Smart Connected Buildings Design Automation: Foundations and Trends

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Abstract

Buildings are the result of a complex integration of multi-physics subsystems. Besides the obvious civil engineering infrastructure, thermal, electrical, mechanical, control, communication and computing subsystems must co-exist and be operated so that the overall operation is smooth and efficient. This is particularly important for commercial buildings but is also very relevant for residential buildings especially apartment buildings. Unfortunately, the design and deployment of these subsystems is rarely synchronized: lighting, security, heating, ventilation and air conditioning systems are often designed independently. However, simply putting together a collection of sub-systems, albeit optimized, has led to inefficient buildings of today. Worldwide, buildings consume 42% of all electrical power – more than any other asset – and it can be proven that much of this can be reduced if a holistic approach to design, deployment and operation is taken.

Government agencies, academic institutions, building contractors and owners have realized the significant impact of buildings on the global environment, the electrical grid, and the mission of their organizations. However, the economic impact for all constituencies is still difficult to assess. Government regulations can play a fundamental role, as it has been the case for the transportation industry where regulations on emission and fuel consumption have been the single most important factor of innovation in automotive design.

We are convinced that by leveraging technology and utilizing a system-level approach to buildings, they will provide comfort, safety and functionality while minimizing energy cost, supporting a robust electric grid and mitigating environmental impact. Realizing this vision requires adding intelligence from the beginning of the design phase, to deployment, from commissioning to operation, all the way to the end of the building's life cycle.

In this issue, we attempt to provide an overview of the activities in the field of smart connected building design automation that attempts to make the vision a reality. The overarching range of such activities includes developing simulation tools for modeling and design of buildings, and consequently control algorithms proposed to make

buildings smarter and more efficient. Further, we will review real-world and large-scale implementation of such control strategies on physical buildings. We then present a formal co-design methodology to design buildings taking the view that buildings are prime examples of cyber-physical systems where the virtual and physical worlds meet, as more traditional products such as thermostats are able to connect online and perform complicated computational tasks to control building temperature effectively. We complete the presentation describing the growing role of buildings in the operation of the *smart grid* where buildings are not only consumers of energy, but also providers of services and energy to the smart grid.

The audiences for this monograph are industry professionals and researchers who work in the area of smart buildings, smart cities and smart grid, with emphasis on energy-efficiency, simulation tools, optimal control, and cyber-physical systems design for the emerging and connected power markets.

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Introduction

The term *intelligent* or *smart building* refers to the next generation of buildings that provide new levels of comfort to the occupants with minimum possible energy consumption. They not only follow commands, but also proactively learn from occupants' behavior and adapt their operation based on the indoor and outdoor conditions. These buildings are no longer solely consumers of energy, but also significant players in the ecosystem of smart grid, in that they provide regulation services to the grid as well as energy if equipped with solar panels or other green sources. Intelligent buildings not only are safe by design, but also react in the case of a fault, system malfunction, or cyber-attack to steer the system into a safe operating region. There has been much research in academia and industry towards this goal. Companies such as Nest (https://nest.com/), recently acquired by Google, have been formed over the last few years to bring new technologies in this space to the public. In this paper, we present an overview of the work done in this domain over the last two decades.

1.1 Why Buildings?

But why buildings are so important? According to an Environmental Protection Agency (EPA)[1] survey, on average, Americans spend approximately 90% of their time indoors. Commercial Buildings Energy Consumption Survey (CBECS)[2] estimates that there were 5.6 million commercial buildings in the United States in 2012, comprising 87 billion square feet of floor-space. This level represents a 14% increase in the number of buildings and a 21% increase in floor-space since 2003, the last year for which results are available. Between the first CBECS (conducted in 1979) and the latest 2012 CBECS, the number of commercial buildings in the United States has increased from 3.8 million to 5.6 million, and the amount of commercial floor-space has increased from 51 billion to 87 billion square feet. On the residential side, nearly 130 million residential housing units existed in the U.S. in 2010. Approximately 7.188 million new housing units were built between 2005 and 2009, according to the American Housing Survey (AHS [2008]). The total primary energy consumption in the United States increased from 35 quads[3] in 1950 to 78.3 quads in 1980 to over 98.5 quads in 2014 as shown in Figure 1.1 by the Energy Information Administration (EIA)[4]. In 2014 the building sector accounts for 39.87% of this total consumption according to the EIA as shown in Figure 1.2. The industrial and transportation sectors represent the remaining 31.33% and 27.12%. Electrical energy consumption of buildings doubled in the last 18 years, and another 25% growth is projected through 2030. Residential buildings accounted for 54.6% of the total energy consumption in the building sector, while commercial buildings accounted for the other 45.4%. The building sector is also responsible for almost 40% of greenhouse gas emissions and 70% of electricity use. The energy consumption by Heating Ventilation and Air Conditioning (HVAC) systems is 50% of the total energy usage in buildings and 20% of the total national en-

