.

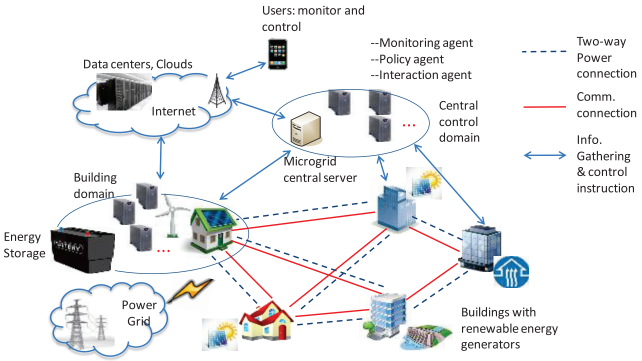


Fig. 7. A simple illustration of our vision for microgrid networking and control structure.

C. *Smart Microgrids from a Networking Perspective*

For sustainability, we envision that in the future, buildings will not only act as a sole consumer of the electrical energy; they will also become a source of energy, given the fact that many new buildings are being installed with renewable energy generators like solar panels, wind turbines, and biofuel-based energy generators. Multiple distributed intelligent buildings in the microgrid connect together and share their energy generation capabilities, and function as an independent unit to the outside power grid. "Local generation, local consumption" policies can significantly reduce the energy dependence of the grids of different scales.

1) *Interconnecting Multiple Intelligent Buildings*

To enable a smart microgrid concept, it is necessary to network multiple intelligent buildings through a “knowledge plane” by using multiple communications and networking technologies. As shown in Fig. 7, neighboring buildings in a microgrid are networked such that each building is an “Autonomous System” monitoring itself and interchanging real-time consumption and generation capacity information with neighboring buildings as well as a central knowledge server. The central “knowledge plane” in a central server is then in charge of the dynamic scheduling of the energy capacity of the microgrid and communicating with the agents of multiple buildings to collect real-time information through distributed networking. Individual buildings work in a distributed manner as well as interact with the central server without creating "single-point-of-failure" when the central server is down.

2. *Monitoring, Dynamic Scheduling, and Optimization*

As shown in Fig. 7, the central “knowledge plane” allows microgrids to dynamically monitor, schedule, and allocate energy generation and consumption capacities across multiple intelligent buildings.

On top of the networking topology and protocol problems, the energy efficiency maximization problem can be formalized assuming that the central microgrid server gathers all the real-time energy consumption and generation information through the microgrid networking infrastructure and protocols. Once the central microgrid server has all the information, and also the distributed location of each building in its territory, the problem can be modeled and simplified as a computing optimization problem. The detailed optimization algorithm is under development in our research project.

Given multiple distributed energy sources and consumers, the goal is to optimally allocate the extra energy to the places that need them in closely located buildings. By doing this, the renewable energy generated by the green buildings can be fully utilized by multiple buildings. Making full use of renewable energy also means reduction of the energy import from the outside grid and also reduction of the energy lost due to long-distance transmission. With such optimization, peak energy demands can be reduced, and significant amounts of power transmission loss can be saved. It also potentially saves 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 in microgrids.

Power stability is an important issue for microgrid energy optimization. Dynamicity is a norm in the buildings, including both the energy generation and consumption. For example, energy generated from solar panel is primarily in daytime, and the consumption in non-office hours can be significantly less than office-hours. To take full advantage of such relative stable or predictable patterns, it is possible to use a series of **simple machine learning approaches** to enable smart learning in the pattern of energy generation and consumption, and schedule the energy generation and consumption in the microgrid appropriately. By doing this, we can reduce the risks of radical changes in the microgrid energy pattern that can affect the power quality.

VIII. KEY ISSUES AND TRENDS DISCUSSIONS

In this section, we discuss some key issues and trends for the intelligent building and building-side grid research, especially focused on the energy efficiency and networking perspectives.

A. *Energy Proportionality of the Buildings*

According to our on-going research on the green and conventional buildings’ energy consumption, the data analysis results show that the actual energy consumption on most of the existing buildings (regardless of whether they are green buildings or not) is not proportional to the actual usage [78], [118]. In other words, a large portion of the energy is wasted, especially during hours when the building is unused or underutilized.

In our research efforts, we propose a method inspired by the computer industry in creating energy proportional computers. Specifically, the original computers consumed the same amount of electricity regardless of whether they were busy running programs or not. This has changed in recent years when multiple new technologies emerged to enable the core parts of the computer like CPU to consume less energy when they are idle or underutilized. We investigate the computer systems and the buildings and find that there are some common essences that potentially enable us to apply some key technologies in energy-proportional computing into creating energy-proportional buildings. As a simple definition, ***energy proportional building is a building whose energy consumption is approximately proportional to the actual occupancy rate***.

