How Smart Do Intelligent Buildings Need to Be?

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Abstract

Intelligent Buildings have enhanced operation, monitoring, and control, and promise greater energy efficiency, business productivity, and building security and safety. However, increased complexity and energy overhead — resulting from the supporting networking, sensors, and controls — is an overlooked consequence of connected devices and systems. Such overhead adds cost, energy load, and operations and maintenance (O&M) complexity. Instead of an "all of the above" approach to building intelligence, this project investigated how the intelligent technologies need to be optimized with respect to the specific needs and uses of the occupants of the space and the staff who are responsible for operating and maintaining the space. Intelligent building systems offer benefits in energy savings, productivity, and health and safety but can yield increased costs, baseload power consumption, and O&M. Through analysis and modeling, the energy costs of building intelligence are weighed against the benefits that are provided to determine both opportunities and constraints of these technologies. Lab testing was also performed to investigate potential opportunities for office plug load control. A market analysis investigated the factors that may be necessary to promote wider adoption of intelligent building technologies.

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AC	Alternating Current
APS	Advanced Power Strip
ARCs	Automatic Receptacle Controls
ARPA-E	Advanced Research Projects Agency – Energy
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
ASO	Automatic System Optimization
BAS	Building Automation System
BENEFIT	Buildings Energy Efficiency Frontiers & Innovation Technologies
BIG	Building Intelligence Group
BIG-TC	Building Intelligence Group of the Twin Cities
C4SB	Coalition 4 Smarter Buildings
CABA	Continental Automated Buildings Association
CBE	University of California Berkeley, Center for the Built Environment
CBECS	Commercial Buildings Energy Consumption Survey Estate
CC	Connected Community
CMMS	Computerized Maintenance Management Software
CRE	Commercial Real Estate
DALI	Digitally Addressable Lighting Interface
DC	Direct Current
DERs	Distributed Energy Resources
DF	Demand Flexible
DOE	U.S. Department of Energy
ECM	Energy Conservation Measure
EMIS	Energy Management Information System
ESG	Environmental, Social, and Governance
FDD	Fault Detection and Diagnosis
GEB	Grid-interactive Efficient Building

GHG	Greenhouse gas
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	Indoor Air Quality
IB	Intelligent Building
IBT	Intelligent Building Technology
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
IWMS	Integrated Workplace Management System
LAN	Local Area Network
LED	Light-Emitting Diode
LLC	Luminaire-level Lighting Controls
MBTF	Mean Time Between Failures
MELs	Miscellaneous Electric Loads
NARUC	National Association of Regulatory Utility Commissioners
NASEO	National Association of State Energy Officials
NGOs	Non-Governmental Organizations
NLC	Networked Lighting Controls
O&M	Operations and Maintenance
PCS	Personal Comfort System
PNNL	Pacific Northwest National Laboratory
PoE	Power over Ethernet
PPLs	Plug and Process Loads
PUE	Power Usage Effectiveness
PV	Photovoltaic
ROI	Return on Investment
ROV	Return on Value
SBIR	Small Business Innovation and Research
STTR	Small Business Technology Transfer

TIA	Telecommunications Industry Association
UI	User Interface
UL	Underwriter Laboratories
USB	Universal Serial Bus
USGBC	US Green Building Council
UX	User Experience
VFD	Variable Frequency Drive
X-PoE	Extended Power over Ethernet

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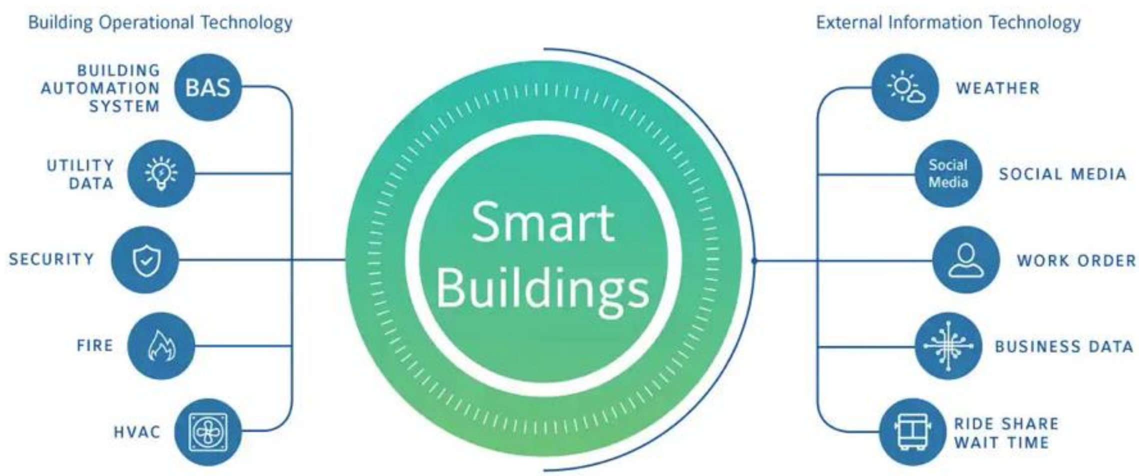
Executive Summary

Intelligent building technologies (IBTs) enable communication between devices, equipment, building systems, and business systems within the local area network (LAN) of the building and connected through the internet (i.e., the cloud) so that previously disparate systems can now share information and be operated by a set of integrated management systems. IBTs communicating across the cloud allow remote monitoring, communication, and management by property management and contracted service providers. Figure 1 shows the range of technologies that can comprise an intelligent building. Intelligent buildings can integrate the operation of building systems such as IT, lighting, HVAC, security, fire/safety, etc. to provide more efficient building operation and improved user experiences.

Figure 1. Intelligent Building Technologies.



A 2017 American Council for an Energy-Efficient Economy report[1] found that "[w]hereas an upgrade to a single component or isolated system can result in energy savings of 5–15%, [an intelligent][2] building with integrated systems can realize 30–50% savings in existing buildings that are otherwise inefficient. Savings can reach 2.37 kWh/sq. ft."

Intelligent Buildings and Demand Flexibility

While intelligent buildings (IBs) with connected systems have been promoted to stakeholders including developers, building owners, and tenants as having the potential to be operationally

[1] J. King and C. Perry. Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings. American Council for an Energy-Efficient Economy. Report A1701, February 2017. https://www.aceee.org/sites/default/files/publications/researchreports/a1701.pdf

[2] The King and Perry report uses the term "smart buildings." Currently, it has become accepted practice to refer to commercial buildings that incorporate IoT or smart technologies as "intelligent buildings," while residential buildings are usually referred to as "smart homes." For this report, to avoid confusion, we will use the term "intelligent buildings" for smart commercial buildings.

superior, these same connected systems can be enhanced to provide communication with the grid. This makes IBs an important component in providing grid-flexibility to utilities. These grid-interactive efficient buildings (GEBs) will promote the use of intermittent energy sources and support the transition to non-carbon energy sources. The U.S. Department of Energy (DOE) defines GEBs as "energy-efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way."[3] DOE has announced a national goal for GEBs to "triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels" and have published a national roadmap in support of the development and implementation of GEBs.[4]

In a multi-building application of GEBs, DOE has been fostering the development of Connected Communities (CCs).[5] In 2021, DOE invested $61 million for ten CC projects to equip over 7,000 buildings with smart controls, sensors, and analytics to demonstrate how CCs can reduce energy cost use, costs, and greenhouse gas (GHG) emissions.[6] CCs are defined as "a group of contiguous or non-contiguous buildings that incorporates central controls to manage multiple DERs at the multi-building scale, enabling communication to and from the grid for optimized and coordinated operations and dispatch."[7] CCs can provide utilities with the grid flexibility needed to reduce GHG emissions. DOE expects that CCs will help to attain a carbon-free electricity system by 2035 and zero-carbon energy sector by 2050. IBTs enable the benefits that are created by GEBs and CCs as long as they are implemented properly and used appropriately and to their greatest advantage.

The Hidden Energy Cost of Building Intelligence

An important component of demand flexibility is energy efficiency, so it must be recognized that, as with most technological solutions, reliance on IBTs comes with an energy cost. Within the context of building energy use, IBTs have: (1) components that are on standby when not in

[3] A. Satchwell, M.A. Piette, A. Khandekar, J. Granderson, N. Mims Frick, R. Hledik, A. Faruqui, L. Lam, S. Ross, J. Cohen, K. Wang, D. Urigwe,D. Delurey, M. Neukomm, and D. Nemtzow. 2021. A National Roadmap for Grid-Interactive Efficient Buildings. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Building Technologies Office. https://eta-publications.lbl.gov/sites/default/files/a_national_roadmap_for_gebs_-_final_20210517.pdf

[4] A. Satchwell et al., op. cit.

[5] DOE Solar Energy Technologies Office Connected Communities Funding Program webpage. https://www.energy.gov/eere/solar/connected-communities-funding-program

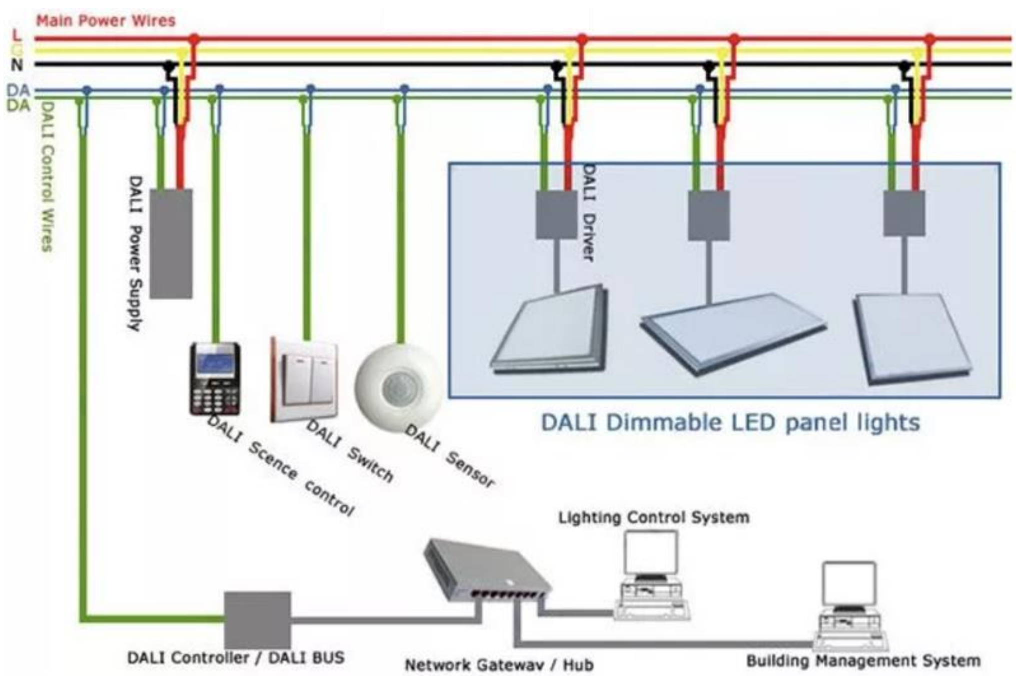
[6] DOE Press Release, "DOE Invests $61 Million for Smart Buildings that Accelerate Renewable Energy Adoption and Grid Resilience," October 13, 2021. https://www.energy.gov/articles/doe-invests-61-million-smart-buildings-accelerate-renewable-energy-adoption-and-grid

[7] V. Olgyay, S. Coan, B. Webster,and W. Livingood. 2020. Connected Communities: A Multi-Building Energy Management Approach. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-75528. https://www.nrel.gov/docs/fy20osti/75528.pdf

use and therefore can result in phantom loads[8] and (2) devices that must operate continuously and add to the building's baseload power. In this way, the infrastructure that is required to support IBTs has an energy cost. For example, the intelligence that comes with the networked lighting system requires that the sensors (occupancy and daylighting), controllers, gateways, servers, and network switches will be drawing power whether the lights are on or off. This baseload or standby power is an energy cost that is incurred 24/7. The benefits brought by greater building intelligence must offset the energy required to power these IBTs. Otherwise, adding IBTs to a building's energy load is simply adding to the building's capital and operations and maintenance (O&M) costs.

For example, consider an intelligent lighting system such as the Digitally Addressable Lighting Interface (DALI) lighting system. DALI is a two-way communications protocol used by building automation systems (BASs) to control individual lights and lighting groups. The DALI system uses a controller that is network-connected to individually addressable DALI LED drivers and LED bulbs. Figure 2 shows a schematic of a DALI lighting system that consists of a network gateway/hub, DALI controller/DALI BUS, DALI power supply, sensors, wall switches, ballasts/drivers, and network servers/switches for network control.

Figure 2. Schematic Diagram of a DALI Lighting System.



The intelligence that comes with the networked lighting system requires that the sensors (occupancy and daylighting), controllers, gateways, servers, and network switches will be

[8] A phantom load exists when a device or appliance consumes electricity when it is turned off. An example would be a television that is controlled by a remote control. When it is turned off, it sits in standby, using electricity as it waits for a signal from the remote to turn on.

drawing power whether the lights are on or off. This baseload or standby power is an energy cost that is incurred 24/7. Table 1 shows the comparison of the power draw from three lighting systems that were monitored in a school classroom and administrative offices in a Power over Ethernet (PoE) study.[9] The classroom has normal AC-powered LED troffers that were connected to a wall switch without any network connections. The two administrative offices had networked LED troffer lighting systems: one a PoE troffer lighting system and the other an AC-powered DALI LED troffer lighting system.

Table 1. Comparison of Power Draws of Non-Networked and Networked Lighting Systems.

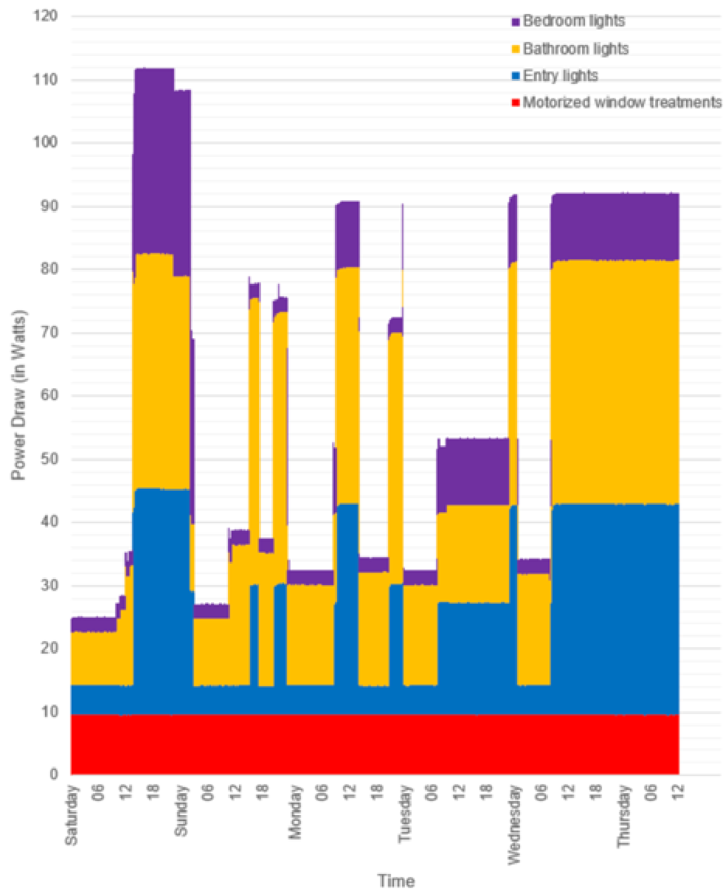
Lighting System	Non-networked AC LED lighting	PoE networked LED lighting system	DALI networked lighting system
Power/Fixture	31 W	21 W	48 W
Baseload/Fixture	0.3 W	4.2 W	4.8 W

The variation in power between the three systems is a result of the difference in illumination in each of the spaces. The baseload power per fixture shows that the IBT infrastructure of the two networked systems had similar baseload/standby power draws. This power draw could be defined as the energy penalty of lighting system intelligence.

Another example of the magnitude of the baseload/standby power of the IBTs is shown in Figure 3. The figure shows the power draw of the PoE devices in a guest room of a luxury hotel (which included connected PoE lighting system and motorized window treatments) over a five-and-a-half-day period of occupancy. The baseload/standby power was about 25 W or about 23% of the total power draw of the guest room when the room was at its greatest illumination over the time period of occupancy.

[9] Shen et al. 2022. The Demonstration of Power over Ethernet (PoE) Technologies in Commercial and Institutional Buildings. Minneapolis, MN: Center for Energy and Environment. https://mn.gov/commerce-stat/pdfs/137582_CEE_PoE-Project_Report-and-addendum-final-secure.pdf

Figure 3. Power Draw of the PoE Lights and Motorized Window Treatments in a Hotel Guestroom.



The baseload/standby power can also be considered the ***non-effective power*** which is defined as the power drawn by the network switch or a powered device that produces no work perceived by the user. ***Effective power*** is the power drawn from device hardware that produces effects that the user directly perceives as work. These networked building systems continue to draw power around the clock as the sensors, controllers, and network devices remain on alert in case a change in state requires the system to alter its operation (such as when the occupancy changes and the lighting and HVAC systems adjust) or a pre-determined schedule calls for a change in the operational state of the building.

Optimization of Intelligent Technologies to Building Space Use

For the appropriate implementation of IBTs, it is important to weigh the added energy loads and system complexities against the level of intelligence that is suitable for the use of the space or room and its occupants. Understanding space use will help determine the level of control that is needed for the specific technologies such as lighting, HVAC, and plug loads and the types of sensors and intelligent systems required. This can ensure that the IBTs fit the needs of the specific space and are usable by its occupants. This system optimization can allow capital costs of the equipment and IBT baseload and standby power to be minimized while ensuring that the

IBTs are accepted and used by the occupants and staff in the buildings. To understand how smart a space should be, the following details need to be understood:

1. How will the space be used and what are the needs of the space's occupants?
2. Within that context, what building systems are needed in the space and what level of intelligence could optimize the performance of those systems?
3. What sensors and controls are needed to provide that intelligence?
4. Can the sensors and controls be integrated with the other systems serving the space?
5. How are the IBTs serving the space expected to operate in concert with the intelligent systems serving other spaces and with the services provided to the entire building?

Table 2 outlines the potential needs of commercial building space use types. Each building is composed of a number of different space types which will have their own uses and operational needs. For example, an intelligent lighting system in an open office area of cubicles will have different needs and functionality than the lights in a conference room or the lobby. In the case of an open office plan, the intelligent lighting system could be either networked lighting controls (NLC) where all or groups of lights in the space are controlled over the network or via luminaire-level lighting control (LLC), where occupancy and daylighting (photocell) sensors inform the operation of individual light fixtures. Similarly, sensors and controls working with the BAS would regulate the indoor environment based on occupancy levels and schedules, manage the power consumption of miscellaneous electric loads (MELs), and operate automated window treatments.

Table 2. Commercial Building Space Use Types.

Building Type	Space Type	Potential Intelligent Systems						
		Lighting	HVAC	IAQ	MELs	Occupancy Management	Window Treatments	Security
Office	Open Office Plan	x	x	x	x	x	x	
	Small Collaborative and/or Small Conference Area	x	x	x	x	x	x	
	Traditional Large Conference Room	x	x	x	x	x	x	
	Lobby/Common Area	x	x	x	x	x	x	x
	Kitchen/Break Room	x	x	x	x	x		
	Toilets	x	x	x		x		
	External Building	x						x
School	Classroom	x	x	x	x		x	x
	Auditorium	x	x	x	x	x		x
	Corridors/Hallways	x	x	x		x		x
	Reception Area	x	x	x	x	x	x	x
	Admin Office	x	x	x	x	x	x	x
	Gym	x	x	x				x

	Cafeteria	x	x	x			x	x
	Locker Rooms	x	x	x		x		
	Toilets	x	x	x		x		
	External Building	x						x
Hospitality	Guestrooms	x	x	x	x	x	x	
	Corridors/Hallways	x	x					x
	Exit Staircase	x				x		x
	Common Spaces	x	x	x	x	x	x	x
	Restaurant	x	x	x		x	x	x
	Toilets	x	x	x		x		
	External Building	x						x
Warehouse	Floor Space	x	x	x		x		x
	Offices	x	x	x	x	x	x	x
	Toilets	x	x	x		x		
	External Building	x						x
Big-Box Retail	Floor Space	x	x	x	x			x
	Offices	x	x	x	x	x	x	x
	Toilets	x	x	x		x		
	External Building	x						x
Data Center	Aisle Space	x	x		x	x		x
	Offices	x	x	x	x	x	x	x
	Toilets	x	x	x		x		
	External Building	x						x

The type of controls that are available for the different building systems will help to define the appropriate level of intelligence needed for a space. In Table 3, control types are shown for several building systems. The lighting system can have either zone/space/or building level control or luminaire-level control. The HVAC system can be controlled by thermostats in the space or by network control through the BAS. Plug loads can be controlled on the individual device level or via outlet or power strip control. Finally, occupancy management can be controlled by the individual or by space.

Table 3. Building System Control Types.

System	Type of Control		Level of Detail and Control	Examples
Lighting	Zone/space/building-level control	Networked scheduled on/off; occupancy sensors and manual control override possible	Primarily automated; highly integrated, low level of manual control	Lighting in common areas or exterior building security lights
		Network control with occupancy and/or photocell sensors to control groups of lights, seasonal and daylight	Mix of individually adjustable and non-adjustable lighting; on smaller scales, manual	Lighting in classrooms, meeting rooms, and office spaces

		adjustment of lighting possible	adjustments usually possible	
	Luminaire-level control	Occupancy and/or photocell sensors	Primarily automated; highly integrated, individual manual control possible	Aisles in warehouse where overhead lights illuminate storage racks as operators advance down the aisle to the shelves of interest
		Automated	Programmed by network lighting system or BAS and possibly integrated with another system	Lights in a school hallway are integrated with the security system to direct occupants toward building egress or to signify security alerts using color tunable lights
HVAC	Thermostat control	Individual spaces controlled by thermostats; Can be connected to larger thermal control system	Primarily manual, though large scale control also possible	Spaces conditioned by dedicated HVAC system or zone control
	Network control	Adjustment of heating and cooling based on overall need, floor-wide or zonal systems	Managed by Facilities through BAS	Building automation system
Electronics	Device-level control	Scheduled downtime for appliances; timer-based plug load controls such as scheduled automatic computer, printer, or copier power on or shutoff	Primarily automated; low level of control and detail	IT-controlled via network or by device
	Outlet or power strip control	Plug load controls	Primarily automated via network control or occupancy sensor, moderate level of individual control and integration, for some aspects	A controlled-circuit outlet or a smart power strip in an office or cubicle
IAQ	Space-level control	Monitoring of air quality and other environmental conditions with active sensors	Automated data collection; adjustments to indoor environment are made as needed, high level of integration, managed by facilities through BAS	Auditoriums, meeting rooms, cafeterias, gymnasiums, and locker rooms
Occupancy Management	Individual control	Visitor management; occupancy sensors, ID badges, and/or fobs	High level of manual operation of systems; high level of integration	Building or office entry points and other secure areas
	Space control	Scheduling of rooms	Higher level of control, by individuals	Meeting and conference rooms

With these control types in mind, a matrix (shown in Table 4) was created that recommends the types of control options that are appropriate for the various building systems and space types. For example, based on the previous experience with classrooms, luminaire-level control would be a case of over-engineering and the lighting control in the classroom should either be for the entire space or at most two or three zones.