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[1] Buildings and their Impact on the Environment: A Statistical Summary. http://www.epa.gov/greenbuilding/pubs/gbstats.pdf

[2] http://www.eia.gov/consumption/commercial/

[3] A quad is a unit of energy equal to 1.055×10^{18} joules.

[4] Annual energy outlook 2015. http://www.eia.gov/totalenergy/

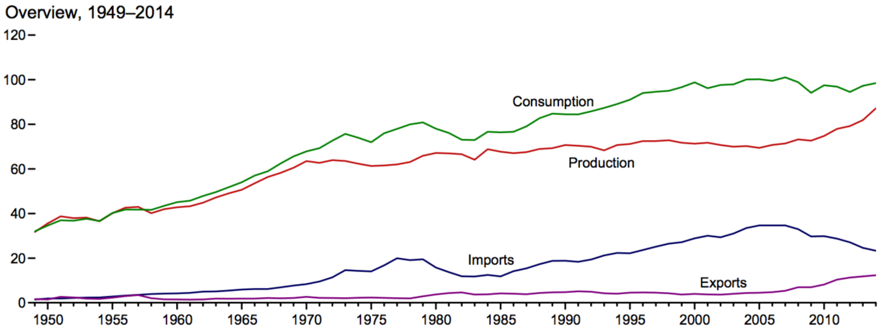
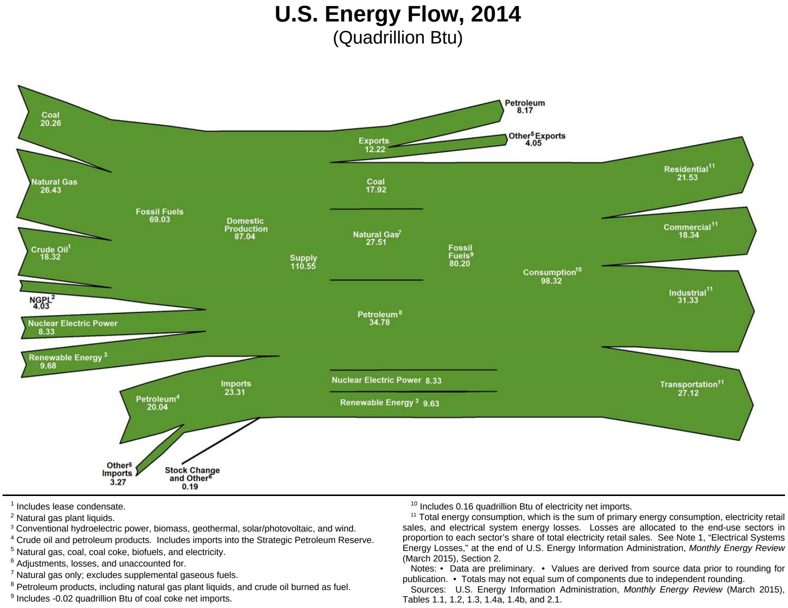


Figure 1.1: US Primary Energy Overview (Quadrillion Btu).

ergy usage in European and American countries Pérez-Lombard et al. [2008]. HVAC energy consumption can exceed 50% of the total energy usage of a building in tropical climate Chua et al. [2013].