We found that several basic methods and technologies in supporting the energy-proportional computing can be applied to the buildings. They include: (1) identifying the key energy-consuming components; (2) wide dynamic power ranges; (3) active low-power modes; (4) seamless transition among multiple running modes. With these features identified and appropriately incorporated into the building environment with the assistance of the advanced networking and information technologies, we can enable the key components of the buildings and their running and operation to be energy proportional to the actual usage. Specifically, we list the two different application areas about energy proportionality and compare the key aspects in Table IV.

A typical example of creating such energy proportionality in the building environment is in our work [79] as we discussed in Section V.

B. Human Behavior Factors

People's awareness to the energy consumption and their behavior [80] 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 owners or occupants. Neglect or unfamiliarity to the systems can lead to low effectiveness and efficiency of the advanced intelligent systems in the buildings. For example, we notice that most people may not care too much about the energy consumption in their work places while being opposite in their own home buildings. If the intelligent technology is too complicated for them to operate, there will be high possibility that the systems will be under- or unutilized. We summarize the following several key factors that can impact the adoption of intelligent systems and hence energy efficiency inside the buildings.

- **Awareness:** The occupants or the building owners may not know in detail how much energy is consumed and how it is consumed. Hence, creating real-time data display applications for the stakeholders' online access can make them aware of the energy consumption before improvement measures are taken. A study by Oregon Sustainability Center [81] shows that we can generally reduce the commercial building energy consumption by 10% if we provide occupants with their energy usage information.
- **Sensitiveness:** The building stakeholders may have different degree of sensitivity to the energy consumption. Methods associating such sensitiveness with the economic benefits may motivate them to take actions to actively interact with the intelligent systems in the buildings to improve energy efficiency and cut costs. Another study [82] shows that providing users with in-home display on their real-time energy usage helps reduce the energy consumption by 15%. It demonstrates that combining energy awareness and sensitiveness has a great potential in saving energy.
- **Participation:** Conventional buildings barely involve any participation from the general occupants hence the energy policies formulation and decision processes 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 are good ways to encourage such participation. Typical positive results are proved by two sustainability efforts of "Green Cup" energy-saving competition [83] and "Green Lab Initiative" [84] at Washington University in Saint Louis.
- **Social Factors:** The energy consumption issue is not only about costs but also about environmental sustainability. Hence, saving energy and introducing intelligence in buildings also have social implications. Besides the long-term cost benefits, introducing intelligent building designs and certificates may help stakeholders improve their public images in term of social roles and responsibilities. Future social network based applications (like in Facebook or Google Plus) involving energy saving profiles may help the energy efficiency efforts in much larger scales and potentially has profound impacts.

In short, besides the advanced technologies involved in the intelligent buildings, human behavior of the stakeholders also has huge impacts on the adoption of intelligent buildings. Using technical and non-technical methods (such as smart phones) to enable and encourage the stakeholders to be aware of the energy issue, and to actively participate in the operation and decision process can make it more effective in terms of saving energy and supporting global sustainability. Advances in the standardization and certifying organizations and activities can also magnify such benefits.

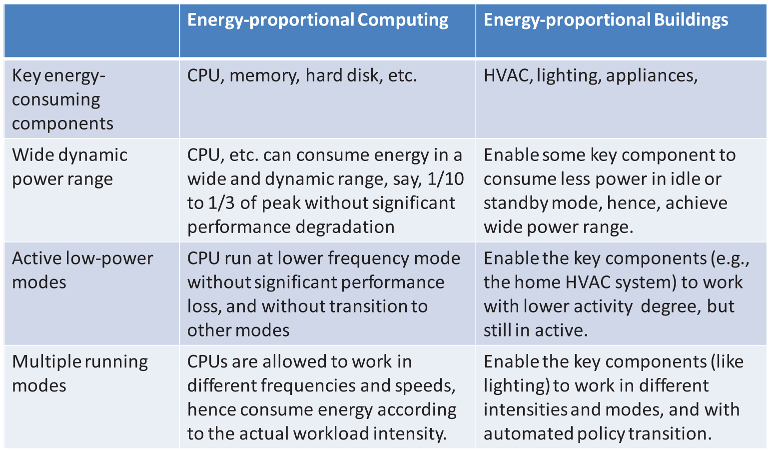
C. Networking Convergence and Interaction with the Grids

Using consolidated multiple network infrastructures with open standards and protocols to enable the intelligent buildings to operate as integrated and harmonious systems have become necessary. Such convergence trend reminds us of what had happened in the developing history of computer and networking areas in which the broad acceptance and adoption of the TCP/IP (Transmission Control Protocol/Internet Protocol) protocol suite [10] significantly expedited the successful deployment of the Internet. For intelligent building developments, we believe that a unified and broadly-accepted building automation protocol can similarly accelerate this process.