Table 4. Building Space Use Controls Matrix.

Building System	Control Type	Office							School										Hospitality							Warehouse				Big-Box Retail				Data Center			
		Open Office Plan	Small Collaborative and/or Small Conference	Traditional Large Conference Room	Lobby/Common Area	Kitchen/Break Room	Toilets	External Building	Classroom	Auditorium	Corridors/hallways	Reception Area	Admin Office	Gym	Cafeteria	Locker rooms	Toilets	External Building	Guestrooms	Corridors/Hallways	Exit Staircase	Common Spaces	Restaurant	Toilets	External Building	Floor Space	Offices	Toilets	External Building	Floor Space	Offices	Toilets	External Building	Aisle Space	Offices	Toilets	External Building
Lighting	Zone/space/building-level control	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Luminaire-level control	x									x		x							x						x	x				x			x	x		
HVAC	Thermostat control	x	x	x					x	x			x						x			x	x				x				x			x	x		
	Network control	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x			x	x	x	x	x		x	x	x		x	x	x		x	x	x	
Electronics	Device-level control	x	x	x	x	x		x	x	x	x	x	x	x	x			x	x		x	x	x		x	x	x		x	x	x		x	x	x		x
	Outlet or power strip control	x				x			x				x						x								x				x			x	x		
IAQ	Space-level control	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x	x		x	x	x		x	x	x		x	x	x	
Occupancy Management	Individual control	x						x										x	x						x	x	x				x		x	x	x		x
	Space control	x	x	x	x			x	x	x	x	x	x					x	x		x	x	x	x	x	x	x	x		x	x		x	x	x		x

Power Usage Effectiveness (PUE)

With the development of IBTs, the emphasis has been on functionality rather than the energy use of the system itself. Consequently, IBTs have not necessarily been designed to optimize their baseload and standby power demands. ENERGY STAR[10] has provided ratings for many electronic devices and appliances, including IT and network devices that are part of or support IBTs.[11,12] While this is useful in selecting energy-efficient components for IBTs, a rating system for how the system as a whole operates would be an important metric to assess the amount of non-effective power the IBT draws during its operation. A possible approach could be taken from data centers and the Power Usage Effectiveness (PUE) factor. Energy Star defines PUE for datacenters as: "A standard industry metric, equal to the total energy consumption of a data center (for all fuels) divided by the energy consumption used for the IT equipment." It provides a measure to compare the power consumption of one data center to another. The larger the PUE, the less efficiently the data center is consuming power. A PUE of 2.0 means that only half the incoming power is used for data processing. Most data centers have a PUE in the range of 1.25 to 3.0 (from a high of 80% efficiency down to 33% efficiency).

For IBTs, we would define the PUE_{IBT} as follows:

$$PUE_{IBT} = \frac{Total\ Power}{Effective\ Power}$$

Where the Total Power of the IBT is the sum of the non-effective power (or baseload/standby power) and the effective power. A non-intelligent system should have a PUE_{IBT} nearly equal to 1, and as an intelligent system incorporates sensors, controls, and networking capability, the PUE_{IBT} will be greater than 1. In that way, the PUE_{IBT} could be a measure of the intelligence of a system.

Intelligent Building Taxonomy

To provide some guidance in the development of IBs, we have created an intelligent building taxonomy which defines five levels in which IBs can be categorized. These are:

- Level 0 which is the baseline building, defined as complying with U.S. building codes. The building has segregated, decentralized building systems with independent controls and sensors.
- Level 1 is the automated building which has automated systems that allow for centralized operation and management.

[10] ENERGY STAR "About ENERGY STAR" webpage. https://www.energystar.gov/about?s=mega

[11] ENERGY STAR "Choose ENERGY STAR IT Equipment" webpage. https://www.energystar.gov/products/low_carbon_it_campaign/choose_energy_star_it_equipment

[12] ENERGY STAR "Data Center Equipment" webpage. https://www.energystar.gov/products/data_center_equipment

- Level 2 is the integrated building in which the building systems communicate with the cloud through Internet of Things (IoT) devices and systems to allow remote coordination with onsite building, facilities, and IT staff.
- Level 3 are GEBs which have DERs and are integrated with the grid.
- Level 4 are buildings that are part of a connected community that shares energy resources with other buildings while also providing grid services.

Table 5 describes in greater detail the taxonomy that was developed. The features of each IB level describe the building systems and types of sensors and controls that define the level, along with the enabling technologies that provide the intelligent operation. The final column of the table lists the sublevels of system controls that could exist under each IB level.

Table 5. Intelligent Building Taxonomy.

Intelligent Building Levels		Description	Features	Enabling Technologies	Sublevels
0	**Baseline Building (code minimum in US)**	Building has segregated, decentralized building systems with independent controls and sensors connected to systems in individual floors, zones, and/or spaces.	• Thermostatic control of individual spaces. • Lights controlled manually with possible PIR occupancy sensors • RFID fobs for building entry • Elevators • IT • Telecomm • O&M performed by in-house facilities and building operator • Water, sewage, food wastes • Analog or digital meters	• Thermostats • PIR occupancy sensors/wall switches • RFID door lock and entry system • Utility savers switch	0.0 thermostatic control of space conditioning 0.1 Building entry security system 0.2 Utility AC savers switch 0.3 some lights controlled by PIR occupancy sensors
1	**Automated Building**	Building has automated systems that allow for centralized operation and management.	• HVAC system controlled by a computerized and centralized BAS • BAS may be managed remotely by mechanical contractor • EMIS with FDD and AI may be an option • Security system may be managed by remote contractor • Spaces may have internal networked lighting systems • Security cameras recorded on video within the building • Plug loads, MELs • Elevators • IT • Telecomm • IT becoming involved with O&M along with building operator • Water, sewage, food wastes • Digital meters	• Common network building LAN infrastructure (MDF and IDFs) is recommended, but not required. • BAS server, controllers, and sensors • Network lighting system server, sensors, switches • Control circuit outlets and networked smart strips • BAS gateway, cloud services optional • EMIS an option • Network lighting system gateway, cloud services optional • Security system gateway, cloud services optional • CCTV cameras, monitors, and recording equipment, building security system server and controllers	1.0 building security system 1.1a BAS/EMIS 1.1b networked lighting system 1.1c networked MELs control 1.2a connected contractor-managed security system 1.2b contractor-managed BAS/EMIS 1.2c contractor-managed networked lighting system 1.2d contractor-managed MELs
2	**Integrated Building**	Building systems are connected to the cloud using IoT devices and systems with	• Sensors employed by multiple systems (special requirements on the sensors)	• Building system bridges and gateways (need to be defined if replaced or built upon automate building techs)	3.1 BAS + networked lighting system 3.2 + security system 3.3 + MELs

		remote system O&M in coordination with onsite building, facilities and IT staff. This stage marks the bringing together of OT and IT. Building systems are integrated with each other and through the cloud with building systems sharing sensor, data, and operational sequences.	• Networked lighting system managed be cloud management system • Building systems can communicate with each other and work in tandem • Multiple systems controlled by the same management system (single pane of glass) • IT and building operations work as on-site staff for contractors with some O&M services provided by contractors • Requires some form of IT controls to manage remote access for contractors • Water, sewage • Smart meters	• Centralized network management with segregation of systems into separate VLANs or similar controls • Common building wireless infrastructure to support IoT sensors • Electrified window glazing • Auto shading (blinds/louvers) • Structural load sensing	
3	**Grid-Interactive Efficient Building**	Grid-interactive efficient buildings (GEBs) are energy efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way. (demand response)	• Two-way communications with the grid to optimize building operation with energy use • Building has integrated Distributed Energy Resources (DERs) including but not limited to PV, battery storage, EV charging. • Water, sewage, food wastes	• AMD smart meters • DERs and cloud management systems • Inverters • Submeters	4.0 Smart meters with 2-way communications with the grid 4.1a on-site generation 4.1b energy storage 4.1c EV charging 4.1d "Resiliency" Resource management 4.1e "Sustainability"
4	**Connected Community**	A community of GEBs that are designed to share energy resources amongst themselves and provide services back to the grid. (not limited to electricity, e.g. water)	• Grid-interactive and efficient. • Multiple technologies. • Multi-building optimization. • Shared systems. • Water, sewage, food wastes (e.g. grocery store food wastes to vodka)	• Multi-building or campus management system • Microgrid	5.0 Community-, campus-, or portfolios level- DER (and/or microgrid) connected to GEBs with 2-way communication with the grid

Energy Savings Potential and Cost-Effectiveness

To assess the energy savings potential of IBTs for Minnesota buildings, the team modeled the energy use and demand impacts of several classes of IBTs. We employed EnergyPlus[13] as the modeling tool since it is:

- Able to calculate impacts on both an energy (kWh) and demand (kW),
- Calibrated to Commercial Buildings Energy Consumption Survey (CBECS) data, and
- Able to model the Minnesota climate zones 6A and 7.

DOE standard commercial buildings were modeled to estimate and quantify the energy savings potential for Minnesota of the various IBT strategies on both a building and space use/type level. Simulated energy performance of the DOE standard small and large office (2016 and 2019 versions), as well as the primary school commercial building prototype models provided the basis of comparison for simulated energy performance of building models with intelligent technology. We conducted multiple simulations of the energy performance for each building model, considering different categories of intelligent technology being studied. This approach enabled us to assess the individual impact and cost-effectiveness of each technology separately. For each category of intelligent technology, we made one or more adjustments to the prototype models, including occupant-adjusted controls, time of day setpoints, plug load controls, daylight harvesting, exterior lighting control, vacancy sensor lighting controls, motorized shades with solar sensors, and variable volume air distribution.

The research team discovered that certain IBT strategies we wanted to evaluate could not be accurately modeled using EnergyPlus parameters. The effectiveness of IBTs heavily relies on real-time conditions specific to each building, which are constantly changing. Occupant behavior and building operator actions play a significant role in achieving desired results. Energy efficient IT solutions are designed to optimize energy consumption by smoothing the peaks and valleys. Attempting to model these optimizations without actual data would lead to skewed and unreliable results.

An operator of an office building or primary school will typically want a return on energy conservation measure (ECM) investments within 5–7 years. Payback periods greater than 5–7 years typically are not considered for investment. This payback period will vary by property owner and by property, and will be based on whether the investment consists of new construction or retrofit/replacement of an existing system, each of which may shorten the desired payback period.

In general, the payback period for large office building ECMs was shorter than for small offices. This is likely due to the scale of the impact to the energy savings, coupled with the fact that the small office has a smaller total energy cost and thus the energy savings delta was smaller. The cost to implement many of the ECMs in the small office building did not scale well and

[13] EnergyPlus homepage. https://energyplus.net/

compounded with the smaller impact to energy savings to extend the ROI payback period. Unsurprisingly, the ECMs with the shortest payback periods were those that only required programming changes to the building system setpoints. The following sections summarize the favorable and unfavorable ECM investments identified from the computer simulations.

Favorable ECM Investments

The impactful programming changes for each type of building include time of day heating/cooling setbacks, which started setting back the heating/cooling setpoint two hours earlier (at 17:00), and lighting control vacancy sensor setbacks to turn off lights in unoccupied spaces, which were modeled by reducing the lighting load during occupied hours by 10%. The payback period for these programming changes was under a year, often significantly so.

ECMs that required additional hardware to be installed had longer modeled paybacks. For both small office and primary school buildings, adding plug load controls to an additional 10% of the building's outlets so they can be added to the plug load setback schedule produces a favorable payback period under both ASHRAE 90.1-2016 and 2019.

By adding daylight harvesting sensors to either a small office or primary school, lighting energy loads can be reduced by dimming the lights when natural sunlight is entering the space. Under ASHRAE 90.1-2016 the cost to add daylighting sensors can be paid back in less than 5–7 years, but under the stricter requirements of ASHRAE 90.1-2019 the payback is extended beyond the favorable period and would not be advisable.

In the primary school setting, applying a ventilation-on-demand strategy to ventilate spaces based on the number of individuals present rather than on a schedule had a payback period that varied based on the cost of the implementation. A cost analysis for specific buildings will need to be conducted to determine actual costs for evaluating if the ROI is favorable on a case-by-case basis.

Unfavorable ECM Investments

Adding user-adjustable thermostats to the modeled small office building had a payback greater than 5–7 years. Given the small scale of the building and the meager cost savings relative to the cost to install user-adjustable thermostats do not make the investment in this ECM feasible.

Small office building exterior lighting controls are potentially worth incorporating. If exterior lighting can be controlled by a schedule that is configured through an existing control system, the cost to program the system to turn off exterior lighting is minimal and would meet the 5–7 year payback goal. However, if a photocell or other hardware is required to control the exterior lighting the payback period would exceed the goal.

The addition of variable frequency drives (VFD's) to modulate air-source heat pump fan air flow had an extremely long payback for the small office building and would not be an advisable investment.

Application of IBTs to Individual Office Spaces

Lab and field testing allowed us to examine the use of IBTs in the individual working spaces of office staff. Plug and process loads (PPLs) consume 47% of the total energy used by commercial buildings.[14] Hackel et al. measured savings of about 20% in a field study of Tier 1 advanced power strips (APSs) in Minnesota offices.[15] IBTs can provide smart control and operation of PPLs in workspaces along with the ability to integrate with the BAS to provide greater localized and individualized control with tempered zone control. This can not only provide energy savings benefits but also improve worker job satisfaction and enhance productivity, important non-energy benefits of IBTs.

Comfort and lighting issues are a major concern for office workers. Surveys performed on office building workers (with over 400 responses per survey) for a recent study[16] found that nearly two-thirds of respondents answered that the workplace physical environment impacted overall job satisfaction. Personal temperature and temperature control for staff working in their individual workspaces received among the lowest ratings in terms of satisfaction with nearly two-thirds of respondents wanting greater control of their local environment in the 2023 survey. When dissatisfied with space temperature, women were more likely to say it was too cool while men were more likely to say their office temperature was too warm. When workers were not satisfied with lighting levels in individual workspaces, the most frequently reported problem was that lighting was too bright.

For this testing, we studied the potential of two systems:

1. The opportunities of Raspberry Pi microcomputers to provide control of workspace PPLs.
2. The use of Personal Comfort System (PCS) chairs to offer office workers individual, localized control of their comfort needs at their workstations.

Raspberry Pi Microcomputer

We explored the implementation issues associated with plug load control using a combination of low-cost, open-source electronics hardware and software. Our experiments used a Raspberry Pi Pico W microcontroller which was chosen because of its low cost, integrated Wi-Fi support, and ability to execute scripts written in the popular, flexible, open-source Python language. The strengths of the microcontroller we chose are its flexibility and communication capabilities. It runs off a range of voltages from 1.8–5.5 V and has low power consumption, using 25 mA

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[14] EIA (U.S. Energy Information Administration). 2020. Annual Energy Outlook 2020. https://www.eia.gov/outlooks/aeo/.

[15] Hackel et al. 2016. Impacts of Office Plug Load Reduction Strategies Final Report for Conservation Applied Research & Development.

[16] Shen et al., 2023. The Integration of Wi-Fi Location-Based Services to Optimize Energy Efficient Commercial Building Operations. Minneapolis, MN: Center for Energy and Environment.

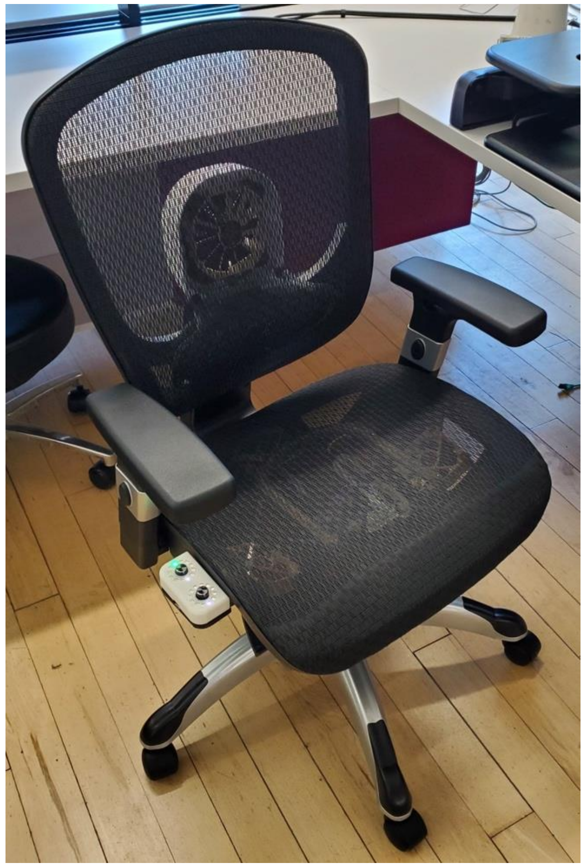
(0.125 W) while idle in standby mode. This would be a small energy penalty compared to the standby loads of the workplace PPLs that it could eliminate.

With this device, we demonstrated the ability to measure a space temperature and transmit it to other devices, and to energize outputs based on control messages received from other clients. For this demonstration we used the Wi-Fi capabilities of the microcontroller and an open-source library implementing the MQTT protocol, a popular IoT communication tool that is used in a wide range of applications. Ultimately, some form of commercial building automation communication protocol would need to be implemented on the microcontroller to integrate with a BAS. There are several open-source implementations of the BACNet stack that may deliver this functionality.

PCS Chair

The University of California Berkeley, Center for the Built Environment (CBE) designed and fabricated a kit, in the form of a cassette, to convert an ordinary mesh office chair into a PCS chair. Cooling functions were delivered by three small fans mounted beneath the seat and one fan in the chair back. Heating functions were delivered by resistive heat tape in the back and seat. The power source for the chair was a rechargeable battery pack mounted beneath the chair, which allowed the chair to move freely while in use. An occupancy sensor was used to ensure that the comfort system only activated when the chair was occupied. Heating and cooling functions were controlled by a pair of dials mounted on the side of the seat. Figure 4 shows the PCS chair that was used.

Figure 4. Personal Comfort Chair.



If deployed at scale, the data from these chairs would aid a building operator in a variety of building optimization tasks. The ability to visualize a fine grid of indoor air conditions, with temperature and humidity at each desk location and an overlay of comfort indicators in the form of control input levels, would allow building operators to balance comfort and energy efficiency by regulating ambient room temperatures in coordination with the individual comfort levels at each workspace. Yang et al (2022) noted that during the heating season, the ambient room temperature could be lowered without affecting comfort or satisfaction while individuals managed their personal comfort using their PCS chairs. In their field study they reported savings of over 50% of the heating energy for the space.[17]

The occupancy sensor offers additional intelligent control opportunities. Building operators could obtain detailed occupancy counts and understand the spatial distribution of staff to know whether consolidation is possible. The direct benefits these chairs provide to building occupants make this technology preferable to dedicated distributed sensing infrastructure for IBs. Since the PCS cassettes are powered by batteries, recharging the batteries at night results in load shifting of the heating/cooling energy provided by the PCS chairs and increases grid flexibility.

[17] Yang et al. 2022. Thermal comfort and energy savings of personal comfort systems in low temperature office: A field study, Energy and Buildings, 270, Article 112276.

Market Opportunities and Approaches

On February 7, 2023, Governor Tim Walz signed a clean energy bill that required Minnesota's electric utilities to transition to 100% clean energy by 2040.[18] Xcel Energy has pledged to reduce carbon emissions 80% by 2030 (over 2005 emissions),[19] while Minnesota Power has pledged to achieve this target by 2035.[20] Great River Energy, a wholesale electric cooperative and the state's second largest electric utility, expects that their currently ongoing power supply changes will bring a 95% reduction in carbon emissions (relative to 2005 levels) by 2023.[21] DOE suggests that by 2030, GEBs could reduce CO_2 emissions by 80 million tons per year, or 6% of the total power sector CO_2 emissions[22] and has published a national roadmap in support of the development and implementation of GEBs.[23] GEBs and IBs will be relied on to significantly contribute to those goals. Efforts needed to be expanded and coordinated to accelerate the adoption and implementation of IBTs in Minnesota.

The challenge for IBs is to create a tipping point to grow that market beyond early adopters to mass market acceptance. A major issue that hinders the effective implementation of IBTs is a lack of a coordinated approach by the purveyors of these systems to integrate the various intelligent technologies across the range of building systems. Table 6 summarizes the primary stakeholders for the intelligent buildings market.

Table 6. Intelligent Buildings Stakeholders.

Stakeholders		
Buyers	**Decision Makers**	Building owners
		Developers
		Commercial Real Estate
		Property Managers
		Tenants

[18] Minnesota Legislature Office of the Revisor of Statutes "SF4" webpage. https://www.revisor.mn.gov/bills/text.php?number=SF4&version=latest&session=ls93&session_year=2023&session_number=0

[19] Xcel Energy "Carbon Reduction Plan" webpage. https://mn.my.xcelenergy.com/s/our-commitment/carbon-reduction-plan

[20] W. Ornstein, "Minnesota Power pledges no carbon by 2050, zero coal by 2035," MinnPost, January 12, 2021. https://www.minnpost.com/environment/2021/01/minnesota-power-pledges-no-carbon-by-2050-zero-coal-by-2035/

[21] Great River Energy. 2021 Integrated Resource Plan Update. https://greatriverenergy.com/wp-content/uploads/2021/04/2021-Integrated-Resource-Plan-040121.pdf

[22] A. Satchwell et al., op. cit.

[23] A. Satchwell et al., op. cit.

Enablers	**IB System Design**	Architects
		Engineers
		Utility
		Governmental entities
Suppliers	**Manufacturers and Vendors**	Hardware
		Software
		Services
Maintainers	**Onsite Building Staff**	IT
		Facilities
		Security
		Building managers
Supporters	**Contractors and Service Providers**	Mechanical/Controls
		Electrical/Low Voltage
		IT
		Cabling infrastructure
		Fire/Security/Life safety

While local chapters of professional organizations like ASHRAE[24] and the Association of Energy Engineers (AEEE)[25] and local trade associations like the Building Owners and Managers Association (BOMA)[26,27] and NAIOP, the commercial real estate development association,[28] can provide valuable expertise and guidance, these special interest groups focus on the specific needs and interests of their members. A coordinated network of practitioners, suppliers, vendors, and consumers is needed to trigger an IB tipping point in the region. One possibility is the Twin Cities Chapter of the Building Intelligence Group (BIG-TC)[29] that formed as a professional organization to support the growth and adoption of IBTs with a membership that includes consultants, contractors, integrators, architects, engineers, various end-users, and service provider stakeholders involved in building management and automation. With the backing of DOE and the commitment of the state and utilities, a concerted effort led by public-private partnerships is needed to provide R&D, demonstration projects, and incentive programs that will promote the adoption of IBTs and lead to the implementation of GEBs and CCs.