The industrial sector has always been optimizing its processes to reduce cost and increase profit. In the transportation sector, in the last 30 years a great amount of work has gone into emission and fuel consumption reduction via better engine control, and efforts are already well under way to find suitable alternatives to oil. Bio-fuels are one possibility. Alternative types of vehicles – hybrids, electric vehicles, and vehicles powered by hydrogen fuel cells, for example – all have the goal of reducing our dependence on oil. The Corporate Average Fuel Economy (CAFE) standards, initially adopted in 1975, made more stringent in 2007, and strengthened again in pending legislation, require automobile manufacturers to build cars with higher average fuel economy. On the other hand, historically, not much has been done to improve the energy efficiency of buildings.

Growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside buildings, assure that the upward trend in energy demand will continue in the future. For this reason, energy efficiency in buildings is a prime objective today for energy policy at regional, national and international levels.



U.S. Energy Flow, 2014
(Quadrillion Btu)

[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biofuels, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Natural gas only; excludes supplemental gaseous fuels.
[8] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[9] Includes -0.02 quadrillion Btu of coal coke net imports.
[10] Includes 0.16 quadrillion Btu of electricity net imports.
[11] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note 1, "Electrical Systems Energy Losses," at the end of U.S. Energy Information Administration, *Monthly Energy Review* (March 2015), Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: U.S. Energy Information Administration, *Monthly Energy Review* (March 2015), Tables 1.1, 1.2, 1.3, 1.4a, 1.4b, and 2.1.

Figure 1.2: US Energy Flow in 2014 (Quadrillion Btu).

1.2 Why *Smart* Buildings?

Given that we spend on average more than 90% of our time in buildings and the fact that 40% of total energy consumption is being consumed in buildings, it is crucial that these systems are safe and comfortable while consuming the minimum amount possible of energy. In order to achieve these objectives, we need to make buildings smart about the way they operate. Studies such as the American Housing Survey for the United States by EnergySTAR, have shown that 30% of energy consumption of commercial buildings is wasted and could be saved by continuously monitoring and adjusting operations of these buildings. Achieving safety, energy efficiency and comfort is only feasible if all subsystems in the building continuously sense the environment, communicate between different parts of the system and make the right decision both individually and collectively.

Buildings of the future are perceived as entities for real-time energy trading, as opposed to passive energy consumers. In this scenario, buildings not only need to be aware of and responsive to the internal conditions, but also need to be able to operate their subsystems (e.g. HVAC, and lighting) in coordination with the grid. Real-time pricing combined with the intelligence of the Building Energy Management System (BEMS) to operate the building in a cost-effective way, is an example of such scenarios. More sophisticated scenarios would involve buildings operating in a cost-effective way given not only the real-time energy prices, but also *rewards* that a utility or system operator may offer buildings to provide *flexibility* in their energy consumption. The latter scenario would require a fundamentally different building control design; operating a system in the most cost-effective manner does not typically lead to much flexibility around the operating trajectory. In a scenario where the objective is defined not only by the goal of reducing energy cost, but also by the reward for operating in certain regions, the optimization problem becomes multi-objective and nontrivial.

1.3 Areas of research

According to the building energy data book of the US Department of Energy (DOE)[5], about 50% of the energy consumption in buildings is directly related to space heating, cooling and ventilation as shown in Figure 1.3. As such, reducing building energy consumption by designing smart control systems to operate the HVAC system in a more energy-efficient way is critically important to address the worldwide energy and environmental concerns. With the advent of smart, easily-controllable and remotely-accessible thermostats, smart meters, and two-way broadband communication infrastructure between occupants and buildings via smart devices such as smartphones and next generation connected electric cars, as well as between the buildings as consumers of energy and utility companies as providers of energy, the role of buildings in the operation of the smart grid will be even more significant and crucial compared to the current state-of-the-art.

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[5] http://buildingsdatabook.eren.doe.gov/default.aspx

