Human-Centered Sustainable and Resilient Buildings Enabled by Innovative Cyber-Physical-Systems

By Dr. Jin Wen
Associate Professor, Department of Civil, Architectural, and Environmental Engineering, Drexel University
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Buildings consume more than 40% of the primary energy and 73% of the electricity, which are far more than those by the transportation or industrial sector. On the other side, the National Energy Technology Laboratory (NETL) found that, with 10 percent participation, the potential nationwide value of demand dispatch (within and to buildings) could be several billion dollars per year in reduced energy cost. Moreover, people spent nearly 90% of time indoors, the quality of a built environment significantly affect occupants' health, productivity, and well-being. Despite the significant roles that buildings play in modern energy infrastructure and society at large, existing buildings routinely fail to perform as expected, which result in energy waste, high peak demand, and unsatisfactory indoor environment.

Current sensing, control, and operation practices in buildings have been identified as a major contributor to the poor building performance. We envision that a completely re-designed and cyber-enabled building monitoring and control system (from sensors to strategies) can drastically improve the current building performances by fostering new and better relationships between buildings and grids, buildings and their occupants, and among buildings themselves.

A new cyber-enabled building monitoring and control system integrates buildings as a grid resource

Despite the development in net-zero buildings and smart grid, the relationship between buildings and the grid is still mostly one-way (from grid to buildings). Although large buildings do participate in demand response programs to respond to emergent needs of the grid, such responses are performed in a rudimental (and often heavily manual) manner due to the lack of advanced energy monitoring, forecasting, and automated optimization strategies. Considering the fact that intermittent and/or variable generation sources and load are increasingly available in a distributed manner within the grid, it is envisioned that a two way relationship (transaction-based control) could exist between buildings and the grid so that buildings can respond to the grid (and vice versa) seamlessly to drastically even the overall grid load profile and reduce peak demand. To realize such vision, there is a need for

- Low cost (and plug-n-play) energy meters and other relevant sensors so that the buildings can understand their subsystem energy consumption patterns;
- High fidelity energy forecasting models and automated decision making tools;

- Secure and high resolution cyber infrastructure to support the communications within a building and between buildings and the grid.

A new cyber-enabled building monitoring and control system enables building systems to better serve their human occupants and to place them as the focus of the building performance

Innovative sensing and information exchange mechanisms can reform the relationship between buildings and occupants and place human as the center of building performance. Current building systems have very few means to interact with their occupants. For example, the occupant comfort, is often very indirectly estimated by a remote thermostat. In reality, the occupant's thermal comfort is not only affected by surrounding air temperature, but is more strongly affected by the occupant's metabolism, clothing level, received radiation etc. More direct measurement, such as occupant's skin temperature (through infrared sensing or wearable sensors), provide much more accurate feedback about the occupant's thermal comfort, which in turn, could reduce energy consumption and improve occupant's well-being and productivity. Other new sensors, such as low cost plug-n-play wireless energy measurements, could provide valuable information to the occupants about how their behavior affect building energy consumption, or how energy is consumed in their buildings, which could lead to more energy conscious behavior and decisions. Research needs to realize this vision include

- Innovative sensing mechanism and low cost sensors to better measure human comfort and other environmental variables that affect the occupants' productivity and health;
- Innovative information display and exchange mechanism to enable occupants and/or operators to make energy conscious building operation decisions and to enable building systems to understand and respond to the occupants' needs.

A new cyber-enabled building monitoring and control system makes buildings more sustainable and resilient

Buildings rarely perform as designed due to many factors. Among which, equipment and control faults, as well as the lack of comprehensive optimal control strategies, are often considered as the major contributors. Many studies have suggested that either automated fault diagnosis or optimal control alone can reduce building energy consumption by at least 15 to 30 %. However, the lack of high quality building data (due to both measurement insufficiency and data problems), the lack of local computation capabilities, and the lack of low cost (including engineering hours) and plug-n-play fault diagnosis and optimal control strategies yields a low adoption rate of such advanced strategies in buildings. Cyber-enabled data exchange and cloud technologies provide new and potentially low cost means for buildings that do not have comprehensive control and monitoring systems, such

as those small to middle sized buildings, to adopt advanced fault diagnosis and control strategies. Such strategies could be provided and performed by a third-party service company, rather than building operators to reduce the training needs and cost. To realize such vision, similar research needs, such as low cost sensor, high data quality, and cyber security, exist. Meanwhile, new fault diagnosis and control strategies that are self-learning, robust to data quality, and plug-n-play need to be developed.

In summary, innovative cyber-enabled building monitoring and control systems, including new sensing technologies, data and communication technologies, control strategies, and data analysis strategies, have the potential to significantly reduce building energy consumption, open buildings up as a grid resource, and improve building occupants' health and well-being.