[24] ASHRAE Minnesota Chapter homepage. https://mnashrae.org/

[25] Association of Energy Engineers Twin Cities Chapter homepage. https://aeetwincities.org/

[26] BOMA Greater Minneapolis homepage. https://www.bomampls.org/

[27] Greater Saint Paul BOMA homepage. https://www.bomasaintpaul.org/

[28] NAIOP Minnesota Chapter homepage. https://www.naiopmn.org/Prod

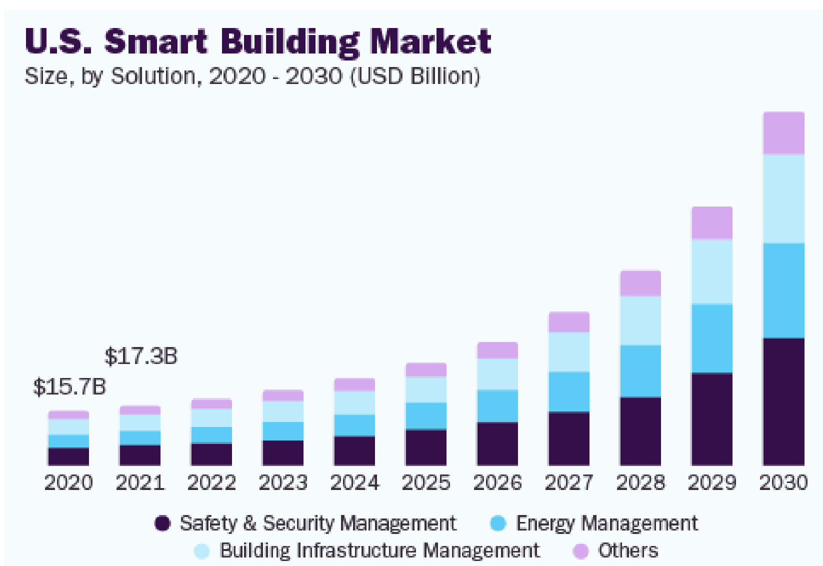
[29] BIG-Twin Cities homepage. https://www.buildingintelligencegroup.org/twincities

Background

The Internet of Things (IoT) has brought connected, automated processes to commercial buildings. The use of sensors and automated controls has enhanced building operations to provide greater comfort and enhanced productivity to the occupants and raise expectations and demands in the commercial building market. With the addition of sensors, software applications, automated controls, and information system dashboards, IoT and connected devices have introduced automated processes that enhance operation, monitoring, and control in commercial buildings.

Intelligent building technologies (IBTs) are becoming ubiquitous in commercial buildings and demand for intelligent buildings from developers and tenants is growing. A recent MarketsandMarkets™ report projects that the intelligent building (IB) market in the commercial segment will grow from $72.6 billion in 2021 to $121.6 billion by the end of 2026.[30] The operation, monitoring, and control provided by IBTs promise greater energy efficiency, boosted business productivity, efficient facilities management, enhanced building security and safety, and upgraded customer experience. Figure 5 shows the anticipated growth of the IB market in the U.S. to 2030.[31] North America accounted for a revenue share of the global market in 2022 of 32.9%.

Figure 5. Growth of the U.S. IB Market by Solution to 2030.



[30] MarketsandMarkets "Smart Buildings Market" webpage. https://www.marketsandmarkets.com/Market-Reports/smart-building-market-1169.html

[31] Grand View Research "Smart Building Market Size & Share Analysis Report, 2030" webpage. https://www.grandviewresearch.com/industry-analysis/global-smart-buildings-market

Grand View Research segmented the IB market into three major demand categories:[32]

1. Solutions
    a. Access Control Systems
        i. Video Surveillance Systems
        ii. Fire and Life Safety Systems
    b. Energy Management
        i. HVAC Control Systems
        ii. Lighting Management Systems
        iii. Others (Data Management, Asset Performance Optimization, and Application Platform)
    c. Building Infrastructure Management
        i. Parking Management Systems
        ii. Water Management Systems
        iii. Others (Elevators and Escalators Management and Waste Management)
    d. Safety and Security Management
    e. Others (Network Management and Workplace Management)
2. Services
    a. Consulting
    b. Implementation
    c. Support and Maintenance
3. End-Uses
    a. Residential
    b. Commercial
        i. Healthcare
        ii. Retail
        iii. Academic
        iv. Others (Hotels, Public Infrastructure, and Transport)
    c. Industrial

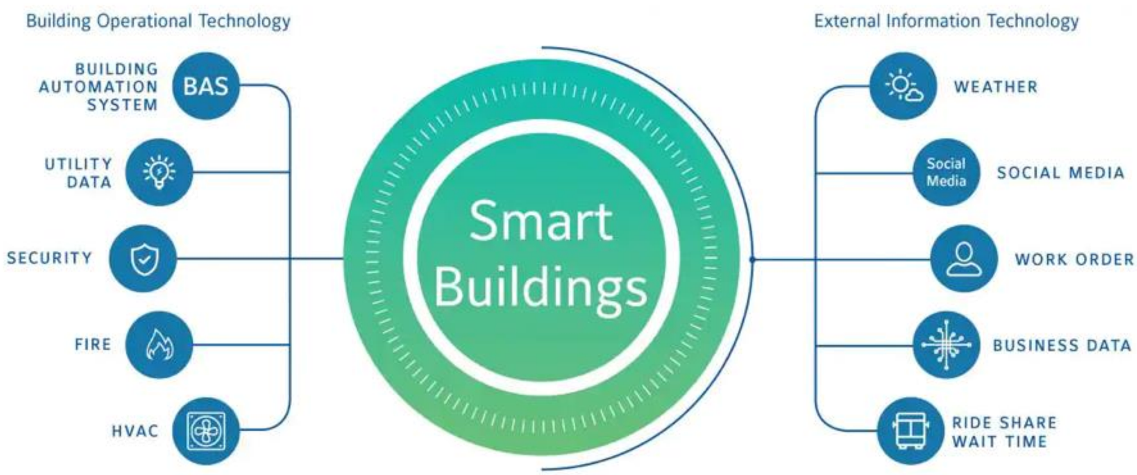
Often, the introduction of new technologies and systems can carry unintended consequences alongside the promised advances and benefits. Overlooked consequences of these intelligent systems — with their sensors, controls, and supporting networking — are the added costs of the equipment, the increased energy overhead to operate the devices, and the greater operations and maintenance (O&M) complexity. Unless the benefits of IBTs outweigh their inherent costs, market adoption of IBTs in the commercial building sector could fall short of projections. The purpose of this market study is to understand the opportunities of IBTs, the underlying costs of that intelligence, and the appropriate application of the IBTs to maximize the benefits while minimizing ramifications. It is possible that the implementation of IBTs can be "too smart for its own good."

[32] Bloomberg press release, "Smart Building Market to Hit $570.02 Billion by 2030: Grand View Research, Inc." September 15, 2022. https://www.bloomberg.com/press-releases/2022-09-15/smart-building-market-to-hit-570-02-billion-by-2030-grand-view-research-inc

The Features of Intelligent Building Technologies

IBTs enable communication between devices, equipment, building systems, and business systems within the local area network (LAN) of the building and connected through the internet (i.e., the cloud) so that previously disparate systems can now share information and be operated by a set of integrated management systems. IBTs communicating across the cloud allow remote monitoring, communication, and management by property management and contracted service providers. Figure 6 shows the range of technologies that can comprise an intelligent building. IBs can integrate the operation of building systems such as IT, lighting, HVAC, security, fire/safety, etc. to provide more efficient building operation and improved user experiences.

Figure 6. Intelligent Building Technologies[33]



Building automation systems (BASs) are being further enhanced by add-on applications that can help improve energy efficiency. The marketplace for energy management applications is dynamic and quickly evolving. Some primary energy management applications include energy management information systems (EMIS), fault detection and diagnostics (FDD), and automatic system optimization (ASO), each discussed in greater detail in the paragraphs that follow. These tools work in conjunction with the suite of facilities management tools an operator may deploy, including BAS, lighting control, computerized maintenance managements systems (CMMS), integrated workplace management systems (IWMS), and other systems to help make the building smarter and improve the overall user experience. These tools and others are used to create digital twins of the physical building and its assets. These additional capabilities are described in the following.

[33] Johnson Controls "Smart Buildings" webpage. https://www.johnsoncontrols.com/digital-solutions/smart-buildings

Energy Management Information System

EMIS are software-based systems that provide building operators with tools to monitor, analyze, report, and optimize energy efficiencies for their properties. EMIS software provides access to real-time and historical data on energy use and environmental conditions that can be visualized on dashboards and generated as custom reports. EMIS helps operators track energy-related costs, and provides data-driven decision support to manage energy efficiency, waste, water, etc. By providing visibility and control over energy consumption, an EMIS can help building managers save money, improve operational efficiency, manage sustainability metrics, and improve occupant comfort.

Fault Detection & Diagnostics

FDD systems take building system data and use advanced algorithms to analyze, identify, and diagnose building system faults, inefficiencies, or malfunctions in building systems. FDD continuously monitors system performance and can recognize anomalies in building operations. By promptly detecting and diagnosing faults, FDD enables building operators to take corrective actions, optimize system performance, and improve energy efficiency. Algorithms used to predict equipment failures can help building operators be proactive with strategic maintenance.

This approach is often coupled with continuous commissioning, which involves ongoing monitoring and adjustment of building systems to ensure they operate at peak efficiency. By leveraging FDD and continuous commissioning, building operators can optimize the performance of building systems, improve energy performance, and maintain efficient operation over time.

Automatic System Optimization

ASO is the next generation of FDD technology that acts on detected faults and mis-optimizations by pushing commands back to the BAS to adjust setpoints and operating parameters without human intervention. ASOs attempt to continuously optimize the performance and energy efficiency of a building's systems. ASOs dynamically adjust system settings based on various factors like occupancy trends, weather conditions, and energy pricing. By fine-tuning and optimizing system operations in response to changing conditions, ASO can improve energy efficiency, optimize equipment runtime to maximize lifespan, provide occupant comfort by ensuring optimal setpoints, and identify and address inefficiencies or malfunctions.

Improvements in electronics efficiency and battery life have helped create battery-powered wireless sensors that can run for 10 years on a single charge. Battery-less sensors that harvest their power from ever present electro-magnetic waves are becoming more common. Software applications provide the interface for wireless sensors to enable monitoring and control of building systems and provide convenience, safety, comfort, energy efficiency, insight, etc. to end users.

Sensors for indoor air quality (IAQ) focus on wellness in the built environment. Sensors for occupancy, people counting, and location awareness can be used to adjust temperature setpoints, ventilation, light levels, etc. to improve the energy efficiency of a building. Daylight sensors can be leveraged by multiple building systems to control light levels, HVAC settings, motorized shades or dynamic glazing. Weather stations or online weather feeds can be used to predictively heat or cool a building before peak energy rates structures are initiated.

Integrated Workplace Management System

IWMS is a category of software applications used by facilities directors, building engineers and technicians, workplace managers, business managers, and possibly even building occupants. IWMSs may include many related products such as CMMS, a computerized work order system used for logging and tracking maintenance requests, service orders, equipment asset and maintenance records, and compliance reporting documentation. The CMMS may include as-built documentation for the building and O&M manuals, or this information may be stored in a separate facilities management documentation software module.

A company's workplace manager may use an IWMS's workplace management tools. These applications typically include asset management capabilities, space management tools for storing floor plans and furniture plans used to track existing conditions and moves/adds/changes to a space layout. Systems may also include occupancy utilization applications that may use manual or automated inputs for tracking space utilization.

An IWMS may include an occupant engagement system that allows the building occupants to interact with the building, and the variety of interactions can be broad. An occupant engagement app may be used to control the space temperature or light settings, for digital wayfinding, to interact with building amenities to order food, or to make fitness center reservations, for example. The app may work as a digital credential for admitting an occupant into the building or into a space they are authorized to access. An occupant may use the app to request maintenance or report comfort feedback. As buildings become smarter there will be more features for the occupants to engage with, and the value of having all of those features aggregated into a single application — a digital front door for the building — will become even more apparent.

There is no single set of capabilities that defines an IWMS. Many companies who offer IWMS products offer some or all the capabilities listed above. Some companies are building suites of complementary software tools for managing buildings — either by developing their own tools or acquiring other companies, and often a combination of both — and the features and capabilities vary by company, by product, and by the family of products within a suite of tools.

Digital Twin

The digital twin, like the IWMS, is an evolving product category that is not well defined. In general, digital twins digitize data from sensors, actuators, and other physical characteristics of a building and represent them in a computerized digital model. The digital model can display real-time conditions, it may be possible to control aspects of the building through the digital twin's user interface, and some digital twin models support the ability to virtually pilot new equipment, operating conditions, or system settings in order to predict how the physical twin will perform.

The concept of a digital twin is not unique to buildings and can be applied to any system that can be digitized and computer modeled. The user interface (UI) and user experience (UX) can vary widely depending on the intended application of a digital twin. In some ways, the typical BAS is a type of digital twin, digitizing the space and representing it graphically in real-time for an operator to monitor or control. Digital twins for commercial real-estate tend to incorporate many of the features of the systems described above into a single model that looks like an accurate representation of the physical space.

Benefits and Positive Outcomes Generated by IBTs

IBs put technology at the service of their building owners, managers, and occupants to offer a variety of benefits to many different types of end users. While the ability to collect, process, and analyze building and occupant data can improve the real-time operation of the building, the return on investment (ROI) on these benefits is not always as clear as calculating an energy payback because the benefits may not be tangible outcomes that can be measured. While there is no single definition for an IB, for the purposes of this report we will define an IB as a built environment that enables a greater level of physical and digital interactions by the occupants and operators than traditional buildings, offering a level of insight, bi-directional interaction, and automation that gives the appearance of intelligence. The non-energy benefits of IBTs can vary by market sector, ranging from offices to healthcare and retail to hospitality, and by building sector, from building owners and operators to the building occupants. These benefits can include increased comfort, productivity, health/well-being, and building occupancy. Appendix A: Benefits of IBTs by Sector and Stakeholder lists the potential non-energy benefits of IBTs for major market sectors and the principal building stakeholders.

The Energy Savings Potential of Intelligent Buildings

A 2017 American Council for an Energy-Efficient Economy report[34] found that "[w]hereas an upgrade to a single component or isolated system can result in energy savings of 5–15%, [an intelligent][35] building with integrated systems can realize 30–50% savings in existing buildings that are otherwise inefficient. Savings can reach 2.37 kWh/sq. ft." The report examined a range of smart technology opportunities that included the following:

[34] J. King and C. Perry. Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings. American Council for an Energy-Efficient Economy. Report A1701, February 2017. https://www.aceee.org/sites/default/files/publications/researchreports/a1701.pdf

[35] The King and Perry report uses the term "smart buildings." Currently, it has become accepted practice to refer to commercial buildings that incorporate IoT or smart technologies as "intelligent buildings," while residential buildings are usually referred to as "smart homes." For this report, to avoid confusion, we will use the term "intelligent buildings" for smart commercial buildings.

- HVAC systems
- Plug loads
- Lighting
- Window shading
- Automated system optimization
- Human operation
- Connected distributed generation and power

Figure 7 shows how these technologies interact within the IB system. The figure divides the elements of IBs into two groups: the connected building systems governed by the BAS (shown by the elements denoted with green backgrounds in the figure) and the building performance monitoring provided by the EMIS (shown by the elements denoted with blue backgrounds in the figure).

Figure 7. Overview of Intelligent Building Technologies [from King and Perry (2017)].

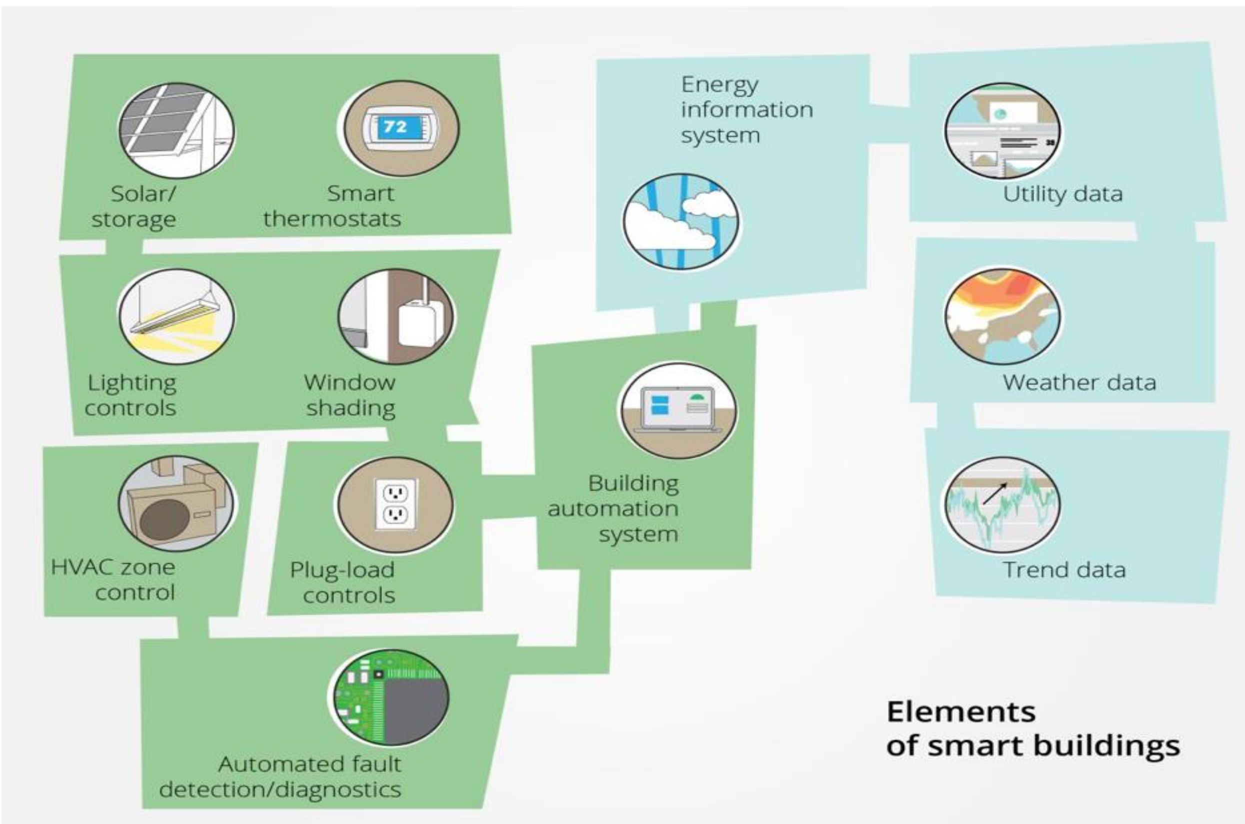


Table 7 provides their list of the various IBT options with the associated estimated energy savings.

Table 7. Savings Estimates for Intelligent Building Technologies [from King and Perry (2017)]

Category	Technology	Components	Energy Savings
HVAC	Wired sensor	Energy, temperature, flow, pressure, humidity sensors	Not applicable
	Wireless sensor	Energy, temperature, flow, pressure, humidity sensors	Not applicable
	Variable frequency drive (VFD)	Variable frequency drive (pumps and motors)	15–50% pump or motor
	Smart thermostat	Smart thermostat	5–10% HVAC
HVAC & lighting	Hotel guest room occupancy controls	Door switches, occupancy sensors	12–24% HVAC, 16–22% lighting
Lighting	Advanced lighting controls	Occupancy/vacancy, daylighting, task tuning, lumen maintenance, dimming, daylighting	45%
	Web-based lighting management system	Software and hardware	20–30% above controls savings
Plug load	Smart plug	120v 220v	50–60%
	Advanced power strip	Tier 1 types	25–50%
Window shading	Automated shade system	Shades w/ automatic controls	21–38%
	Switchable film	Self-adhered	32–43%
	Smart glass	Thermochromic Electrochromic	20–30%
Building automation	Traditional BAS	Sensors, controllers, automation software	10–25% whole building
Analytics	Cloud-based EMIS	Sensors, communication systems, web-based software	5–10% whole building
DER	Smart inverter	Smart inverter	12%

Table 8 replicates the data King and Perry reported for the energy savings these IBTs could provide to various commercial building subsectors.

Table 8. Commercial Building Subsector Energy Savings from Intelligent Building Technologies.[36]

Building Type	Floor Area (sq. ft.)	Intelligent building technology	Average energy consumption (kWh/year)	Percent savings	Average savings (kWh/year)
Education	100,000	Occupancy sensors; Web-based lighting control management system	190,000	11%	20,900
Office	50,000	Lighting controls; Remote HVAC control system	850,000	23%	200,000
Hotel	200,000	Guest room occupancy controls	4,200,000	6%	260,000
Laboratory	70,000	Air quality sensors; Occupancy sensors; Real-time ventilation controllers	980,000	40%	390,000
Hospital	120,000	Lighting controls + LED upgrade; Data analytics software package	7,900,000	18%	1,400,000

Through two-way communication with the grid, IBs can be operated to modulate their load in response to grid conditions to maintain normal building operations. This flexible demand will ensure grid reliability and assist in the transition to a non-carbon energy future with greater reliance on intermittent renewable energy resources like solar and wind power. In this way, IBs will serve as the basis for two important initiatives supported by The U.S. Department of Energy (DOE): grid-interactive efficient buildings (GEBs) and connected communities (CCs). DOE defines GEBs as "energy efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way."[37] DOE has a national goal for GEBs to "triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels."[38]

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[36] King and Perry, op. cit.

[37] A. Satchwell, M.A. Piette, A. Khandekar, J. Granderson, N. Mims Frick, R. Hledik, A. Faruqui, L. Lam, S. Ross, J. Cohen, K. Wang, D. Urigwe, D. Delurey, M. Neukomm, and D. Nemtzow. 2021. A National Roadmap for Grid-Interactive Efficient Buildings. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Building Technologies Office. https://eta-publications.lbl.gov/sites/default/files/a_national_roadmap_for_gebs_-_final_20210517.pdf

[38] A. Satchwell et al., op. cit.

CCs represent a further development and implementation of IBs and GEBs by incorporating central controls to manage a collection of GEBs and multiple DERs that can communicate with the grid to optimize and coordinate generation, delivery, and use of electricity.39 In 2021, DOE invested $61 million for ten CC projects to equip over 7,000 buildings with smart controls, sensors, and analytics to demonstrate how CCs can reduce energy cost use, costs, and GHG emissions.40

Baseload/Standby Power: The Hidden Energy Cost of Building Intelligence

When dealing with residential energy efficiency, understanding and minimizing phantom loads in the house are important steps to reduce the energy bill. Phantom loads are the energy loads that are drawn by electronic devices that are standing by, waiting to be activated and used. These devices include televisions, gaming consoles, cable boxes, computers, and printers. Any electronic device that continuously has a glowing light or shows a clock (such as microwaves) are drawing standby power. The only way to eliminate these phantom loads or standby power is to cut off the power when they are not in use by unplugging the device when not in use or by using a smart power strip that will shut off the power to the device when it is drawing power below a minimum threshold. When the house is unoccupied, it will still be drawing baseload power which consists of the phantom loads and the power from appliances that must remain on such as the refrigerator. ENERGY STAR certified appliances and devices are rated to operate efficiently, during use and in standby mode, and are another way to minimize both phantom loads and the baseload power of the house.