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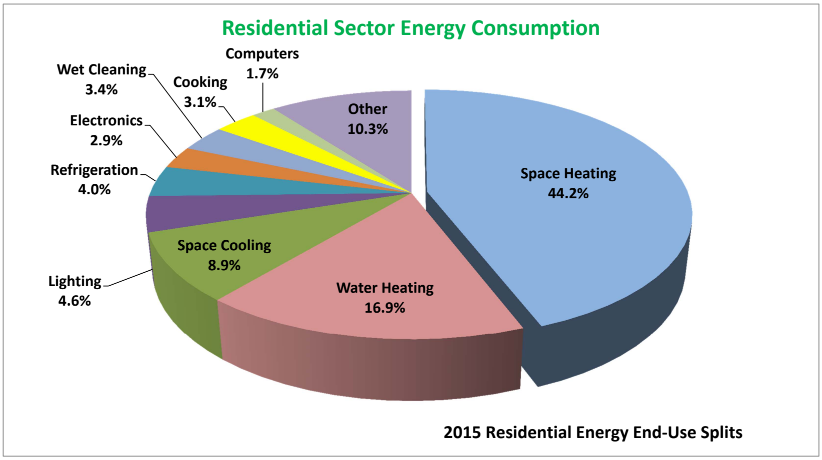

Figure 1.3: Breakdown of energy consumption in a typical building. Over 50% of energy consumption is related to HVAC systems.

In the last decade a significant amount of work has been done in areas that, directly or indirectly, have contributed to achieving improved performance, reliability and efficiency of buildings. We categorize this work into the following areas:

- Simulation tools;
- Building models;
- Building control design;
- Test-beds and real-scale experiments;
- Buildings as cyber-physical systems;
- Smart buildings in the smart grid ecosystem.

In this monograph, we provide an overview of what has been achieved in each of these areas, and we highlight emerging or existing areas for research.

1.4 Organization

The remaining chapters of this monograph are organized as follows:

We start by reviewing the simulation tools that have been developed over the years in Chapter 2. We cover EnergyPlus and Modelica Libraries among other building simulation tools.

We then present our work in modeling buildings. In particular, we first present Resistor-Capacitor (RC) models, which are the building blocks of the majority of building simulation tools. Next, we show how we use related available information from additional sensors such as CO2 sensors, outside air temperature, and Global Horizontal Irradiance (GHI) to infer quantities that are not measured, such as internal and external heat gains and un-modeled dynamics.

Furthermore, we show how the proposed modeling framework can be enhanced by introducing a Parameter-Adaptive Building (PAB) model. The proposed PAB model leverages a Kalman filter-based state estimation algorithm to simultaneously estimate the states and parameters of the system, resulting in a parameter-varying model.

We first provide an overview of classical building HVAC controllers. We then present a hierarchical control scheme in which the high-level controller optimizes a cost function and sends the optimal set-point to the local low-level PID controllers. The majority of Chapter 4 is devoted to obtaining and studying Model Predictive Control (MPC), Robust Model Predictive Control (RMPC), Stochastic Model Predictive Control (SMPC), and Exergy-based Model Predictive Control (XMPC), and studying the performance of each in the presence of model uncertainty. At the end of this chapter we provide a guideline for selecting the most appropriate control strategy based on the accuracy of the building model.

In Chapter 5 we review some of the outstanding efforts in this domain, and present some findings on how effective new control techniques are when implemented on real buildings. We focus on real-scale implementation of novel control algorithms on buildings and classify the studies according to the system that was controlled (e.g. whole building, test cell), the actuators, the total experiment time, and the MPC model.

After presenting various control strategies in Chapter 4, and reviewing real-scale implementation of such algorithms on real, physical buildings, we present a framework to co-design the control algorithm and the embedded platform for building HVAC systems in Chapter 6, thus treating a building as a cyber-physical system. As complex cyber-physical systems, HVAC systems involve three closely related subsystems – the control algorithm, the physical environment and the embedded implementation platform. In this chapter, we propose a co-design approach that analyzes the interaction between the control algorithm and the embedded platform through a set of interface variables, in particular the sensing accuracy. Based on the proposed models, we explore the design space of the control algorithm and the embedded platform to optimize a system with respect to energy cost and monetary cost while satisfying the constraints for user comfort level.

In Chapter 7, we address the future role of smart buildings in the context of the smart grid. We first propose a means to define and quantify the flexibility of a commercial building. We then propose a contractual framework that could be used by building operators and utility companies to declare flexibility on one side and reward structure on the other. Subsequently, we design a control mechanism for the building to decide its flexibility for the next contractual period to maximize the reward, given the contractual framework. Finally, we perform at-scale experiments to demonstrate the feasibility of the proposed algorithm.

Finally, Chapter 8 draws the conclusions of the monograph with a discussion on the possible directions for future work.

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