The convergence has several potential benefits: (1) it will reduce the initial construction costs and the maintenance costs; (2) reduce the complexity of the networks inside the buildings; (3) facilitate the automation and interaction among different subsystems.

Another important issue and trend, as mentioned earlier, is that future ***intelligent buildings will not only act as end energy consumers but also energy providers***. In such cases, the buildings generating more energy than what they consume will feed the rest of the energy to the neighbored buildings or even back to the grid. This scenario is also called Distributed Generators (DG) and microgrid scenario in some other circumstances. In such prospect, the building-side intelligent systems will connect and interact effectively with each other and with the smart grid. Integrated with appropriate "demand response" and dynamic energy pricing strategies, the building stakeholders can achieve cost-effectiveness while the smart grid can realize optimization and efficiency in even

TABLE IV
ENERGY PROPORTIONALITY KEY ASPECTS COMPARISON BETWEEN TWO APPLICATION AREAS: COMPUTERS AND BUILDINGS.



	Energy-proportional Computing	Energy-proportional Buildings
Key energy-consuming components	CPU, memory, hard disk, etc.	HVAC, lighting, appliances,
Wide dynamic power range	CPU, etc. can consume energy in a wide and dynamic range, say, 1/10 to 1/3 of peak without significant performance degradation	Enable some key component to consume less power in idle or standby mode, hence, achieve wide power range.
Active low-power modes	CPU run at lower frequency mode without significant performance loss, and without transition to other modes	Enable the key components (e.g., the home HVAC system) to work with lower activity degree, but still in active.
Multiple running modes	CPUs are allowed to work in different frequencies and speeds, hence consume energy according to the actual workload intensity.	Enable the key components (like lighting) to work in different intensities and modes, and with automated policy transition.

larger scales, as what we envisioned and discussed in Section VII.

IX. CLOUD COMPUTING [85] IN FACILITATING THE INTERACTION BETWEEN CONSUMER-SIDE AND PROVIDER-SIDE GRID

The Internet is a great example for comparison with the power grid. While the current Internet has changed from the previously relative simpler role of delivering information from one place to another, the recent dramatic developments of several Internet companies like Facebook, Google, and Apple have dramatically changed the ways people acquire information and interact with each other, and deeply shape the new directions for future Internet evolution.

Particularly, besides the smart phone technology, the emergence of cloud computing technology is an important factor that can potentially lead to somewhat similar “paradigm shift” for the power grid. The current power grid looks more or less like the previous Internet in the sense that the gird just delivers the power from one place to another without too much advanced intelligence incorporated. Potentially, we find the following places that the cloud computing technology can make a difference in the energy efficiency of buildings and microgrids:

- **Cloud-assisted In-building Energy Monitoring and Optimization:** Using clouds to store energy consumption data and to carry out offline modeling computation will free the building owners and operators from tedious and expensive maintenance on all kinds of servers and devices. Moreover, clouds can interact well with the smart phone technology in creating user-aware and user-customizable energy optimization applications in the building environments, just as we have found in our research [79].
- **Cloud-assisted Energy Capacity Allocation and Optimization in Micrograms:** In the above discussion on distributed generation and microgrid trend, there is a potential demand of creating interaction and synergy among intelligent buildings in a neighborhood to optimize the energy generation and utilization in a local scale. Cloud computing technology is very scalable and its usage can be easily generalized from the in-building optimization into the microgrid optimization usage. Using clouds, energy generation and consumption information of multiple intelligent buildings can be shared and exchanged to create an optimized capacity allocation strategy to achieve maximum efficiency in the microgrids, or even “smart community” and ”smart cities” [86] grids in the future. The conventional power grid can benefit by using the cloud computing technology for information sharing and data storage without bearing significant amount of construction and maintenance costs. Locally optimized energy allocation and consumption can help reduce the overall consumption and achieve cost-effectiveness across the whole smart grid. Specialized applications can be built on top of such cloud computing platforms with lower costs and faster development and implementation speeds. An example of using clouds in the area of energy is the IBM’s smart energy cloud [89] which tries to gather energy information through the smart metering infrastructure. The “Green Cup” energy-saving competition [83] and “Green Lab Initiative” [84] in Washington University in Saint Louis campus, mentioned earlier, also demonstrate fruitful benefits of engaging clouds in intelligent buildings and energy efficiency related applications.