Commercial buildings also have many electronic devices that draw standby loads including office equipment such as printers and copiers. Mission critical equipment like data centers and security systems are like refrigerators that need to be on 24/7 and are an important contributor to the baseload of the building.

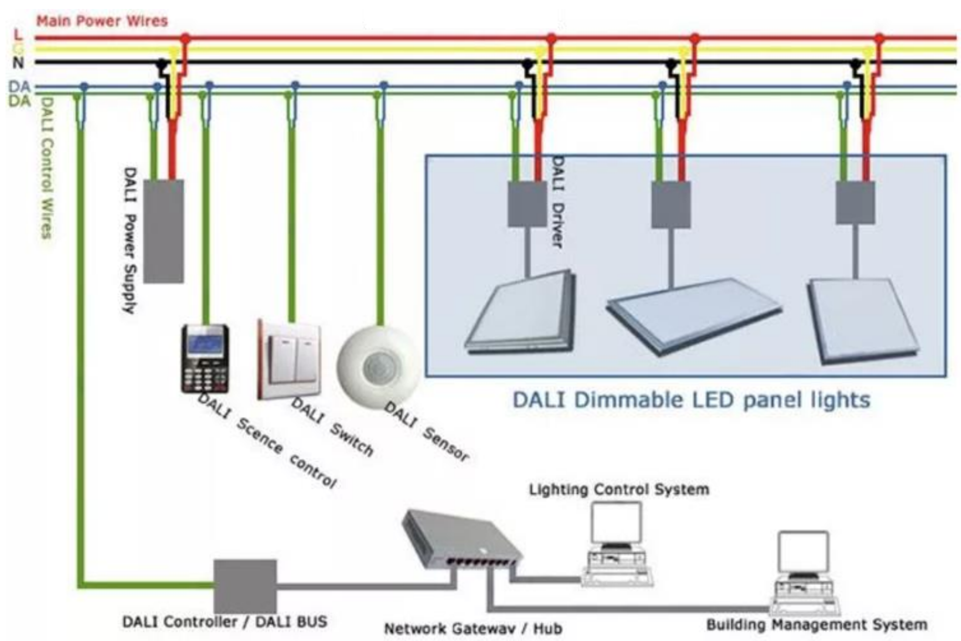
Within the context of building energy use, IBTs have: (1) components that are on standby when not in use and therefore can result in phantom loads and (2) devices that must operate continuously and add to the building's baseload power. In this way, the infrastructure that is required to support IBTs carries an energy cost. As an example, consider an intelligent lighting system such as the Digitally Addressable Lighting Interface (DALI) lighting system. DALI is a two-way communications protocol used by BASs to control individual lights and lighting groups. The DALI system uses a controller that is network-connected to individually addressable DALI LED drivers and LED bulbs. Figure 8 shows a schematic of a DALI lighting system that consists of a

[39] V. Olgyay, S. Coan, B. Webster,and W. Livingood. 2020. Connected Communities: A Multi-Building Energy Management Approach. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-75528. https://www.nrel.gov/docs/fy20osti/75528.pdf

[40] DOE press release. "DOE Invests $61 Million for Smart Buildings that Accelerate Renewable Energy Adoption and Grid Resilience." October 13, 2021. https://www.energy.gov/articles/doe-invests-61-million-smart-buildings-accelerate-renewable-energy-adoption-and-grid

network gateway/hub, DALI controller/DALI BUS, DALI power supply, sensors, wall switches, ballasts/drivers, and network servers/switches for network control.

Figure 8. Schematic diagram of a DALI Lighting System.

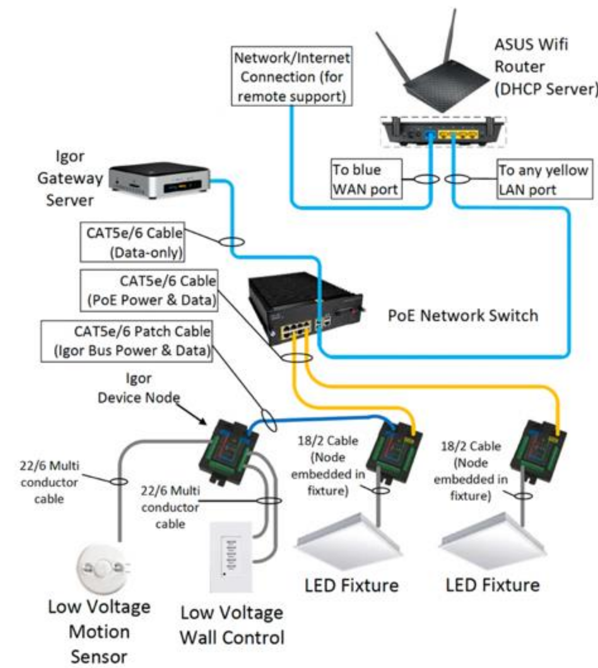


The intelligence that comes with the networked lighting system requires that the sensors (occupancy and daylighting), controllers, gateways, servers, and network switches will be drawing power whether the lights are on or off. This baseload or standby power is an energy cost that is incurred 24/7.

A recent study looking at Power over Ethernet (PoE) technologies was able to quantify the baseload/standby power load of IBTs.[41] PoE connected lighting systems are a low-voltage DC-powered networked system similar to the AC-powered DALI lighting system. For comparison, Figure 9 shows a schematic of an Igor PoE lighting system.

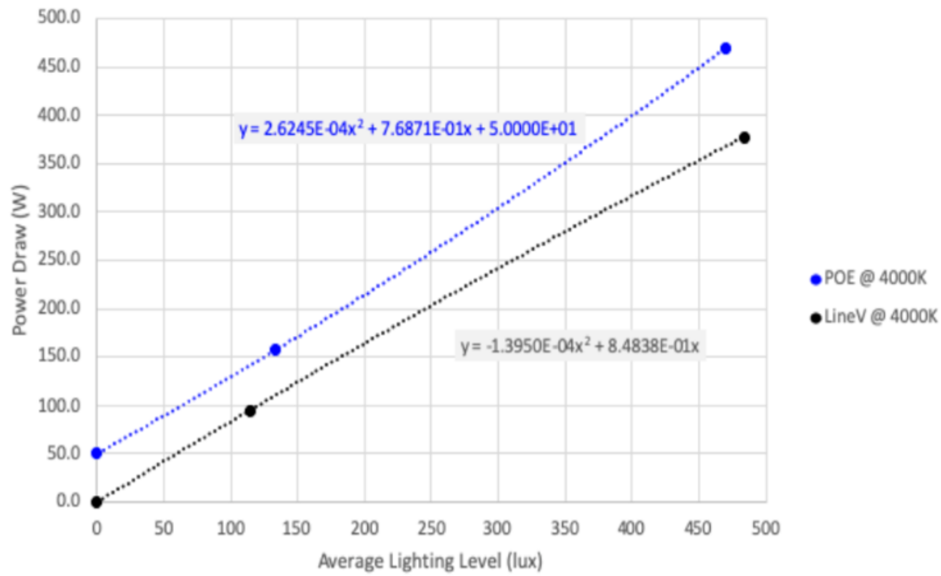
[41] Shen et al. 2022. The Demonstration of Power over Ethernet (PoE) Technologies in Commercial and Institutional Buildings. Minneapolis, MN: Center for Energy and Environment. https://mn.gov/commerce-stat/pdfs/137582_CEE_PoE-Project_Report-and-addendum-final-secure.pdf

Figure 9. Schematic of an Igor PoE Lighting System.



The lighting systems in two classrooms were monitored. One classroom had AC-powered LED lights that were not network connected (non-DALI) while an adjacent classroom had a connected PoE lighting system with occupancy and daylighting sensors. We obtained the lighting system performance of the two classrooms by comparing the power consumption as a function of average lighting levels for both classrooms. Figure 10 compares the performance of the line voltage (AC-powered) lighting system with the PoE connected lighting system. The rated power output of the AC and DC lamps was the same.

Figure 10. Light and Power Measurements of the Line Voltage and PoE Classrooms.



The lighting performance of the two systems is comparable (similar slopes), but the PoE system has a non-zero y-intercept of about 50 W. This is the baseload/standby power that is associated with the network control that comes with the PoE lighting system. The baseload/standby power of the line voltage lights was also non-zero, measured at about 3 W, which accounts for the occupancy sensors and other sensors and controls in the room. For the PoE lighting system, that baseload/standby power can be about 10% of the power draw at full lighting level and a greater proportion at lower levels. The baseload/standby power can also be considered the ***non-effective power***, the power drawn by the network switch or a powered device that produces no work perceived by the user. In the example of lighting, the power draw for control processes or AC-DC conversion losses within the node or network switch that is not directly translated into the output of light is non-effective power. ***Effective power*** is the power drawn from device hardware that directly translates to work as perceived by the user. For lighting applications, this is the power drawn from the LED fixtures that produces light. At 0% lighting, all power is non-effective power from the nodes and additional sources in the system, including potential cable losses.

Table 9 shows the comparison of the power draw from three lighting systems that were monitored in a school classroom and administrative offices in the PoE study. The classroom has normal AC-powered LED troffers that were connected to a wall switch without any network connections. The two administrative offices had networked LED troffer lighting systems–one a PoE troffer lighting system and an AC-powered DALI LED troffer lighting system.

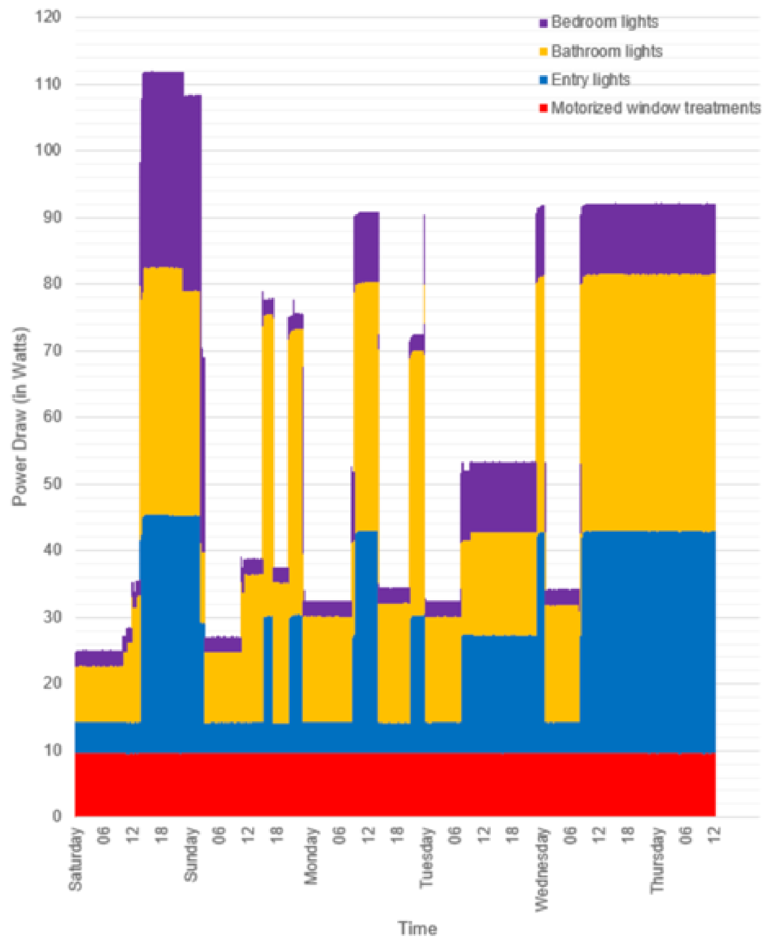
Table 9. Comparison of Power Draws of Non-Networked and Networked Lighting Systems.

Lighting System	Non-networked AC LED lighting	PoE networked LED lighting system	DALI networked lighting system
Power/Fixture	31 W	21 W	48 W
Baseload/Fixture	0.3 W	4.2 W	4.8 W

The variation in power between the three systems is a result of the difference in illumination in each of the spaces. The baseload power per fixture shows that the IBT infrastructure of the two networked systems had similar baseload/standby power draws. This power draw could be defined as the energy penalty of lighting system intelligence.

In the same PoE study, the baseload/standby power of the IBTs in a guestroom of a luxury hotel (which included connected PoE lighting system and motorized window treatments) was about 25 W. Figure 11 shows how the power draw of the PoE devices varied over a five-and-a-half-day period of occupancy. The baseload/standby power is about 23% of the total power draw of the guest room when the room was at its greatest illumination over the time of occupancy.

Figure 11. Power Draw of the PoE Lights and Motorized Window Treatments in a Hotel Guestroom.



These networked building systems continue to draw power around the clock as the sensors, controllers, and network devices remain on alert in case a change in state requires the system to alter its operation (such as when the occupancy changes and the lighting and HVAC systems adjust) or a pre-determined schedule calls for a change in the operational state of the building. Further, recent studies of the use of PoE technologies have shown that these IBT devices draw an increasing proportion of the total power as the end use devices (like LED lighting) become more efficient and can reduce the effective savings by as much as 21%–39%. The benefits that are provided by IBTs must be realized to justify the added cost, energy load, and operational complexity. They should not be installed for the sake of adding intelligence to a building without being wisely used. Over-engineered systems can be an issue with the application of intelligent technologies as functionalities and complexity not needed for the specific uses are included. IBs require networked systems to be integrated to perform as designed. Likewise, separate contractors and trades need to coordinate to minimize redundancy in installation and operation. IT and building operating technologies (OT) must also be unified in their approach to provide services to the building occupants.

Optimization of Intelligent Technologies to Building Space Use

For the appropriate implementation of IBTs, it is important to weigh the added energy loads and system complexities against the suitable level of intelligence for the use of the space or room and its occupants. Understanding space use will help determine the level of control that is needed for specific end uses such as lighting, HVAC, and plug loads and the types of sensors and intelligent systems required. This can help to ensure that the IBTs fit the needs of the specific space and are usable by its occupants. This system optimization can minimize capital costs of the equipment and IBT baseload and standby power while ensuring that the IBTs are accepted and used by the occupants and staff in the buildings.

A couple of networked lighting examples are useful to understand how overelaborate IB systems can result in higher costs rather than greater energy efficiency. During an office remodel, a PoE lighting system was installed over a row of cubicles with the legacy AC-powered fixtures kept over an adjacent row of cubicles to allow comparison of energy use.[42] Figure 12 shows the layout of the cubicles with the two respective lighting systems along with a photo of the space.

Figure 12. Floor Plan and Photo of the Networked (PoE) and Non-Networked Legacy Lighting Systems over the Rows of Office Cubicles.

A Signify Ledalite 4' suspended PoE luminaire[43] was installed over each cubicle while the T8 lamps in the legacy luminaires were replaced with LED lamps. The PoE fixtures allowed for dimming and each had occupancy sensors and photocells for daylighting control. The power draw of the PoE LED fixtures was 31 W at 100% brightness including 2 W of baseload/standby

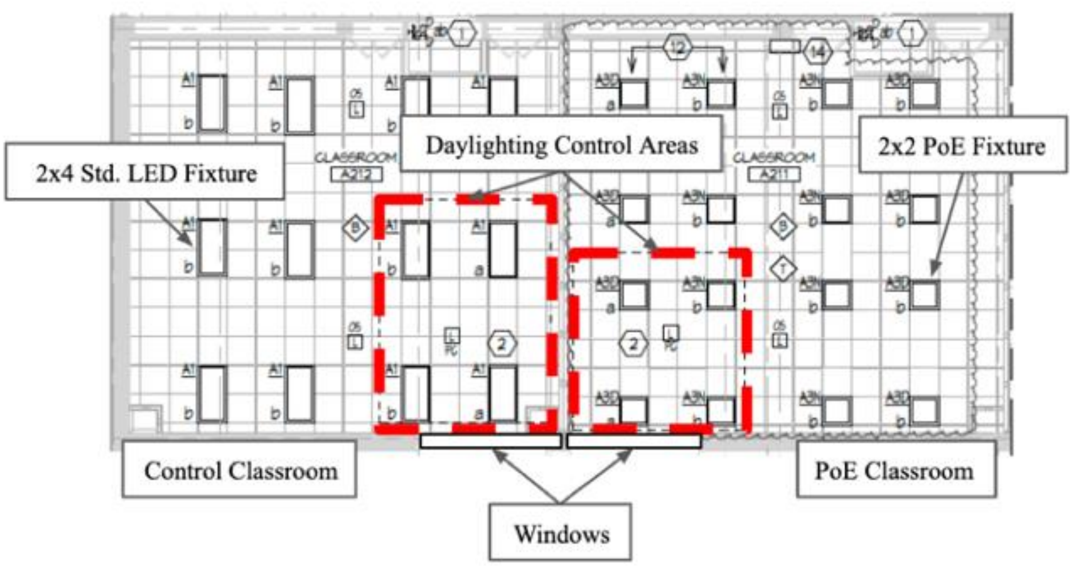
[42] Ibid.

[43] Signify "FloatPlane suspended" webpage. Bergv10kamp https://www.signify.com/en-us/products/indoor-luminaires/linear/suspended/floatplane-suspended

power. The power draw of the AC-powered LED fixture with ballast was 26 W with no standby load. During a normal workday, the PoE luminaires were not exposed to any daylight so there was energy saved via the photocells for daylight dimming. In addition, because of the occupancy of the office during the workday (pre-COVID), the occupancy sensors never turned off the lights of empty cubicles because of the continuous traffic past the row of cubicles. In this case, not only was the functionality provided by luminaire level, networked lighting unused but it actually used more energy than the legacy, non-networked lights. Assuming a workday from 8 a.m. to 6 p.m. with the office lights turned off during non-working hours, each legacy fixture would consume 0.26 kWh per workday (10 hours * 26 W) while the networked fixture consumed 0.34 kWh per work day [(10 hours * 31 W) + (14 hours * 2 W)] or 30% more energy per work day. Savings occur for the networked system only if the use and design of the space justifies the fine level control of the occupancy sensors and photocells where the lights above the cubicles turn off or dim enough to make up for the baseload power that is consumed 24/7. With the lower office occupancies that are occurring post-COVID, luminaire-level lighting control might be more justified in this setting although downsizing and optimizing space use might be even more economical.

The second example concerns the use of a networked lighting system in a middle school classroom. During a remodel of a middle school, one classroom was fitted with a PoE networked lighting system with 2x2 troffers, while an adjacent classroom had 2x4 non-networked AC-powered 2x4 fixtures installed. Figure 13 shows the layout of the two classrooms.

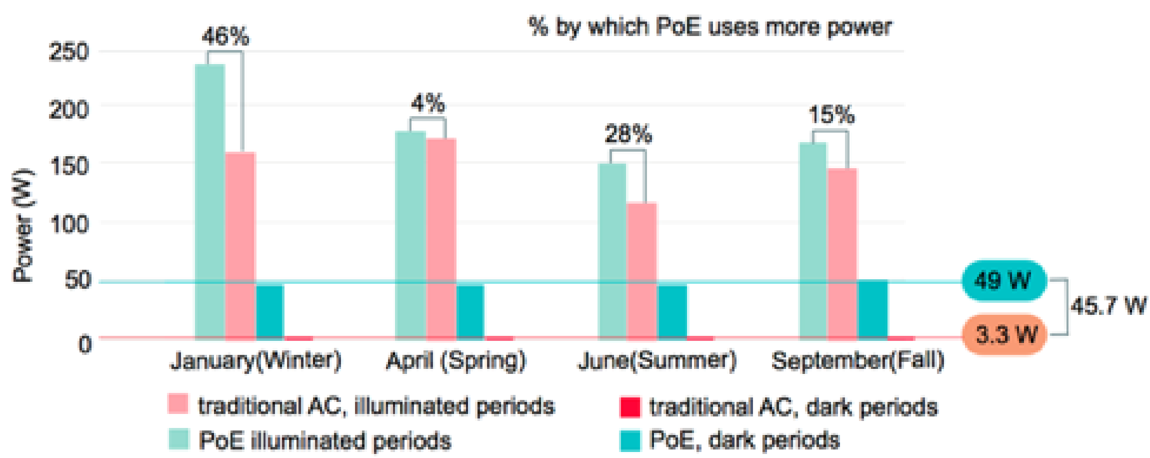
Figure 13. Floor Plan of the PoE and Control Lighting Systems in the SVMS Adjacent Middle School Classrooms.



The PoE luminaires were dimmable and color tunable. All the PoE fixtures were IP-addressable and could be individually controlled and scheduled. The PoE classroom had two occupancy sensors and two photocells that could control two defined zones in the room. The non-networked lights also had an area with daylighting control and one occupancy sensor controlled all the lights in the room.

Figure 14 presents a power comparison between both systems during illuminated and dark periods. Illuminated and dark labels correspond to periods when lights are on and off, respectively. During dark periods or periods at which each system is drawing power at a level comparable to that measured at a 0% lighting level, PoE indisputably draws more power for standby processes than the traditional line voltage system. Standby power draw in the PoE system is 49 W. This is significantly greater than standby power in the traditional AC system, which is 3 W. The difference is attributed to the power required by the network switch (approx. 15 W) and the PD nodes (approx. 34 W for 16 devices) to stay online, send data, and expect commands. This can be considered the energy cost for networked luminaire-level lighting control with occupancy and photosensors. The granular control level for the PoE system was clearly unwarranted for this classroom space use as lighting levels were consistent across the area and the teacher did not see any benefit in the color tuning, individual luminaire-level variation, or networked on/off scheduling of the fixtures.

Figure 14. Comparison of average monthly power use for each classroom during illuminated and dark periods



The percentage by which the PoE system average power draw is greater than that of the traditional AC system is shown for illuminated times. However, illuminated data does not account for differences in lumen output and other uncontrollable variables (e.g., teacher lighting preferences).

The one benefit of the networked lighting system was integration with the building security system so that the lights could also signal a threat situation in the building by flashing on and off. However, luminaire-level networked lighting control however was unnecessary for this classroom case where the teacher did not find cause to use the features that were available. For this space use, network lighting control could have been limited to one or two groupings of fixtures or via network connection with the wall controller of the lights.

The set of intelligent technologies employed by IBs include lighting systems (networked and luminaire-level), HVAC, plug loads (miscellaneous electrical loads or MELS), sensors (including photocells and occupancy sensors), and controls (BAS and EMIS). These technologies are employed on a building level, room level, or device level. An important feature of IBs is the ability of system integration where, as described previously, the lighting system can communicate with the fire and security system. This ability can reduce redundancies while providing synergies from system interactions. For energy efficiency, it is important to understand how the planned and actual use of the space will dictate the optimal nature and level of IBTs that should be installed. It is important to assess the use of these intelligent technologies and the systems integration on both a space use/type and building level to develop recommendations and guidelines for best practices.

Assessment of Intelligent Technology Needs per Space Use

To understand how smart a space should be, the following details need to be understood:

1. How will the space be used and what are the needs of the space's occupants?
2. Within that context, what building systems are needed in the space and what level of intelligence could optimize the performance of those systems?
3. What sensors and controls are needed to provide that intelligence?
4. Can the sensors and controls be integrated for use with the other systems serving the space?
5. How are the IBTs serving the space expected to operate in concert with the intelligent systems serving other spaces and with the services provided to the entire building?

First, we need to identify the main commercial building types that could benefit from the use of IBTs by space use. For the purposes of this report, we define the primary IBT-capable commercial building types as offices, schools, hospitality, warehouses, big box retail, and data centers. Almost all the building types will employ the same technologies to provide the typical end uses needed for its occupants and building services. Within these space uses, it can be assumed that some technologies are universally applicable, such as plug load controls, adjustable heating and cooling, and indoor air quality (IAQ) monitoring. In other aspects, different controls are needed based on the space use in question, with specific opportunities for IBTs. For example, a typical commercial office building can be divided into office area(s), meeting and/or conference rooms, and common areas (e.g., kitchens, breakrooms, lobbies). Each of these spaces will have different occupancy patterns and different sensor and control strategies. Other building types will have similar uses but will also add others. Whether an office space has closed offices, open offices, cubicles, or hoteling will impact the lighting and HVAC strategies.

Table 10 outlines the potential needs of commercial building space use types. Each building is composed of a number of different space types that will have their own uses and operational needs. For example, an intelligent lighting system in an open office area of cubicles will have different needs and functionality than the lights in a conference room or the lobby. In the case of an open office plan, the intelligent lighting system could be either networked lighting controls (NLC) where all or groups of lights in the space are controlled over the network or luminaire-level lighting control (LLC), where occupancy and daylighting (photocell) sensors inform the operation of individual light fixtures. Similarly, sensors and controls working with the BAS would regulate the indoor environment based on occupancy levels and schedules, manage the power consumption of miscellaneous electric loads (MELs), and operate automated window treatments.

Table 10. Commercial Building Space Use Types.

Building Type	Space Type	Potential Intelligent Systems						
		Lighting	HVAC	IAQ	MELs	Occupancy Management	Window Treatments	Security
Office	Open Office Plan	x	x	x	x	x	x	
	Small Collaborative and/or Small Conference Area	x	x	x	x	x	x	
	Traditional Large Conference Room	x	x	x	x	x	x	
	Lobby/Common Area	x	x	x	x	x	x	x
	Kitchen/Break Room	x	x	x	x	x		
	Toilets	x	x	x		x		
	External Building	x						x
School	Classroom	x	x	x	x		x	x
	Auditorium	x	x	x	x	x		x
	Corridors/hallways	x	x	x		x		x
	Reception Area	x	x	x	x	x	x	x
	Admin Office	x	x	x	x	x	x	x
	Gym	x	x	x				x
	Cafeteria	x	x	x			x	x
	Locker rooms	x	x	x		x		
	Toilets	x	x	x		x		
	External Building	x						x
Hospitality	Guestrooms	x	x	x	x	x	x	
	Corridors/Hallways	x	x					x
	Exit Staircase	x				x		x
	Common Spaces	x	x	x	x	x	x	x
	Restaurant	x	x	x		x	x	x
	Toilets	x	x	x		x		
	External Building	x						x
Warehouse	Floor Space	x	x	x		x		x
	Offices	x	x	x	x	x	x	x

	Toilets	x	x	x		x		
	External Building	x						x
Big-Box Retail	Floor Space	x	x	x	x			x
	Offices	x	x	x	x	x	x	x
	Toilets	x	x	x		x		
	External Building	x						x
Data Center	Aisle Space	x	x		x	x		x
	Offices	x	x	x	x	x	x	x
	Toilets	x	x	x		x		
	External Building	x						x

The type of controls that are available for the different building systems will help to define the appropriate level of intelligence needed for a space. In Table 11, control types are shown for several building systems. The lighting system can have either zone/space, building-level, or luminaire-level control. The HVAC system can be controlled by thermostats in the space or by network control through the BAS. Plug loads can be controlled on the individual device level or via outlet or power strip control. Finally, occupancy management can be controlled by the individual or by space.

Table 11. Building System Control Types.

System	Type of Control		Level of Detail and Control	Examples
Lighting	Zone/space/building-level control	Networked scheduled on/off; occupancy sensors and manual control override possible	Primarily automated; highly integrated. Low level of manual control.	Lighting in common areas or exterior building security lights
		Network control with occupancy and/or photocell sensors to control groups of lights. Seasonal and daylight adjustment of lighting possible.	Mix of individually adjustable and non-adjustable lighting. On smaller scales, manual adjustments usually possible	Lighting in classrooms, meeting rooms, and office spaces
	Luminaire-level control	Occupancy and/or photocell sensors	Primarily automated; highly integrated. Individual manual control possible.	Aisles in warehouse where overhead lights illuminate storage racks as operators advance down the aisle to the shelves of interest
		Automated	Programmed by network lighting system or BAS and possibly integrated with another system	Lights in a school hallway are integrated with the security system to direct occupants toward building egress or to signify security alerts using color tunable lights.
HVAC	Thermostat control	Individual spaces controlled by thermostats; can be connected to larger thermal control system	Primarily manual, though large scale control also possible.	Spaces conditioned by dedicated HVAC system or zone control

	Network control	Adjustment of heating and cooling based on overall need. Floor-wide or zonal systems	Managed by Facilities through BAS	Building automation system
Electronics	Device-level control	Scheduled downtime for appliances; timer-based plug load controls such as scheduled automatic computer, printer, or copier power on or shutoff	Primarily automated; low level of control and detail	IT-controlled via network or by device
	Outlet or power strip control	Plug load controls	Primarily automated via network control or occupancy sensor. Moderate level of individual control and integration, for some aspects	A controlled-circuit outlet or a smart power strip in an office or cubicle
IAQ	Space-level control	Monitoring of air quality and other environmental conditions with active sensors	Automated data collection; adjustments to indoor environment are made as needed. High level of integration. Managed by Facilities through BAS	Auditoriums, meeting rooms, cafeterias, gymnasiums, and locker rooms
Occupancy Management	Individual control	Visitor management; occupancy sensors, ID badges, and/or fobs	High level of manual operation of systems; high level of integration	Building or office entry points and other secure areas
	Space control	Scheduling of rooms	Higher level of control, by individuals	Meeting and conference rooms

With these control types in mind, a matrix (shown in Table 12) was created that recommends the types of control options that are appropriate for the various building systems and space types. For example, based on the previous experience with the classrooms, luminaire level control would be a case of over-engineering and the lighting control in the classroom should either be for the entire space or at most two or three zones.

Table 12. Building Space Use Controls Matrix.

Building System	Control Type	Office							School										Hospitality							Warehouse				Big-Box Retail				Data Center			
		Open Office Plan	Small Collaborative and/or Small Conference	Traditional Large Conference Room	Lobby/Common Area	Kitchen/Break Room	Toilets	External Building	Classroom	Auditorium	Corridors/hallways	Reception Area	Admin Office	Gym	Cafeteria	Locker rooms	Toilets	External Building	Guestrooms	Corridors/Hallways	Exit Staircase	Common Spaces	Restaurant	Toilets	External Building	Floor Space	Offices	Toilets	External Building	Floor Space	Offices	Toilets	External Building	Aisle Space	Offices	Toilets	External Building
Lighting	Zone/space/building-level control	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Luminaire-level control	x									x		x							x						x	x				x			x	x		
HVAC	Thermostat control	x	x	x					x	x			x						x			x	x				x				x			x	x		
	Network control	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x			x	x	x	x	x		x	x	x		x	x	x		x	x	x	
Electronics	Device-level control	x	x	x	x	x		x	x	x	x	x	x	x	x			x	x		x	x	x		x	x	x		x	x	x		x	x	x		x
	Outlet or power strip control	x				x			x				x						x								x				x			x	x		
IAQ	Space-level control	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x	x		x	x	x		x	x	x		x	x	x	
Occupancy Management	Individual control	x						x										x	x						x	x	x				x		x	x	x		x
	Space control	x	x	x	x			x	x	x	x	x	x					x	x		x	x	x	x	x	x	x	x		x	x		x	x	x		x

Energy Efficiency and the Design of IBTs

With the development of IBTs, the emphasis has been on functionality rather than the energy use of the system itself. Consequently, IBTs have not necessarily been designed to optimize their baseload and standby power demands. ENERGY STAR (https://www.energystar.gov/about?s=mega) has provided ratings for many electronic devices and appliances, including IT and network devices that are part of or support IBTs.[44,45] While this is useful in selecting energy efficient components for IBTs, a rating system for how the system as a whole operates would be an important metric to assess the amount of non-effective power the IBT draws during its operation. A possible approach could be taken from data centers and its Power Usage Effectiveness (PUE) factor.

Power Usage Effectiveness

Energy Star defines the PUE for datacenters as "a standard industry metric, equal to the total energy consumption of a data center (for all fuels) divided by the energy consumption used for the IT equipment." It provides a measure to compare the power consumption of one data center versus another. The larger the PUE means that the data center is consuming power less efficiently. A PUE of 2.0 means that only half the incoming power is used for data processing. Most data centers have a PUE in the range of 1.25 to 3.0 (from a high of 80% efficiency down to 33% efficiency).

For IBTs, we would define the PUE_{IBT} as follows:

$$PUE_{IBT} = \frac{Total\ Power}{Effective\ Power}$$

Where the Total Power of the IBT is the sum of the non-effective power (or baseload/standby power) and the effective power. A non-intelligent system should have a PUE_{IBT} nearly equal to 1 and as an intelligent system brings in sensors, controls, and networking capability, the PUE_{IBT} will be greater than 1. In that way, the PUE_{IBT} could be a measure of the intelligence of a system. For instance, consider the LED lighting systems in the two classrooms compared in the PoE project described previously.[46] The classroom with non-networked AC-powered LED troffers were controlled by a manual wall switch with an occupancy sensor and a photocell that controlled a zone of lights near the windows. The PoE lighting system classroom had luminaire-level networked control with occupancy sensor and a photocell for daylighting control (cf. Figure 13).

[44] ENERGY STAR "Choose ENERGY STAR IT Equipment" webpage. https://www.energystar.gov/products/low_carbon_it_campaign/choose_energy_star_it_equipment

[45] ENERGY STAR "Data Center Equipment" webpage. https://www.energystar.gov/products/data_center_equipment

[46] Shen et al., op. cit.

Table 13. Comparison of PUEs for the Classroom with the AC-Powered Lighting System and the Classroom with the PoE Lights.

	Non-Networked AC LED Lighting System	PoE Networked LED Lighting System
Total Power	368 W	469 W
Effective Power	365 W	420 W
PUE_{IBT}	1.00	1.12

From Table 13, comparison of the PUE_{IBT} shows that the level of intelligence of an IBT simply because of the power required to support the added functionality that the IBT provides, such as, for the case of the PoE lighting system, luminaire-level control, networked scheduling, and integration with other building systems such as the BAS and building security system. With this metric for intelligence, a measure of the power overhead that building intelligence brings can be used to weigh the energy cost of the system for the functionality that is both provided and used. For the case of the classrooms, we calculate the PUE_{IBT} for the two classrooms and find that the PUE_{IBT} of the non-networked lighting system is 1.0 while the PoE system had a PUE_{IBT} of 1.12. In this case the PUE_{IBT} is a measure of the amount of intelligence of the system, and given the needs of the classroom, a system with a PUE_{IBT} close to 1 should be expected.

The PUE_{IBT} metric can also be used as a measure to compare the efficiency of IBTs that provide the same functionality and, in that way, also serve as a kind of ENERGY STAR rating. It is a direct measure of the non-effective power that results from the intelligent capabilities provided by the design and operation of that system. This suggests another need. When emerging technologies are developed, the focus is on functionality, but we are now reaching a point with IBTs that we should consider how these systems can be optimized to minimize their non-effective power requirements.

Opportunities for the Efficient Design of IBTs

The existing energy optimization approaches to IBTs have generally been incremental improvements of the same power distribution architecture that has been used over the last 100 years. This is based on the traditional AC (line voltage) power system within a building, which is a shared power system going back to a breaker at a load center. A shortcoming of this system is that the standard line voltage system does not provide inherent metering of loads and provides no communications capability for reporting or control of loads within the IBT. To achieve equipment intelligence and automation, additional devices (submeters, current transformers (typically at the circuit level), relays, and wired or wireless communications) are required for load management and reporting. For intelligent improvement in the energy efficiency of buildings to take place, changes in this power distribution architecture are needed.

Because electrical loads in buildings are becoming dominated by electronic devices that are internally DC powered, internal plug load conversions are required because of the delivered AC power from the building's electrical distribution system. These AC-to-DC conversions bring inefficiencies, and the most efficient IBT design would be DC power delivered from a DC microgrid. A recent PNNL published a white paper titled DC Lighting and Building Microgrids[47] stated the case for a building DC microgrid.

In the past, the reason DC power distribution systems were not adopted on a large scale was because of the power losses when transmitted over long distances from centralized power plants and because the higher voltages required for transmission were dangerous. Recently, Article 726 of the National Electric Code has been added to the 2023 National Electric Code which allows new safe DC power distribution systems. These systems can transfer bulk power safely over long distances with low power loss. Fault managed power is used today primarily to power digital antenna systems in stadiums, entertainment venues, and large buildings. A building DC microgrid consisting of fault managed power, PoE, and USB is possible to power and control most building infrastructure in a building.

One such system that has changed in buildings is the lighting system. LED lighting is now prolific in buildings due to its energy efficiencies. Until recently, LED lighting systems have been designed with line voltage as a carry-over from the traditional incandescent and fluorescent lighting of years past. Since LEDs operate on DC power and as more thought is placed on the overall efficiency of the design, the option of low voltage DC lighting architectures has gained popularity. PoE lighting in particular has allowed the use of the existing building's IT infrastructure to provide networked power and control capabilities to the lighting system. The integrated sensors and controls of the PoE lighting employs the same cabling and network switches of the IT network (with no conduit requirement) to take advantage of the network's high speed, resilient, wired communication. In PoE lighting networks, the network switch typically provides the AC to DC power transformation in the same way that PoE switches power other PoE devices like digital phones, access points, and security cameras.

Despite the additional benefit of sensor and granular software controls, studies of PoE lighting power consumption show a higher power consumption. The additional power consumption is attributed to the plug load network design and plug load waste, resulting in standby power and baseload consumption. The power consumption of the network switches is an important contributor to this power consumption since they must always stay on. For example, in PoE lighting systems, the network switch is always on regardless of the state of the lights so that network traffic can be communicated back and forth to all devices.

Another source of power consumption for connected systems is the space conditioning needs of centralized server rooms. Typical IT network designs use a hierarchical network topology where large, centralized network switches, whose power supplies typically are AC powered, need fans for cooling the switch because of the power conversion they perform. Additionally, since network systems require a direct cable run from the switch to the network endpoint, these centralized network deployments must be situated so that a maximum distance of 100

[47] PNNL "DC Lighting and Building Microgrids: Opportunities and Recommendations Report" webpage. https://www.pnnl.gov/publications/dc-lighting-and-building-microgrids

meters is not exceeded from the switch to the furthest device. Often, long cable runs are unavoidable, resulting in an additional power inefficiency for PoE devices, with a cable power loss of up to 20% at the longest distance.

Alternative distributed networks with small network switches can provide a network design that improves the energy efficiency of PoE lighting systems. In these designs, the network switch is treated like an AC junction box. The network switches are installed locally in the spaces where its lights are deployed. In this design typical cable runs do not exceed 50’ with a cable loss averaging 3%. Furthermore, smaller switches are typically DC powered and fan-less and consume less power than centralized network switches, reducing IT cooling loads. Remote switches can also be powered with DC fault managed power, making the overall power infrastructure DC and more energy efficient.

Plug load energy waste has been identified as a problem that plagues all building infrastructure systems. In LED lighting systems (both AC and DC), the plug load waste typically occurs at the driver level, which is the point of control for the fixture. Lighting drivers are typically either integrated (1:1) or remote (1 to many) for fixtures of small loads. The plug load waste occurs because the driver is always powered on regardless of whether a fixture is on or off, ready and listening to commands to apply control. PoE lighting systems also utilize a lighting driver, a PoE driver, and these typically consume approximately 2W whether its attached lights are powered on or off.

A new type of PoE system is emerging called extended PoE (X-PoE) that deals with this standby load. At this time, X-PoE is proprietary but will be submitted for standards approval in the near future. In this case the small remote network switch acts as both a standard IEEE 802.3bt network switch when a standard PoE device such as a security camera is plugged in. However, if a specific passive device that has a resistor of a specific value is connected, the switch port internally becomes a two-channel driver for connected light fixtures. The benefit is that when lights are turned off, as there is no remote driver, there is no plug load besides the standard 9W consumed by the network switch. USB-A and USB-C connectors are also available from the switch.

X-PoE is also able to provide a greater resiliency of the PoE lighting system as the switches are fan-less, and since there are fewer active devices on the network, there will be a greater mean time between failures (MTBF). Since the switch provides standard PoE, X-PoE based lighting, and USB outputs, it can become an essential component of powered devices up to 120W per port providing efficient power distribution to the networked lighting system and other connected devices such as shading, sensors, actuators, relays, access points, security cameras, phones, and laptops.

In summary, transforming the building infrastructure to a DC microgrid could provide the most energy efficient power infrastructure and yield the best PUE_{IBT} metric for buildings. Connected networked systems add the intelligence of control and the data collection needed for building automation and optimization. The network switch has not only the ability to provide power and control for devices but now also the ability to provide direct lighting control.

Intelligent Building Taxonomy

To provide some guidance in the development of intelligent buildings, we have created an intelligent building taxonomy that defines five levels in which intelligent buildings can be categorized. These are:

- Level 0 which is the baseline building, defined as complying with U.S. building codes. The building has segregated, decentralized building systems with independent controls and sensors.
- Level 1 is the automated building which has automated systems that allow for centralized operation and management.
- Level 2 is the integrated building in which the building systems communicate with the cloud through IoT devices and systems to allow remote coordination with onsite building, facilities, and IT staff.
- Level 3 are GEBs which have DERs and are integrated with the grid.
- Level 4 are buildings that are part of a connected community that shares energy resources with other buildings while also providing grid services.

Table 14 describes the developed taxonomy in greater detail. The features of each IB level describe the building systems and types of sensors and controls that define the level, along with the enabling technologies that provide the intelligent operation. The final column of the table lists the sublevels of system controls that could exist under each IB level.

Table 14. Intelligent Building Taxonomy.

Intelligent Building Levels		Description	Features	Enabling Technologies	Levels
0	**Baseline Building (code minimum in US)**	Building has segregated, decentralized building systems with independent controls and sensors connected to systems in individual floors, zones, and/or spaces.	• Thermostatic control of individual spaces. • Lights controlled manually with possible PIR occupancy sensors • RFID fobs for building entry • Elevators • IT • Telecomm • O&M performed by in-house facilities and building operator • Water, sewage, food wastes • Analog or digital meters	• Thermostats • PIR occupancy sensors/wall switches • RFID door lock and entry system • Utility savers switch	0.0 thermostatic control of space conditioning 0.1 Building entry security system 0.2 Utility AC savers switch 0.3 some lights controlled by PIR occupancy sensors
1	**Automated Building**	Building has automated systems that allow for centralized operation and management.	• HVAC system controlled by a computerized and centralized BAS • BAS may be managed remotely by mechanical contractor • EMIS with FDD and AI may be an option • Security system may be managed by remote contractor • Spaces may have internal networked lighting systems • Security cameras recorded on video within the building • Plug loads, MELs • Elevators • IT • Telecomm • IT becoming involved with O&M along with building operator • Water, sewage, food wastes • Digital meters	• Common network building LAN infrastructure (MDF and IDFs) is recommended, but not required. • BAS server, controllers, and sensors • Network lighting system server, sensors, switches • Control circuit outlets and networked smart strips • BAS gateway, cloud services optional • EMIS an option • Network lighting system gateway, cloud services optional • Security system gateway, cloud services optional • CCTV cameras, monitors, and recording equipment, building security system server and controllers	1.0 building security system 1.1a BAS/EMIS 1.1b networked lighting system 1.1c networked MELs control 1.2a connected contractor-managed security system 1.2b contractor-managed BAS/EMIS 1.2c contractor-managed networked lighting system 1.2d contractor-managed MELs
2	**Integrated Building**	Building systems are connected to the cloud using IoT devices and systems with remote system O&M in	• Sensors employed by multiple systems (special requirements on the sensors) • Networked lighting system	• Building system bridges and gateways (need to be defined if replaced or built upon automate building techs) • Centralized network management with	3.1 BAS + networked lighting system 3.2 + security system 3.3 + MELs

		coordination with onsite building, facilities and IT staff. This stage marks the bringing together of OT and IT. Building systems are integrated with each other and through the cloud with building systems sharing sensor, data, and operational sequences.	managed be cloud management system • Building systems can communicate with each other and work in tandem • Multiple systems controlled by the same management system (single pane of glass) • IT and building operations work as on-site staff for contractors with some O&M services provided by contractors • Requires some form of IT controls to manage remote access for contractors • Water, sewage • Smart meters	segregation of systems into separate VLANs or similar controls • Common building wireless infrastructure to support IoT sensors • Electrified window glazing • Auto shading (blinds/louvers) • Structural load sensing	
3	**Grid-Interactive Efficient Building**	Grid-interactive efficient buildings (GEBs) are energy efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way. (demand response)	• Two-way communications with the grid to optimize building operation with energy use • Building has integrated Distributed Energy Resources (DERs) including but not limited to PV, battery storage, EV charging. • Water, sewage, food wastes	• AMD smart meters • DERs and cloud management systems • Inverters • Submeters	4.0 Smart meters with 2-way communications with the grid 4.1a on-site generation 4.1b energy storage 4.1c EV charging 4.1d "Resiliency" Resource management 4.1e "Sustainability"
4	**Connected Community**	A community of GEBs that are designed to share energy resources amongst themselves and provide services back to the grid. (not limited to electricity, e.g. water)	• Grid-interactive and efficient. • Multiple technologies. • Multi-building optimization. • Shared systems. • Water, sewage, food wastes (e.g. grocery store food wastes to vodka)	• Multi-building or campus management system • Microgrid	5.0 Community-, campus-, or portfolios level- DER (and/or microgrid) connected to GEBs with 2-way communication with the grid

Energy Savings Potential and Cost-Effectiveness

To assess the energy savings potential of IBTs for Minnesota buildings, the team modeled the energy use and demand impacts of several classes of IBTs. We employed EnergyPlus[48] as the modeling tool since it is:

- Able to calculate impacts on both an energy (kWh) and demand (kW),
- Calibrated to Commercial Buildings Energy Consumption Survey (CBECS)[49] data, and
- Able to model the Minnesota climate zones 6A and 7.