A. Home Building Automation Challenges and Opportunities

As we discussed earlier, the intelligent technologies have been available for some time but the adoption of them have fallen short of expectation, especially for the home or residential buildings. Many researchers have investigated related issues like the home networking, devices interoperability, access control for data sharing, Home OS, and user experience experiments. However, before the related research can really change the stagnant situation and make a difference in the future, several issues or challenges have to be addressed. We summarize them as follows. Note that these challenges also mean potential opportunities if they can be solved appropriately.

- **Relatively High Cost:** Due to the immature market, the current smart devices at home are relatively expensive. Especially, some systems require specialized technical supports which also potentially add to the costs of the projects. Another cost is that of the training needed for the users and the time users have to spend in learning to use the intelligent systems. Reducing these costs is necessary to expedite the development of intelligent buildings industry and market on related products and services. Moreover, affordability is also an important issue for users with different financial capabilities. Differentiating products and services for various categories of demands may be a good strategy to promote the development of intelligent buildings.

- **Complexity and Inconvenience for the Users:** Some existing products have complex user interfaces and functionalities which are relatively difficult to use for customers without special technical knowledge or training. Complexity may also leave some features unused or cause some misuses and bring unexpected losses. User-friendliness can make huge difference for the adoption and popularity of a specific technology and product. Necessary consulting services and technical supports can also help users resolve technical or non-technical issues and enhance their confidence in using the in-home intelligent systems.
- **Reluctance of Sacrificing Security for Functionality:** Users are sensitive about privacy and security issues. So when they are not confident about security, they may leave some of the advanced features alone. Typical example is the Internet-based remote control of the in-home appliances. Though in some specific situations such features can be very useful, many users may leave them alone before the potential security risk is eliminated, which potentially reduces the effectiveness of automation and the related intelligent technologies used in the buildings.
- **Difficulty in Integration:** A true intelligent home building is not only about installing individual smart devices, it also means interconnecting all such devices and putting it under control of the users. Subsystems and devices from different vendors may be difficult to be integrated into a coherent system, hence losing part of the original functionalities. There is also a chance that the users are forced to stick to a few brands to avoid such inflexibility and loss of functionalities. Such inconvenience calls for progress in protocol standardization and full competition in the product markets.
- **Design Incorporating Features that Users Care Most:** Most of the available products in smart homes are actually creating improvements in a specific aspect and few are about a friendly coherent system with user-friendly user interface and features matching the demands well. For example, when designing a fancy feature, security issues that the users care should be considered. More innovations in this aspect are of great importance and hence potential in the near feature. Other typical such features include group-based authorizations (like adults, children, grand-parents, visitors, etc.), easiness for changes when occupants move, flexibility of using different product brands and vendors, and getting timely technical supports or consulting services when needed.

B. *New Opportunities in a Smart World*

Recently, there is a very significant paradigm shift happening which is the mobile Internet trend. In this shift, smart phones/pads with GPS, various network connections (such as 3G/4G, WiFi, Bluetooth, etc.), and multiple sensors are becoming much more popular and potentially can be a very important part of the intelligent building technologies. For example, there are smart thermostat devices coming with iPhone or Android applications enabling common device holders to be able to monitor and control the appliances in the buildings. More than that, every smart phone has multiple sensors (such as location sensors) which can be used to create location-sensitive applications to improve the energy efficiency of the building by introducing interaction among multiple buildings [79].

Internet of Things (IoT) [87] concept and the development of Cyber-Physical Systems (including wireless sensor networks [7]) also produce new opportunities. For example, the wireless sensor based power meters [88] enable easy and cheap indoor power metering without wirings. It is easy to gather information, maintain, and reconfigure the networks. Low-cost small-sized smart tags can also be used to monitor the occupancy rate inside the buildings and the information can be further used in deciding the building control policies to save energy, provide best human comfort, and increase human productivity.

In the future, it is expected that more such devices and applications will emerge and come into the intelligent buildings or smart homes and change everyone's daily life. These new intelligent technologies can be embedded and applied into the conventional buildings to improve the energy efficiency, security, human comfort, productivity, coordination with the smart grid, and global sustainability.

X. CONCLUSIONS

In this paper, we presented a survey of the current research and development status of the intelligent buildings and microgrids in a combined perspective of energy efficiency and mobile Internet. It focused on the major related technologies as well as discussions on key issues and trends that can potentially motivate the adoption and revival of the area after a relatively long history of stagnancy. We have attempted to draw an overall picture of the research status in this area and to discuss potential areas for further research that can potentially generate huge impacts on everyone's daily life as well as global environmental sustainability which is important not only for the current population but also future generations.

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