DOE standard commercial buildings were modeled to estimate and quantify the energy savings potential for Minnesota of the various IBT strategies on both a building and space use/type level. Simulated energy performance of the DOE standard small and large office (2016 and 2019 versions), as well as the primary school commercial building prototype models provided the basis of comparison for simulated energy performance of building models with intelligent technology.

Baseline Model Descriptions

The following sections describe the details for each of the reference buildings that were used in the simulations.

Small Office

The small office building model is a single-story structure with a conditioned floor area of 511 square meters (27.7 meters x 18.4 meters). It consists of four perimeter zones and one core zone, with a 5-meter depth for the perimeter zones. The building also has an unconditioned attic space. The window-to-wall ratio is approximately 24.4% for the south orientation and 19.8% for the other three orientations. The dimensions of the windows on all facades are 1.8 meters x 1.5 meters. The construction of the exterior walls is done using wood-frame walls, while the roof is constructed with wood joists. The foundation type is an unheated slab-on-grade, where a 0.2-meter concrete slab is poured directly onto the earth. The building HVAC system comprises air source heat pump systems with a gas furnace as back up. The system is a constant volume single zone system, which has one unit per occupied thermal zone.

Large Office

The large office building model consists of a basement and twelve floors with a conditioned floor area of 46,321 square meters (73.2 meters x 48.8 meters). It consists of twelve perimeter zones and three core zones. The building also has unconditioned plenum spaces. The window-

[48] EnergyPlus homepage. https://energyplus.net/

[49] U.S. EIA "Commercial Buildings Energy Consumption Survey (CBECS) Overview" webpage. https://www.eia.gov/consumption/commercial/

to-wall ratio is approximately 37.8% of gross walls. The construction of the exterior walls is done using mass (precast concrete panel), while the roof is constructed with metal decking. The basement is modeled as two zones, one for storage and one as a yoga room. Two thermostats are used to simulate the basement with all the other floors. A gas-fired boiler provides main and reheat hot water coils in the core and peripheral offices, and a water-to-air heat pump unit with electric backup heat in the basement and datacenter/IT closets. VAV with ERV and terminal hot water reheat for the core and perimeter; CAV units supply the basement and all four floors of the data center (data center: heat pumps). VAV is used throughout the remainder of the building, CAV is used in the basement unit, and heat pumps are used throughout the data center.

Primary School Building

The primary school building model is a single-story structure with a conditioned floor area of 85,230 square meters (104 meters x 82.3 meters). The window-to-wall ratio is approximately 37.8% of gross walls. The construction of the exterior walls is done using steel-framed walls, while the roof is constructed with metal decking. The school models represent existing structures built in or after 1980, and their operations generally align with the performance levels outlined in ASHRAE Standard 90.1 (2019).

The modeled prototype primary school buildings incorporate different features for climate zone 6A and 7. For instance, the equipment sizing for heating and cooling is adjusted based on the specific needs of each climate zone. In the elementary school prototype model, the HVAC system utilizes packaged two-stage direct expansion (DX) rooftop units (RTUs) for air conditioning. Heating is provided by a gas hot water boiler for primary heating, and zone-level reheat coils are used. Most of the school is equipped with variable air volume (VAV) zones, but there are a few small dedicated packaged units with gas heating and electric air conditioning for specific zones like the cafeteria, gym, auditorium and kitchen.

Energy Modeling

We conducted multiple simulations of the energy performance for each building model, considering different categories of intelligent technology studied in this project. This approach enabled us to assess the individual impact and cost-effectiveness of each technology separately. For each category of intelligent technology, we made one or more adjustments to the prototype models, such as changes in schedule, setpoint, or the proportion of the loads controlled by intelligent systems, as described in this section.

Occupant-Adjusted Controls

Occupant-adjusted controls can save energy by operating the HVAC system to maintain more extreme baseline space temperatures and allowing occupants to modify the temperatures of the spaces they use. In the model, we represented the impact of this technology by raising the default cooling setpoint from 75°F to 77°F and lowering the default heating setpoint from 70°F to 68°F. Costs for this strategy were negligible if adjustable thermostats were already installed, and the cost of replacing thermostats was estimated between $250 and $500 per unit for five units in the small office.

Time of Day Setpoints

Modified time of day setpoints can reduce the energy intensity of HVAC systems by changing the time when the HVAC system allows the space temperature to coast toward the setback temperature. In the model, we modified the setpoint schedule to start unoccupied mode earlier in the afternoon (17:00) and reduced the fan duty cycle from continuous operation to 50% between 17:00 and 19:00. We assumed that the cost of implementing this change was $100, based on the labor cost of one hour of BAS programming.

Plug Load Controls

While ASHRAE 90.1-2004 requires a certain fraction of plug loads to be connected to controlled outlets, additional savings can be achieved by increasing the share of building plug loads that are controlled. We increased the share of the building plug loads controlled by the plug load schedule by 10% and assumed a corresponding 5% increase in plug load infrastructure costs, equivalent to $2,500 for a 5,500 sq. ft. space.

Daylight Harvesting

Daylight harvesting can achieve reduced energy use by dimming interior lights when sufficient natural light is present. To represent this effect, we reduced the modeled lighting intensity by 10% during occupied hours. Costs of this upgrade are associated with installing lighting sensors and integrating them with the lighting control system, estimated between $500 and $1,000 for the small office.

Control Exterior Lighting

The baseline models operated exterior lighting continuously. We adjusted the exterior lighting schedule to operate exterior lighting only outside of daylight hours, and assumed the cost was $100 based on the labor cost of one hour of BAS programming.

Vacancy Sensor for Lighting Controls

While vacancy sensors are typical requirements for energy code, they were not included in the baseline model. To model implementation of occupancy sensors, we reduced the lighting intensity by 10% during occupied hours. As these sensors are already included by code, we assumed the cost was negligible.

Motorized Shades with Solar Sensors

Automated window shading is an effective way to reduce thermal gains through fenestration. There are no parameters in Energy Plus to control window shading directly, so to simulate the effect of automated shading, we reduced the Solar Heat Gain Coefficient (SHGC) of windows in the model. For the small office, we assumed that the costs of implementing motorized shades and sun sensors would range from $15,000 to $25,000.

Variable Volume Air Distribution

Variable frequency drives (VFDs) enable air distribution fans to modulate to lower speeds when the full design airflow volume is not required, and operating fans at lower speeds requires less energy. To model the effect of VFDs in the air distribution system, we reduced the duty cycle of air distribution fans from 100% to 80% during occupied hours. We assumed the cost of adding a VFD to air distribution fans ranged from $2500/unit to $4000/unit for a total cost of $12500 to $20000 for the small office.

Modeling Tool Limitations

The research team discovered that certain IBT strategies we wanted to evaluate could not be accurately modeled using EnergyPlus parameters. The effectiveness of IBTs heavily relies on real-time conditions specific to each building, which constantly change. Occupant behavior and building operator actions play a significant role in achieving desired results. Energy efficient IT solutions are designed to optimize energy consumption by smoothing the peaks and valleys. Attempting to model these optimizations without actual data would skew and destabilize results. Therefore, additional case studies are recommended.

Economic Analysis

The calculation began by converting the modeled energy savings (in kW) into an annual energy cost using an average February 2023 Minnesota commercial utility rate of 11.49 cents/kWh.[50] The simple payback calculation was derived by dividing the estimated cost of the energy conservation measure (ECM) investment by the calculated annual energy savings (in $/year) for that particular ECM.

Simple Payback (years) = Cost to Implement ECM ($) / Annual Energy Savings ($/year)

An operator of an office building or primary school will typically have a goal of paying back ECM investments within a 5–7 years. Payback periods greater than 5–7 years typically are not considered for investment. This payback period will vary by property owner and by property, and will be based on whether the investment consists of new construction or

[50] U.S. EIA "Minnesota State Profile and Energy Estimates Data" webpage. https://www.eia.gov/state/data.php?sid=MN#Prices

retrofit/replacement of an existing system, each of which may shorten the desired payback period. The following tables show the results for the different building types.

Small Office Energy Conservation Measures Descriptions

Below are the ECMs that were modeled in EnergyPlus for the small office reference building:

- Occupant Adjusted Temperature Controls
  - Description: Allow users to adjust thermostats within the limits of a ±3°F dead band. Energy savings is achieved by decreasing the cooling setpoint temperature by 2°F (i.e., from 75°F to 77°F) and increasing the heating setpoint by 2°F (i.e., from 70°FF to 68°F).
  - Modeling: Adjust the heating and cooling setpoints by ±2°F for 50% of the occupied day
  - ECM Implementation: Replace existing non-adjustable thermostats and program setbacks for new thermostats.
- Time of Day Heating/Cooling Setpoints
  - Description: Be more aggressive than the ASHRAE 90.1 schedule by increasing the number of loads connected to controlled outlets
  - Modeling: Assume 10% more of the building's plug loads are controlled based on the plug load schedule.
  - ECM Implementation: Replace existing non-adjustable outlets and program schedules for new outlets.
- Plug Load Controls
  - Description: Be more aggressive than the ASHRAE 90.1 schedule by increasing the number of loads connected to controlled outlets
  - Modeling: Assume 10% more of the building's plug loads are controlled based on the plug load schedule.
  - ECM Implementation: Replace existing non-adjustable outlets and program schedules for new outlets.
- Daylight Harvesting
  - Description: The model appears to include a lighting control system. Lighting energy loads can be reduced by dimming the lights when natural sunlight is entering the space.
  - Modeling: Reduce lighting load by -0.1 each hour during occupied hours
  - ECM Implementation: Add daylight sensors (as required) and program lighting controls for dimming based on daylight levels.
- Control Exterior Lighting
  - Description: Save energy by turning off exterior lighting during daytime hours.
  - Modeling: Turn off exterior lighting during daytime hours.
  - ECM Implementation: Programing labor for exterior lighting schedule adjustments; cost assumes technician labor for 1 hour @ $100/hr. Additional costs will be incurred if exterior lighting is not already connected to lighting control system.

- Lighting Control Vacancy Sensor Setbacks
  - Description: Savings is based on turning off lights in unoccupied spaces
  - Modeling: Reduce lighting load by -0.1 during occupied hours; This reduction is in addition to the daylight harvesting energy savings contribution
  - ECM Implementation: Change occupancy sensors to vacancy sensors. Additional cost will be incurred if existing sensors cannot be configured for vacancy mode.
- Variable Frequency Drives
  - Description: Add Variable Frequency Drive (VFD) to air-source heat pump fan to modulate air flow.
  - Modeling: Reduce fan duty cycle from 1 to 0.8 during occupied hours.
  - ECM Implementation: Add VFD for heat pump.

Table 15. 2019 ASHRAE-Small Office Return on Investment (ROI).

Energy Conservation Measure (ECM)	kWh/Year	Energy Savings	Annual Energy Cost	Cost Savings	Payback (Years)
Baseline (2019)	47,044	-	$5,405.39	-	-
Occupant Adjusted Temperature Controls	45,647	1,397	$5,244.85	$160.5	7.8-15.6
Time of Day Heating/Cooling Setpoints	45,399	1,644	$5,216.45	$188.95	0.5
Plug-load Controls	43,399	3,644	$4,986.65	$418.75	6.0
Daylight Harvesting	46,363	680	$5,327.20	$78.20	6.4-12.8
Control Exterior Lighting	46,891	152	$5,387.84	$17.55	5.7
Lighting Control Vacancy Sensor Setbacks	45,660	1383	$5,246.45	$158.94	0.0
Variable Frequency Drives (VFD)	44,819	2,224	$5,149.74	$255.65	48.9-78.2

Table 16. 2016 ASHRAE-Small Office Return on Investment (ROI).

Energy Conservation Measure (ECM)	kWh/Year	Energy Savings	Annual Energy Cost	Cost Savings	Payback (Years)
Baseline (2016)	49,135	-	$5,645.72	-	-
Occupant Adjusted Temperature Controls	47,655	1,481	$5,475.61	$170.12	7.3-14.7
Time of Day Heating/Cooling Setpoints	46,369	2,767	$5,327.83	$317.89	0.3
Plug-load Controls	45,383	3,753	$5,214.53	$431.19	5.8
Daylight Harvesting	47,761	1375	$5,487.74	$157.99	3.2-6.3
Control Exterior Lighting	48,983	153	$5,628.17	$17.55	5.7
Lighting Control Vacancy Sensor Setbacks	47,308	1,828	$5,435.71	$210.01	0.0
Variable Frequency Drives (VFD)	46,611	2,525	$5,355.60	$290.1	43.1-68.9

Large Office Energy Conservation Measures Descriptions

Below are the ECMs that were modeled in EnergyPlus for the large office reference building:

- VAV ECM Strategy 1
    - Description: Close VAV terminal units (or go to standby mode) for certain area when zone is unoccupied.
    - Modeling: Temperature: VAV unit temperature control based on occupancy schedule. An occupied schedule of 0.5 means 1 out of 2 rooms is unoccupied. Perimeter zone has a higher standby temperature during daytime, core zone just uses unoccupied temperature.
    - ECM Implementation: Programing labor for VAV unit control based on occupancy schedule; cost assumes technician labor for 1 hour @ $100/hr.
- VAV ECM Strategy 2

    - Description: Close VAV terminal units for core zones when there's no occupants during the day.
    - Modeling: VAV terminal unit on/off schedule updated based on occupied schedule of 0.3 meaning 3 out of 10 offices are unoccupied.
    - ECM Implementation: Programing labor for VAV unit control based on occupancy schedule; cost assumes technician labor for 1 hour @ $100/hr.
- VAV ECM Strategy 3
    - Description: Demand control ventilation.
    - Modeling: Turn off DCV in the baseline
    - ECM Implementation: Programming labor to implement demand control ventilation using existing CO_2 sensors; cost assumes technician labor for 1 hour @ $100/hr. Additional cost would be incurred if CO_2 sensors are to be added or if advanced sensors like people counting sensors are added.
- Heat Pump ECM Strategy
    - Description: Fresh air delivery only for occupied areas, winter cooling with fresh air.
    - Modeling: There are no people simulated for the data center so the ventilation can be set back to minimum. Use of free cooling with fresh air. When OAT can be used for free cooling, the mechanical cooling energy use can be saved and the fan energy use is all that remains.
    - ECM Implementation: Programing labor for energy setbacks based on unoccupied areas; cost assumes technician labor for 1 hour @ $100/hr.

Table 17. 2016 ASHRAE-Large Office Return on Investment (ROI).

Energy Conservation Measure (ECM)	kWh/Year	Energy Savings	Annual Energy Cost	Cost Savings	Payback (Years)
Baseline (2019)	7,873,689	-	$904,686.87	-	-
VAV ECM Strategy-I	7,724,223	149,466	$887,513	$17,173.67	0.006
VAV ECM Strategy-II	7,814,436	59,253	$897,878.75	$6,808.13	0.015
VAV ECM Strategy-III	7,838,236	35,453	$900,613.36	$4,073.15	0.025
Heat pump ECM Strategy	7,832,014	41,675	$899,898.43	$4,788.44	0.021

Primary School Energy Conservation Measures Descriptions

Below are the ECMs that were modeled in EnergyPlus for the primary school reference building:

- Occupant Adjusted Controls & Time of Day Heating/Cooling Setpoints
    - Description: Allow users to adjust thermostats within the limits of a ± 3°F dead band. Energy savings is achieved by decreasing the cooling setpoint temperature by 2°F (i.e., from 68°F to 66°F) and increasing the heating setpoint by 2°F (i.e., from 66°F to 64°F)
    - Modeling: Adjust the heating and cooling setpoints by 2°F in each direction
    - ECM Implementation: Replace existing non-adjustable thermostats and program setbacks for new thermostats.
- Plug Load Controls
    - Description: Be more aggressive than the ASHRAE 90.1 schedule by increasing the number of loads connected to controlled outlets
    - Modeling: Assume 10% more of the building's plug loads are controlled based on the plug load schedule.
    - ECM Implementation: Replace existing non-adjustable outlets and program schedules for new outlets.
- Daylight Harvesting
    - Description: Save lighting energy by dimming the lights when there's good natural sunlight coming into a space
    - Modeling: Cutback on lighting percentage from 0.95 to 0.85 during occupied hours
    - ECM Implementation: Add daylight sensors (as required) and program lighting controls for dimming based on daylight levels.
- Lighting Control Vacancy Sensor Setbacks
    - Description: Savings is based on turning off lights in unoccupied spaces
    - Modeling: Cutback on lighting percentage from 0.95 to 0.85 during occupied hours; additive to the daylight harvesting energy savings contribution.
    - ECM Implementation: Change occupancy sensors to vacancy sensors. Additional cost will be incurred if existing sensors cannot be configured for vacancy mode.
- Ventilation on Demand
    - Description: Ventilate spaces based on the number of individuals present rather than on a schedule.
    - Modeling: Reduce fan on/off cycle in occupied spaces by 20%.
    - ECM Implementation: Implementation cost assumes no existing sensors for CO_2. Cost includes labor to install and program new CO_2 sensors into existing BAS.

Table 18. 2019 ASHRAE-Primary School Return on Investment (ROI).

Energy Conservation Measure (ECM)	kWh/Year	Energy Savings	Annual Energy Cost	Cost Savings	Payback (Years)
Baseline (2019)	992,986	-	$114,094.10	-	-
Occupant Adjusted Temperature Controls	957,336	35,650	$109,997.93	$4,096.17	0
Plug-load Controls	977,336	19,650	$111,836.33	$2,257.78	6.6
Daylight Harvesting	969,942	23,044	$111,446.30	$2,647.80	7.6
Daylight Harvesting with Vacancy sensor Setbacks	966,564	26,422	$111,058.20	$3,035	0
Ventilation on Demand	963,742	29,244	$110,733.93	$3,360.18	4.5-11.2

Table 19. 2016 ASHRAE-Primary School Return on Investment (ROI).

Energy Conservation Measure (ECM)	kWh/Year	Energy Savings	Annual Energy Cost	Cost Savings	Payback (Years)
Baseline (2016)	1,058,878	-	$121,665.04	-	-
Occupant Adjusted Temperature Controls	1,041,628	17,250	$119,683.02	$1,982.02	0
Plug-load Controls	1,039,969	18,908	$119,492.47	$2,172.56	6.9
Daylight Harvesting	1,022,933	35,944	$117,535.03	$4,130.01	4.8
Daylight Harvesting with Vacancy sensor Setbacks	1,025,116	33,717	$117,791.00	$3,874.03	0

Ventilation on Demand	1,039,364	19,514	$119,422.90	$2,242.14	3-7.4

General Observations

In general, the payback period for large office building ECMs was shorter than for small offices. This is likely due to the scale of the impact to the energy savings, coupled with the fact that the small office has a smaller total energy cost and thus the energy savings delta was smaller. The cost to implement many of the ECMs in the small office building didn't scale well, and compounded with the smaller impact to energy savings to extend the ROI payback period.

The comparison between 2016 and 2019 energy models was generally insignificant, and where there was deviation between the models it was due to the baseline requirements becoming stricter between 2019 and 2016 ASHRAE 90.1 energy standards.

ROI Payback Analysis

Unsurprisingly, the ECMs with the shortest payback periods were those that only required programming changes to the building system setpoints. For the purposes of the ROI calculations, it was assumed that each programming change would take about an hour at an hourly technician rate of $100. This rate will vary depending on factors such as the billing rate of the service technician, the time required to implement the ECM (which is impacted by the scale and complexity of the programming task), and whether the programming can be completed by an in-house operator versus being hired out to the service technician.

Favorable ECM Investments

The impactful programming changes for each type of building include time of day heating/cooling setbacks which started setting back the heating/cooling setpoint two hours earlier, and lighting control vacancy sensor setbacks to turn off lights in unoccupied spaces which was modeled by reducing the lighting load during occupied hours by 10%. The payback period for these programming changes was under a year, often significantly so.

ECMs that required additional hardware to be installed had longer modeled paybacks. For both small office and primary school buildings, adding plug load controls to an additional 10% of the building's outlets so they can be added to the plug load setback schedule produces a favorable payback period under both ASHRAE 90.1-2016 and 2019.

By adding daylight harvesting sensors to either a small office or primary school, lighting energy loads can be reduced by dimming the lights when natural sunlight is entering the space. Under ASHRAE 90.1-2016 the cost to add daylighting sensors can be paid back in less than 5–7 years, but under the stricter requirements of ASHRAE 90.1-2019 the payback is extended beyond the favorable period and would not be advisable.

In the primary school setting, applying a ventilation-on-demand strategy to ventilate spaces based on the number of individuals present rather than on a schedule had a payback period that varied based on the cost of the implementation. A cost analysis for specific buildings will need to be conducted to determine actual costs for evaluating if the ROI is favorable on a case-by-case basis.

Unfavorable ECM Investments

Adding user-adjustable thermostats to the modeled small office building had a payback greater than 5–7 years. Given the small scale of the building and the meager cost savings relative to the cost to install, user-adjustable thermostats were not a feasible investment.

Small office building exterior lighting controls are potentially worth incorporating. If exterior lighting can be controlled by a schedule that is configured through an existing control system, the cost to program the system to turn off exterior lighting is minimal and would meet the 5–7 year payback goal. However, if a photocell or other hardware is required to control the exterior lighting the payback period would exceed the goal.

The addition of variable frequency drives (VFD’s) to modulate air-source heat pump fan air flow had an extremely long payback for the small office building and would not be an advisable investment.

Application of IBTs to Individual Office Spaces

An opportunity for the use of IBTs in the commercial office space that has not been exploited deals with the individual working spaces of office staff. Plug and process loads (PPLs) consume 47% of the total energy used by commercial buildings.[51] IBTs can provide smart control and operation of PPLs in workspaces with the ability to integrate with the BAS to provide greater localized and individualized control with tempered zone control. This can not only provide energy savings benefits but also improve worker job satisfaction and enhance productivity.

Comfort and lighting issues are a major concern for office workers. Surveys performed on office building workers (with over 400 responses per survey) for a recent study[52] found that nearly two thirds of respondents answered that the workplace physical environment impacted overall job satisfaction. Personal temperature and temperature control for staff working in their individual workspaces received among the lowest ratings in terms of satisfaction with nearly two thirds of respondents wanting greater control of their local environment in the 2023 survey. When dissatisfied with space temperature, women were more likely to say it was too cool while men were more likely to say their office temperature was too warm. When workers were not satisfied with lighting levels in individual workspaces, the most frequently reported problem was that lighting was too bright.

For the lab testing, we investigated the potential of two systems:

1. The opportunities of Raspberry Pi microcomputers to provide control of workspace PPLs.
2. The use of Personal Comfort System (PCS) chairs to offer office workers individual, localized control of their comfort needs at their workstations.

Plug Load Control Devices

The distributed nature of plug loads makes them more difficult to manage than relatively centralized HVAC equipment. As efficiency of lighting and HVAC systems increase in commercial building stock, the relative contribution of plug loads to total building electricity use continues to grow, and in some cases plug loads may consume more electricity than any other end use.

There are several ways to reduce electricity consumption by plug loads, but an effective first step is to identify and eliminate parasitic loads, or electricity consumed by a device that is not doing useful work. This can be done by turning devices off when not in use (manually or with automatic controls), using low power settings of devices, and scheduling software updates so that devices can remain off outside of business hours. Subsequent strategies include improving the efficiency of the devices that are plugged in through replacements and consolidating

[51] U.S. EIA. 2023. Annual Energy Outlook 2023. https://www.eia.gov/outlooks/aeo/.

[52] Shen et al., 2023. The Integration of Wi-Fi Location-Based Services to Optimize Energy Efficient Commercial Building Operations. Minneapolis, MN: Center for Energy and Environment.

redundant loads into centralized loads. Eliminating parasitic loads can typically be done with no- and low-cost solutions, so it is more cost-effective to apply this strategy before subsequent strategies of equipment replacement and consolidation.

The means for eliminating parasitic loads can be further divided into procedural and technical solutions. Technical solutions consist of various methods of controlling power to plug loads such as smart outlets, advanced power strips (APSs), automatic receptacle controls, and integrated building controls. King and Perry estimate energy savings from smart plugs to be about 50–60% and from Tier 1 APS to range from 25–50%.[53] Hackel et al. measured savings of about 20% in a field study of Tier 1 APSs in Minnesota offices.[54] Smart outlets, APSs, and automatic receptacle controls may have some of or all the following functions and characteristics:

- Manual on/off controls.
- Automatic on/off controls based on timers, occupancy, and/or load.
- Measure power consumption.
- Wirelessly transmit power and energy data.

The on/off control features provide the energy saving mechanism, while the monitoring and communication features provide additional functionality that building managers can use to prioritize specific equipment upgrades or consolidations and enable integration with building controls.

Integrated building controls connect plug load control systems to full-building automation systems and enable them to be centrally managed. In addition, integrated building controls may be able to leverage occupancy sensors and building schedules from other systems as additional inputs to the plug load control devices.

In recent versions of many commercial energy codes, a portion of the receptacles in commercial spaces, including private offices and workspaces, are required to have automatic receptacle controls (ARCs). Minnesota Energy Code requires that 50% of the AC outlets in the office spaces must be controlled by occupancy sensor or by time control. These ARCs generally need to be operated by a schedule, occupancy sensor, or a signal from a central control system. Adopting these latest energy codes with requirements for ARCs would improve the ability to eliminate plug loads without additional hardware plugged into receptacles, but ARCs face similar interoperability issues as their plug-in counterparts.

[53] King and Perry, op. cit.

[54] Hackel et al. 2016. Impacts of Office Plug Load Reduction Strategies Final Report. Conservation Applied Research & Development.

Plug Load Control Integration

There are many commercially available plug-load control devices, but the variety of devices, communication protocols, and proprietary apps they use can mean that achieving interoperability and integration across different devices and brands of devices is a challenge. On the residential side, the industry has recognized this issue and major players are collaborating to develop and maintain the Matter standard to streamline setup, control, and interoperability of smart home devices including smart plugs. The Matter standard was first announced in 2019, with the first version released in the fall of 2022, and is intended to allow end users to control a wide variety of smart devices from a single platform. For the commercial side, the focus on plug load control is more on ARCs than the plug-in smart plugs and advanced power strips, but there are similar challenges with integration into BASs, namely, converting from the ARC's native communication method, which may be Wi-Fi, Bluetooth, etc., to that used by the BAS, such as BACNet. In some cases, the ARC manufacturer uses a proprietary gateway to facilitate scheduled operation.

Assuming a method of integrating plug load controls existed, the integrator could interact with all the smart outlets and advanced power strips in a facility. The devices plugged into these power controllers could include docking stations, monitors, task lighting, heating appliances, and personal cooling fans, among others. One application of this plug load control aggregation could be to estimate the type of devices connected based on their power consumption and visualize where different equipment is used in the space. For example, it could be possible to identify spatial concentrations of task lighting or auxiliary space heating and adjust the main lighting and HVAC schedules and distribution to correct for shortcomings in space comfort as evidenced by the use of auxiliary devices. A possible outcome of this integration layer of control is to delay obsolescence of existing control solutions. As IBTs proliferate, a control layer that can communicate with both legacy and new devices protects control investments and ensures that new devices can be added without increasing the number of interfaces that building occupants and managers need to manage.

Experiments with Device Integration

We explored the implementation issues associated with plug load control using a combination of low-cost, open-source electronics hardware and software. Our experiments utilized a Raspberry Pi Pico W microcontroller, which was chosen because of its low cost, integrated Wi-Fi support, and ability to execute scripts written in the popular, flexible, open-source Python language. It runs off a range of voltages from 1.8–5.5 V and has low power consumption, using 25 mA (0.125 W) while idle in standby mode. This would be a small energy penalty compared to the standby loads of the workplace PPLs that it could eliminate.

The Raspberry Pi Pico W has 40 input/output pins that can be used in a variety of ways, including sensing, actuation, and communication. In addition, several third-party vendors make specialized sensors and actuators designed to extend the capabilities of the base microcontroller.

The strengths of the microcontroller we chose are its flexibility and communication capabilities. Therefore, we considered the microcontroller as a sort of universal adaptor to third-party controllers as opposed to a direct controller of plug loads itself. In theory, the microcontroller could be programmed to communicate using a wide number of protocols with multiple off-the-shelf plug load control devices, then aggregate the information and provide a single interface for a BAS to read and write to the control devices.

With this device, we demonstrated the ability to measure a space temperature and transmit it to other devices, and to energize outputs based on control messages received from other clients. For this demonstration we used the Wi-Fi capabilities of the microcontroller and an open-source library implementing the MQTT protocol, a popular IoT communication tool used in a wide range of applications.

Next Steps

While connecting the device to the Internet was a good first step in achieving interoperability with plug load control devices, there are several additional required steps. Ultimately, to integrate with a BAS, some form of commercial building automation communication protocol would need to be implemented on the microcontroller. There are several open-source implementations of the BACNet stack that may deliver this functionality. Then, support for each of the plug load control devices would need to be implemented in turn. This is getting simpler on the residential side, where the industry is moving toward the unified Matter standard, but remains a complex task on the commercial side, where communication depends on device manufactures exposing the right interfaces to third-party controls.

Personal Comfort System Chair

Personal comfort systems (PCSs) are a group of technologies that could be included to reduce overall energy intensity in intelligent buildings. They provide focused heating or cooling of body parts. Many cars today are available with heated driver and passenger seats and some can also provide cooling. PCS chairs work in the same way with heating elements and fans embedded in chairs. There are a number of commercially available PCS chairs designed for several distinct end uses. Appendix C: Commercially Available and Experimental PCS Chairs provides examples of commercially available and experimental PCS chairs. PCS chairs could allow HVAC system setpoints to be lowered in the heating season and raised in the cooling season, leading to energy savings. For example, Yang et al. (2022) noted that during the heating season, the ambient room temperature could be lowered without affecting comfort or satisfaction while individuals managed their personal comfort using their PCS chairs. In their field study, they reported savings of over 50% of the heating energy for the space.[55] In addition to their energy benefits, PCSs are better suited to warming or cooling building occupants than HVAC systems. According to models of thermal comfort that assert that the least comfortable part of the body

[55] Yang et al. 2022. Thermal comfort and energy savings of personal comfort systems in low temperature office: A field study, Energy and Buildings, 270, Article 112276.

limits the overall experience of thermal comfort, an HVAC system that successfully maintains uniform space temperatures and over-heats or over-cools certain parts of the body relative to a comfortable baseline inherently limits the thermal comfort.[56]

The University of California Berkeley Center for the Built Environment PCS Chair

Background

The University of California Berkeley, Center for the Build Environment (CBE) designed and fabricated a kit, in the form of a cassette, to convert an ordinary mesh office chair into a PCS chair. Cooling functions were delivered by three small fans mounted beneath the seat and one fan in the chair back. Heating functions were delivered by resistive heat tape in the back and seat. The power source for the chair was a rechargeable battery pack mounted beneath the chair, which allowed the chair to move freely while in use. The battery could be removed for recharging via USB-C or while mounted to the chair. An occupancy sensor was used to ensure that the comfort system was only activated while the chair was occupied. Heating and cooling functions were controlled by a pair of dials mounted on the side of the seat. The forward dial controlled the seat, while the rear dial controlled the back. Clockwise rotation of the dials from a neutral position increased the heating level, while counterclockwise rotation from a neutral position increased the fan airflow. Figure 15 shows the PCS chair that was used in this study and Figure 16 shows the installation of the cassette in the base of the office chair.

[56] G. Brager, H. Zhang, and E. Arens (2015) Evolving opportunities for providing thermal comfort, Building Research & Information, 43:3, 274-287, DOI: 10.1080/09613218.2015.993536

Figure 15. Personal Comfort Chair.

Figure 16. Installation of the PCS Cassette.

This chair was tested previously in a 2016 study that assessed 37 users' experiences with the chair in an office building in Northern California. The 2016 study found that 96% of the chair users reported thermal comfort, and compared that to the ASHRAE 55 standard which states that HVAC systems should be controlled to provide thermal comfort to at least 80% of building occupants.[57]

Methods

We assembled the PCS chair using a PCS cassette that was sent to us from CBE and which we installed onto a Union & Scale FlexFit Hyken office chair[58] that we purchased from a local office supply store and which the cassette was developed for. The experiment was conducted at the LHB offices to gather qualitative feedback on the PCS chair. LHB staff were invited to complete one survey prior to using the chair to gauge their baseline thermal experience in the office space, and then another survey following their use of the chair to gauge the chair's impact on their thermal comfort. Users were invited to use the chair at their workstation for whatever length of time they preferred. Our research built on the previous study by asking participants prior to the test phase about any comfort issues they typically experience. After testing, we asked if the PCS chair aided in alleviating those issues. We also asked participants to identify their level of satisfaction with their workspace temperature and the PCS chair. Finally, we invited participants to comment on the features of the chair they found most valuable and for any other feedback.

Results

Eight participants completed pre- and post-use surveys. While most participants initially indicated that they would be willing to use the chair for at least two days, only three of the eight participants used the chair for more than one day. Five of eight participants indicated that the office was typically slightly cold or too cold (at least some of the time), and this was reflected in the features users considered valuable, with five specifically mentioning the heating feature and only one mentioning the cooling feature. Despite most participants feeling that the space was slightly cold or too cold, only the two that indicated the space was too cold communicated that they were dissatisfied with their workspace temperature, with all others having neutral or satisfied attitudes regarding the space temperature. All users found the chair either easy or very easy to use; however, only half the participants indicated that they would recommend the chair to others. Several users mentioned the non-thermal benefit to the chair of relaxing stiff lower back muscles.

Discussion

Multiple participants expressed curiosity as the driving force behind their participation in the study and that they had a positive perception of the idea of personal temperature control.

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[57] J. Kim. 2018. Advancing comfort technology and analytics to personalize thermal experience in the built environment, PhD Thesis, University of California Berkeley.
[58] Staples "Union & Scale™ FlexFit™ Hyken Ergonomic Mesh Swivel Task Chair" webpage. https://www.staples.com/union-scale-flexfit-hyken-ergonomic-mesh-swivel-task-chair-maroon-un59462/product_2257054?cid=PS:GS:SBD:PLA:OF&gclid=Cj0KCQjwguGYBhDRARIsAHgRm4-l0g5ZsjB2X82ZmdARtmjBsqansOFStWlOZohyIm3nd546tj1QCt8aApsaEALw_wcB

There were mixed reviews on the effectiveness of the heating functions in such a way that we believe the heating system may have stopped working for the participants who tried the chair later in the study. We also heard that the chair was either the same as or less comfortable than the participants’ normal Herman Miller office chairs, and in some cases, physical discomfort due to the limited ergonomic range of the chair, which was a fifth of the cost of their Herman Miller chairs, outweighed any thermal comfort benefits it provided. At the time of the project, CBE was developing a PCS cassette that could be fitted to a Herman Miller office chair. Overall, the pre-use survey results showed that most people had a neutral satisfaction with their space temperature and felt slightly cold, and the post-use survey showed that people appreciated the heating function of the chair. This finding implies that people can accurately identify what they would do to make themselves comfortable, and that when given the tools to improve their thermal comfort, they will, and can derive increased thermal satisfaction from the experience.

In addition to the control input dials and the occupancy sensor, the chair included temperature and humidity sensors that reported measurements to an Arduino single-board microcontroller. The chair collected the values of these inputs as well as the battery voltage at one-minute intervals and whenever a control input changed state. Both the seat and back of the chair had independent controls with four levels of heating and four levels of cooling. Data collected by the chair is sent to a server in the cloud. On an IB level, information from the chair occupancy sensor could be communicated to the individual workplace PPL controller to invoke phantom load reducing protocols.

If deployed at scale, the data from these chairs would aid a building operator in a variety of building optimization tasks. For example, by using the control input levels as a proxy for thermal comfort, building owners could increase the dead band on their primary HVAC system as long as occupants had not reached the limit of the chair’s heating or cooling range. This approach would maximize energy savings by reducing primary HVAC energy use. A comfort maximization strategy would be to adjust the primary HVAC system to minimize the amount of heating and cooling occupants were requesting from their PCS chairs. In any case, the ability to visualize a fine grid of indoor air conditions, with temperature and humidity at each desk location, with an overlay of comfort indicators in the form of control input levels, would allow building operators to achieve the balance of comfort and energy efficiency that worked best in their application.

The occupancy sensor offers additional intelligent control opportunities. One concept is to tie ARCs and lighting controls to occupancy at the workspace level as opposed to the room level, which achieves savings by eliminating lighting and PPLs in unoccupied spaces. Another possibility is to use the chair data to understand use patterns in office spaces. As the utilization rate of office spaces had declined, there are opportunities to consolidate and reduce the footprint of office spaces. Building operators could get detailed occupancy counts and understand the spatial distribution of staff to know whether consolidation is possible. There may be significant energy benefits to moving staff from sparsely populated HVAC zones and clustering staff in a smaller number of HVAC zones so that some HVAC zones could be fully unoccupied and revert to their less energy-intensive unoccupied state.

Overall, use of these chairs could simultaneously give occupants greater autonomy over their own thermal comfort while giving building operators greater visibility to opportunities for building optimization. The direct benefits these chairs provide to building occupants makes this technology preferable to dedicated distributed sensing infrastructure for IBs. Furthermore, since the PCS cassettes are powered by batteries, recharging the batteries at night results in load shifting of the heating/cooling energy provided by the PCS chairs and increased grid flexibility.

Market Opportunities and Approaches

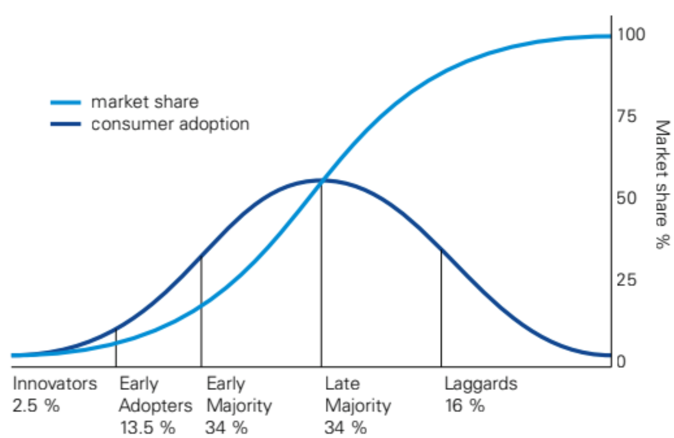
As part of this market analysis, we also want to examine how to increase the market penetration of IBTs so that GEBs and CCs will bring forth the transition to a non-carbon energy future. A major issue that hinders the effective implementation of IBTs is a lack of a coordinated approach by the purveyors of these systems that integrate the various intelligent technologies across the range of building systems. This section will examine the current state of the markets that govern IBTs, determine possible market opportunities, and present recommendations that could promote wider market adoption and implementation. Since the goal is to promote wider adoption of the IBTs, it is useful to consider what underlying factors may exist that allow trends or fashions to take hold and determine how these can be applied to the IB market.

According to Rogers' Law of Diffusion of Innovations, there are five groups of people that comprise the willingness of a market to try new ideas and innovations. These groups are:

1. The Innovators willing to take risks and be the first to try an innovation.
2. Early Adopters are opinion leaders who understand that change is needed and embrace opportunities for change.
3. The Early Majority are willing to adopt an innovation once its effectiveness and value are demonstrated.
4. The Late Majority are skeptical of change but will adopt once a majority adopted.
5. The Laggards are steeped in tradition and skeptical of change and take the longest to adopt a new technology.

Figure 17 shows the distribution of consumers in each of the five groups along with the percent market share that accumulates as the innovation is adopted by these groups.

Figure 17. The Law of Diffusion of Innovations.[59]

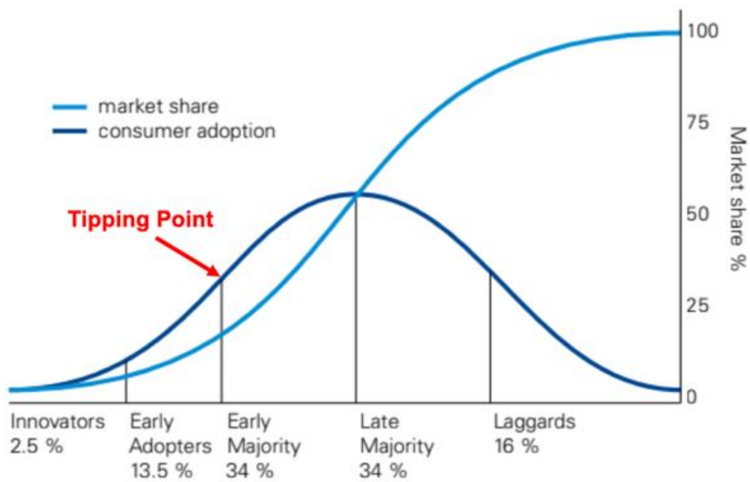


[59] KPMG. Consumer adoption: How to predict the tipping point. November 2016. https://assets.kpmg.com/content/dam/kpmg/uk/pdf/2016/11/open-minds-consumer-adoption-predicting-tipping-point.pdf

The Tipping Point

In 2000, Malcolm Gladwell published his book, The Tipping Point, in which he analyzed how trends arise, propagate, and take hold to shift a paradigm or transform a market. Gladwell defines a tipping point as "the moment of critical mass, the threshold, the boiling point." A tipping point occurs when conditions are favorable for exponential (i.e. viral) growth or adoption, and the exact moment an idea or trend crosses the threshold can be marked as the tipping point moment. On the Law of Diffusion of Innovations curve, the tipping point occurs between the Early Adopters and the Early Majority, as shown in Figure 18.

Figure 18. The Tipping Point on the Law of Diffusion of Innovations Curve.



It is worth examining the adoption of IBs within this context to understand the factors that might inhibit adoption or could spark widespread practice. Gladwell posited two questions—"Why is it that some ideas or behaviors or products start epidemics and others don't?" and "what can we do to deliberately start and control positive epidemics of our own?"

The Three Rules of Epidemics

Through his analysis, Gladwell observed that epidemics require three factors: (1) people who transmit the infectious agent, (2) the agent (virus, idea, or product) that infects and spreads, and (3) an environment where the conditions allow the infectious agent to dwell and operate. Before the epidemic reaches the tipping point, the infectious agent is in an equilibrium state where it exists but does not take hold, thrive, and propagate. Epidemics begin when some change happens with one or more of the factors to cause the equilibrium to break and foment an epidemic. Gladwell identified three change agents that cause this Tipping Point: (1) the Law of the Few, (2) the Stickiness Factor, and (3) the Power of Context. These three rules can serve as a guide to creating reaching a tipping point.

The Law of the Few

The Law of Few reflects the finding that a tipping point often relies on a small number of very special personas who can be classified as *Connectors*, *Mavens*, and *Salespeople*. Connectors are the types of people who have ties with many people, across many realms, and serve as a conduit between these social circles and networks. These are the sorts of influential people who can create word-of-mouth epidemics. Mavens are the individuals with the knowledge and expert opinion that form the basis of the informed decision behind the trend. They are the information brokers whose prime motivation is that they want to educate and help. Finally, tipping points also need persuaders who comprise the third group, the Salespeople. Where Mavens are the information banks who bring the message and Connectors are the social glue who spread the message, the Salespeople are the ones with the skills to convince others that the message is worth believing in and to inspire a critical mass to action. They are the ones with the ability to induce others to participate in the trend and fuel the word-of-mouth epidemic. In today's social media world, Influencers could be considered to embody these three types of personas. Gladwell found that it only takes a small group of these special types of messengers to form the leverage that effectively spreads the message and creates a tipping point.

The Stickiness Factor

The second rule of the tipping point is the Stickiness Factor, which deals with the ability for the content of the message to attract and retain the audience's attention. Successful ideas have two important characteristics: (1) the idea is so memorable, i.e., sticky, that it can create change or spur people to act and (2) the format or packaging of the message is attention grabbing and breaks through the clutter of information that bombards people every day.

The Power of Context

The Power of Context deals with transmission and the environment in which ideas or trends will propagate. An epidemic depends on the conditions and circumstances of the times and settings where the propagation will take place. This rule contends that small changes in context are important in tipping epidemics. Tipping points can depend on specific and relatively small environmental/contextual factors.

The following analysis will examine the current market forces affecting the adoption of Intelligent Building technologies and systems and apply the lessons learned from The Tipping Point to develop insights that might lead to an IB epidemic. We first consider the Law of the Few, and with this we need to define and explore the stakeholders who take part in the IB realm who can take on the roles of Connectors, Mavens, and Salespeople.

Stakeholders

In the exploration of the forces that might induce a tipping point for IBs and application of the Law of the Few, it is important to define the major stakeholders. Their roles in the market and the goals and needs that they have will impact the adoption of IB systems. Amongst these stakeholders, it is likely that Connectors, Mavens, and Salespeople can be identified. There are five types of stakeholders:

- Buyers – These stakeholders are the main decision makers. They decide to purchase and implement the systems and services that will be incorporated into their buildings and workplaces. The Buyers include building owners, developers, commercial real estate firms (CRE), property managers, and commercial building tenants.
- Enablers – There are two types of Enablers—those who guide and those who direct. The guiding enablers are the architects and engineers of the design firms that work with the buyers to plan and specify the intelligent systems that will be implemented in the building or workspace. They provide the information that the buyers need to make their decisions. The directing enablers include utilities who may provide rebates and other incentives to spur adoption of energy efficient technologies and government entities who can influence market penetration through codes, standards, regulations, and programs.
- Suppliers – These are the manufacturers and vendors of the hardware and software IBTs. They market their goods and services to enablers and buyers. They represent the spectrum of commercial building-related markets include mechanical systems, electrical systems (high and low voltage), lighting controls, IT systems, security systems, fire safety, audio-visual (AV) systems, connected systems, and sensors including elevators, motorized shades, occupancy sensors, smart meters, intelligent building applications such as energy management platforms and building analytics, etc.
- Maintainers – These are the dedicated building staff who are directly responsible for operating and maintaining the systems in the building. They have hands–on relationships with the occupants in the building and are the first ones called to address maintenance issues and comfort complaints.
- Supporters – These stakeholders are third-party contractors, service providers, and building managers who provide support service to the maintainers. They can provide on-site or remotes services and may oversee BASs, IT cloud services, security systems, and more. They can generate service tickets and also provide technical support on hardware or software issues. Supporters may also provide services to optimize the operation of a building, such as energy audits and maintenance planning.

Table 20 summarizes the primary stakeholders for the IB market.

Table 20. Intelligent Buildings Stakeholders.

Stakeholders		
Buyers		Building owners

	Decision Makers	Developers
		CRE
		Property Managers
		Tenants
Enablers	**IB System Design**	Architects
		Engineers
		Utility
		Governmental Entities
Suppliers	**Manufacturers and Vendors**	Hardware
		Software
		Services
Maintainers	**Onsite Building Staff**	IT
		Facilities
		Security
		Building Managers
Supporters	**Contractors and Service Providers**	Mechanical/Controls
		Electrical/Low Voltage
		IT
		Cabling Infrastructure
		Fire/Security/Life Safety

The following sections go into greater depth on each of these stakeholder types to understand the goals and motivations of each group.

Buyers

Buyers are the primary target market for IBs. For the building owners and developers of the buyers group, their goal is to maximize occupancy of their buildings, minimize operating costs, streamline maintenance labor, and offer spaces and amenities that are attractive and desirable for their tenants and occupants. Tenants want their office spaces to support the productivity, wellbeing, and values of their staff while also being cost-effective to operate and maintain. Building owners and developers can drive the market through direct purchases and by promoting the benefits of IB to prospective tenants. Tenants can influence the market by demanding the amenities and benefits offered by smart technologies.

IBT implementations are often spearheaded by a visionary or small set of leaders within an end-user's organization who recognize the transformative potential that new technologies can offer. While buyers can drive market demand through capital investment the impact is difficult to measure. Because buyers from different companies generally do not act collectively their potential to sway the market isn't as great as it could be if they acted together to envision a future of ideal IBTs.

Enablers

Enablers are the stakeholders that define what smart technologies are available to meet the needs of the buyers and guide how the smart technologies will be implemented. Enablers may act as gatekeepers, and their endorsement or evangelism helps determine ideas and trends that are introduced and amplified throughout the public zeitgeist. Important enablers are the architects and engineers of the design firms who work with the buyers to plan and design the building or space and help them choose the systems that will be installed. Unless the buyers are already predisposed toward IBs, the architects and engineers will have to take on the roles of maven and salespeople to educate end-users on what is possible and advocate for the adoption of smart technologies. Salespeople from contractors and systems integrators also have a role in guiding end-users toward employing smart technologies.

Utilities can also be enablers and are often incentivized to take up the role if they determine that specific smart technologies can assist them in providing more effective energy services. For instance, they can create programs that incentivize the adoption of smart technologies that allow buildings to be more energy efficient and more interactive with the grid. Utilities offering customers rebates for networked lighting systems is an example of this. Demand response programs are another example where utilities serve as proponents of IBs.

Governmental entities can enable IBs on several levels such as via codes and standards that regulate adoption or programs and public funds that promote adoption. Building codes could be created that dictate requirements in the design and implementation of smart systems. State agencies and commissions can oversee utilities in creating IB programs. Federal programs like ENERGY STAR can have certifications or ratings that promote IBs. DOE’s efforts in helping the development of GEBs and connected communities support research and development of smart technologies and market acceptance of IBs. In addition to codes and incentives, governmental entities can create legislation requiring buildings to achieve carbon reduction and energy efficiency targets that might require IBTs to achieve.

Non-governmental organizations (NGOs) such as U.S. Green Building Council (USGBC) have rating systems and certifications[60] like LEED that can be important tools to drive market adoption of energy efficient practices and technologies. There are many IB scorecards on the market or under development. WiredScore, a company that scores commercial real estate buildings based on their connectivity and technology readiness, has created the SmartScore scoring system for rating IBs Underwriter Laboratories (UL) and Telecommunications Industry Association (TIA) are working together to create the SPIRE score card, and other organizations are creating new scoring systems as well. These can serve as a marketing tool to attract tenants and raise building occupancy. Trade associations and professional organizations can provide information support and expertise while universities and nonprofit research organizations

[60] T. Kenlon, “Which of these 40 sustainability certifications is right for you?”, January 3, 2023, GreenBiz webpage article. https://www.greenbiz.com/article/40-sustainability-certifications

perform research projects that test and evaluate new technologies and often look for buildings to serve as demonstration sites.

Suppliers

Suppliers are the manufacturers and vendors of the smart systems that are installed in IBs. They may be advocates and evangelists of IBs and may serve as both salespeople and mavens. The products that compose the IB landscape, as well as the services offered to support and enhance them, change rapidly with advances in technology. Suppliers seek to understand the business needs of their customers so they can create the right products and product ecosystems to not only meet but anticipate and drive demand, seeking to solve problems the customer may not have even recognized as a need. Sometimes this leads to solutions in search of a problem, which can cause confusion in the marketplace. The sheer abundance of product offerings, new companies, and new product categories, may further add to buyers' confusion, slowing the adoption of IBTs.

Maintainers

Daily maintenance of buildings and intelligent building systems is the responsibility of staff such as building managers, facilities personnel, security staff, and IT staff, who might be decentralized among the tenants who occupy the building. These individuals are directly responsible for addressing any issues that might arise in the buildings and are the first line of response to any complaints from the occupants or directives from the buildings' owners. The senior members of the staff are also responsible for creating budgets for maintenance and capital improvements.

Maintainers are often asked to do more work with fewer resources and may benefit from IB tools that help predict maintenance that is needed before a failure has occurred. Such tools can function as force-multiplier to virtually expand their workforce, and may be adopted by the less experienced junior staff who also tend to belong to generations that are more apt to look to technology to help solve problems and manage their daily lives.

The automation that can come with IB systems may ease maintainers' responsibilities but also creates a new vernacular through electronic applications for producing dashboards and service tickets. As systems become networked and digitized, roles and responsibilities shift. For example, when a light goes out as part of a networked lighting system, this issue may no longer be resolved by facilities staff replacing a light bulb but could now require IT staff to determine if there are any network or software issues affecting the connected lighting system or fixture.

The maintainers will need training to understand the systems that are being installed and how they are intended to function as part of a more complex, integrated system. They need to maintain a working relationship with contractors who have installed the systems and provide service contracts to oversee the systems and ensure that they are working properly. Maintainers are the eyes and ears of the building and provide feedback on how the systems are serving the buildings' occupants. They are the operators of the systems and must understand the needs and goals that the IB systems are intended to meet.

Supporters

The supporter stakeholders are the contractors who assist in the operations and maintenance of the specific IB system through the service agreement they have with the building or specific tenants. These systems can include the BAS, the HVAC equipment, connected lighting systems, IT systems, security systems, AV systems, and other connected systems. Their remote services can include (1) responding to service tickets that are sent to the maintainer stakeholders who are asked to troubleshoot or resolve any issues or alarms that are detected, (2) providing technicians to assist in maintaining or servicing equipment, and (3) providing remote services through programming operating schedules or performing software updates. The supporter stakeholders may also be from the Supplier stakeholders who manufactured the systems or from the contractors who were hired to install the systems. They could have been enlisted by suppliers, enablers, or buyers. Supporters may be buyers of IB tools, which can be used to more efficiently diagnose and address the concerns of the building maintainers, owners, and occupants.

Integrators

A potential subset of the stakeholder group listed above are the integrators who recognize that the potential of IBs is inhibited when building systems are siloed. These individuals advocate for these building systems to be designed, installed, and operated in concert. The term integrator, in this case, must be distinguished from integration contractors who are also often referred to as integrators or system integrators.

Integrators are individuals who can be found among the other stakeholder groups. Integrators bring a systemic approach to IBs. Their viewpoints and voices are often not well-represented and they need to be sought out and brought up front to guide and lead. The Integrators have an important role that strives to overcome the siloed approach that causes the redundancies, inefficiencies, and miscommunication that plagues traditional, less intelligent buildings. James Dice, founder of the online Nexus Labs community,[61] is an example of an Integrator attempting to unify stakeholders under a common vision.

Finding Connectors, Mavens, Salespeople, and Integrators

By the Law of the Few, Connectors, Mavens, and Salespeople are prerequisites to creating and sustaining a tipping point. Within the IB realm, these individuals arise from within the community and among the stakeholder groups. Table 21 shows where Connectors, Mavens, Salespeople, and Integrators might be identified within the various stakeholder groups.

[61] Nexus Labs homepage. https://www.nexuslabs.online/

Table 21. Connectors, Mavens, Salespeople, and Integrators Amongst the Stakeholder Groups.

Stakeholders			Law of the Few			Integrator
			Connector	Maven	Salespeople	
Buyers	Decision Makers	Building owners	x		x	
		Developers	x		x	
		CRE	x		x	
		Property Managers	x		x	
		Tenants	x		x	
Enablers	IB System Design	Architects	x	x	x	x
		Engineers	x	x	x	x
		Utility	x	x	x	x
		Governmental Entities		x	x	x
Suppliers	Manufacturers & Vendors	Hardware	x	x	x	
		Software	x	x	x	x
		Services	x	x	x	x
Maintainers	Onsite Building Staff	IT	x	x	x	x
		Facilities		x		
		Security/Safety		x	x	
		Building managers	x	x	x	x
Supporters	Contractors & Service Providers	Mechanical/Controls		x	x	
		Electrical/Low Voltage		x	x	
		IT		x	x	
		Cabling Infrastructure		x	x	
		Fire/Security/Life Safety		x	x	

As trends are adopted, a positive feedback loop can be observed, and the critical mass that leads to the tipping point is slowly built. Connectors will likely be found amongst those stakeholders who communicate with all the other stakeholder groups and are well networked with the commercial building community. The buyers who purchase the IB technologies and services define the market and can serve as examples of the benefits of these systems. They can serve as Connectors when they network with their peers and interact with their vendors, contractors, and design professionals.

The buyer stakeholders can dictate and shape trends if they and their peers have a sufficient market share to drive demand. This market pressure comes from the building owners, developers, and CRE companies who own or manage the properties and tenants who demand features and services when they lease spaces in the properties. If more buyers adopt IBTs and communicate their benefits to their peers the critical mass reaches an inflection point and a nascent trend reaches its tipping point.

The Stickiness of the Internet of Things

After the Law of the Few is the second rule of the tipping point, the Stickiness Factor, which requires that the message attracts attention and is memorable. The Baby Boomer generation born between the years 1946–1964 make up a large proportion of the target consumer market. They were raised on the promise of new technology and experienced many of its benefits. The future portrayed by the popular early 1960s animated television series, *The Jetsons*,[62] helped shape and inform the technological aspirations of a generation. They then watched as their children enjoyed the reality of the space age future that was predicted. While many Boomers may have been initially resistant and confused by the introduction of personal computers, the world wide web, and smart phones, they quickly became familiar with the conveniences and connectedness that these technologies brought, adopting new technologies in spite of possible hesitancy.

The web bridged the gap between the younger and older generations that turned the tables where the younger generations of digital natives were relied on for know-how and information. IoT now pervades and devices like smartphones, smart watches, smart TVs, digital assistants, and smart speakers are commonplace. IoT which is the foundation of IBs, exemplifies the Stickiness Factor that is needed to grab attention and raise expectations. Smart features are widely accepted in the cars we drive and it is a small step to expect many of these features to be available in our buildings. This stickiness manifests in the expectations of the tenants and the needs of the building owners, developers, and CRE companies. Following a trend that has long held true between consumer and commercial technology adoption, buyer adoption of smart home technology drives the demand for similar functionality in the workplace, increasing adoption of commercial IBTs. Buyers are attracted to smart technology by the promise of highly customized experiences and a system that learns their preferences and patterns over time. As our workspaces shed assigned office and desk spaces, IBs could bridge a gap of personalization for shared spaces. Imagine checking into a shared office and the lighting adjusts, the blinds lower, the temperature bumps up a degree, and the adjustable height desk raises to your preferred standing height. IBs have the ability to turn minor annoyances into feeling pampered and special. Highlighting these creature comforts along with the energy savings and performance enhancements of IB systems could create more direct personal benefits and increase the overall stickiness factor of the technologies.

The Context of Clean Energy and Electrification

The third rule of the tipping point, the Power of Context, describes how circumstances and settings can help propagate an epidemic. The impact of climate change could be producing the

[62] Wikipedia "The Jetsons" webpage. https://en.wikipedia.org/wiki/The_Jetsons

contextual factors that might spark a tipping point for IBs. Minnesota's recently passed 100% Clean Electricity Bill has put a timetable on carbon-free electricity generation in the state. This law will produce major changes in the state's electrical infrastructure and will impact how buildings consume electricity and interact with the grid. IBs can provide many of the functions required for the transition away from fossil fuels to carbon-free forms of electrical power generation.

The Minnesota 100% Clean Electricity Bill of 2023

On February 7, 2023 Governor Tim Walz signed a clean energy bill that required Minnesota's electric utilities to transition to 100% clean energy by 2040.[63] The act stipulated the following clean energy standards:

- Electric utilities are required to generate or procure at least 55% of their electricity from renewable sources by 2035.
- Public utilities are required to generate or procure at least 80% of their electricity from carbon-free sources by 2030 with other utilities required to get 60% from carbon-free sources.
- All electric utilities are required to generate or procure at least 90% of their electricity from carbon-free sources by 2035.
- All electric utilities are required to generate or procure 100% of their electricity from carbon-free sources by 2040.

Xcel Energy and Minnesota Power, Minnesota's two largest electric utilities, had set goals of a net-zero energy future by 2050.[64, 65] The bill contains exemptions and alternatives for utilities to achieve the standard, such as allowing utilities to purchase renewable energy credits to offset electricity generated at natural gas peaker plants. There are also "off ramps" where the Minnesota Public Utilities Commission (PUC) can allow utilities to delay meeting the standards because of impacts to customers from possible higher electric rates or reliability issues caused by the transition.

Relying on intermittent electricity generation from renewable sources like wind and solar will call for increased load flexibility from our major end-use demands such as the commercial building sector. In 2017, Minnesota's commercial building sector consumed 19.5% of the total energy consumed in the state.[66] To assist utilities in achieving the standards set forth by the

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[63] Minnesota Legislature Office of the Revisor of Statutes "SF4" webpage. https://www.revisor.mn.gov/bills/text.php?number=SF4&version=latest&session=ls93&session_year=2023&session_number=0

[64] Xcel Energy "Carbon Reduction Plan" webpage. https://mn.my.xcelenergy.com/s/our-commitment/carbon-reduction-plan

[65] Minnesota Power "EnergyForward" webpage. https://www.mnpower.com/energyforward

[66] Minnesota Department of Labor and Industry and the Minnesota Department of Commerce. 2020. Improving building energy efficiency in commercial and multi-family construction. https://www.dli.mn.gov/sites/default/files/pdf/BuildingsEnergyEfficiency2020.pdf

100% Clean Electricity Bill, commercial building energy use must be improved through more efficient building operation.

GEBs and GHG Reductions

The ability of GEBs to reduce and shift the timing of electricity consumption through demand flexibility can significantly reduce electric utility GHG emissions. DOE suggests that by 2030, GEBs could reduce CO_2 emissions by 80 million tons per year, or 6% of the total power sector CO_2 emissions.[67] This is another benefit that IBs can bring to Minnesota's efforts in achieving carbon-free electrical generation. Since the Next Generation Energy Act of 2007, the State of Minnesota has led the nation in climate policy with a commitment to renewable energy and carbon-free electrical generation.[68] Xcel Energy has pledged to reduce carbon emissions 80% by 2030 (over 2005 emissions),[69] while Minnesota Power has pledged to achieve this target by 2035.[70] Great River Energy, a wholesale electric cooperative and the state's second largest electric utility, expects that the utility's currently ongoing power supply changes will bring a 95% reduction in carbon emissions (relative to 2005 levels) by 2023.[71]

A National Effort to Support GEBs Implementation

As part of their commitment to support greater energy efficiency and demand flexibility in the commercial building sector, DOE has published a national roadmap to develop and implement GEBs.[72] The National Association of State Energy Officials (NASEO) and the National Association of Regulatory Utility Commissioners (NARUC) established the NASEO-NARUC Grid-interactive Efficient Building Working Group to assist "State Energy Officials and state utility regulators to explore GEB/DF technologies and applications; identify opportunities and impediments (technical and non-technical); identify and express state priorities and interests; inform policy, planning, programs and regulation; consider unregulated electric sector investments and implications; and advance GEB/DF road map and pilot options."[73]

Given Minnesota's goal of carbon-free electricity by 2040 and the utilities' pledges to reduce carbon emissions, GEBs and therefore IBs will be counted on to significantly contribute to

[67] A. Satchwell et al., op. cit.

[68] MPCA "Climate change initiatives" webpage. https://www.pca.state.mn.us/air/state-and-regional-initiatives

[69] Xcel Energy "Carbon Reduction Plan" webpage. https://mn.my.xcelenergy.com/s/our-commitment/carbon-reduction-plan

[70] W. Ornstein, "Minnesota Power pledges no carbon by 2050, zero coal by 2035," MinnPost, January 12, 2021. https://www.minnpost.com/environment/2021/01/minnesota-power-pledges-no-carbon-by-2050-zero-coal-by-2035/

[71] Great River Energy. 2021 Integrated Resource Plan Update. https://greatriverenergy.com/wp-content/uploads/2021/04/2021-Integrated-Resource-Plan-040121.pdf

[72] A. Satchwell et al., op. cit.

[73] NASEO "NASEO-NARUC Grid-Interactive Efficient Buildings Working Group" webpage. https://www.naseo.org/issues/buildings/naseo-naruc-geb-working-group

reaching those goals. The commitments of these two stakeholders will be strong contextual factors that can support and drive the adoption of IBTs and GEBs.

The Post-COVID Office Workplace

Another important contextual factor that supports the adoption of IBTs is how the COVID-19 pandemic has changed the office workplace and commercial office buildings. Post COVID, there has been an increase in hybrid and remote work arrangements that create more complex occupancy schedules for buildings. Occupant counts are down overall compared to early March 2020 and attendance varies throughout the week with concentrated use on Tuesdays, Wednesdays, and Thursdays. Adjusting setpoints based on a traditional weekday program that assumes occupied hours of 7:30 a.m. to 5:30 p.m. will result in unnecessary lighting and space conditioning.

Facility managers are left trying to satisfy competing demands. Managers and human resources call for increased occupant comfort and indoor environmental quality to attract people to the office. Financial managers see empty seats as an opportunity to cut operational costs. Switching spaces to unoccupied mode on Mondays and Fridays would save operationally, but risks further alienating a hybrid workforce that highly values flexibility and autonomy related to time and days spent in the office. (Anecdote: one local company has turned down the thermostat on Fridays and the engineering workforce now cynically calls it “Frigid Friday”)

Space types in commercial office buildings are becoming more complex as cubicles are replaced with collaboration spaces, more small, enclosed meeting rooms and offices, tenant lounges, and conference spaces. More spaces are also being designed to flex as needs and uses evolve over time — this is often achieved with moveable furniture and demountable wall solutions. Increased building intelligence within these dynamic environments could increase comfort, energy savings, adaptability, and predictive analysis of use.

Vacancy rates for office space continue to grow as employers settle into long-term hybrid work and continue to downsize real estate footprints. Cushman & Wakefield, a national commercial real estate services firm, estimates that 25% of office property is functionally obsolete and up to 60% of all office buildings are facing competitive obsolescence and classification as a commodity or discount office space. These spaces need investment, and typical repositioning strategies include enhanced amenities, improving performance and sustainability, and improving a building’s sense of place with community with engaging events and offers. IBT can enhance each aspect of the investment and contribute to a competitive advantage in the lease market.

IBTs can provide the flexibility to support these new office space uses while ensuring comfort and efficient energy use. Tenants will expect and demand these types of services and building owners and property managers will need to offer these benefits to maintain occupancy.

Environmental, Social, and Governance (ESG)

The prevalence of ESG policies and reporting grows as corporations and nonprofits vie for investors and donors. ESG reporting is still in its infancy but standards are emerging in the marketplace. The Securities and Exchange Commission is finalizing its Climate Risk Disclosure rules, and these will affect not only publicly traded companies but also clients, vendors, and suppliers of these companies or anyone that wants to do business with government agencies.

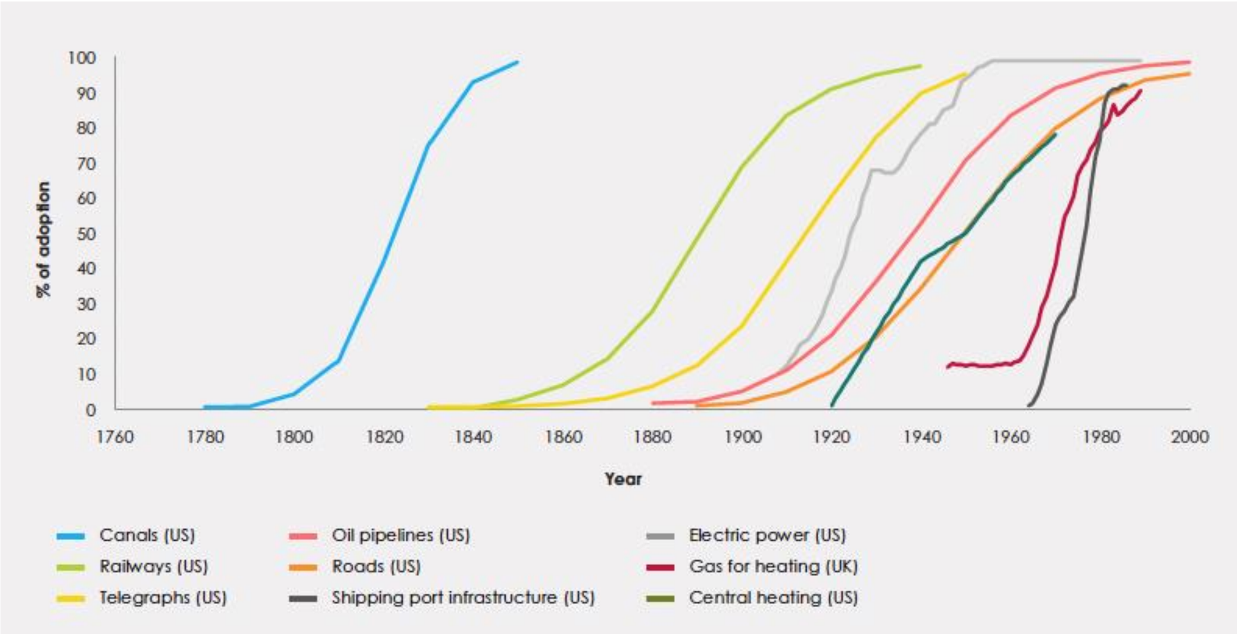
A cornerstone of ESG reporting is measurement, tracking, and verification of energy use and carbon emissions. IBT is instrumental in both measuring and tracking data in repeatable formats that are verified and audited annually by third parties. However, the real power lies in analyzing that data to further optimize energy usage, track preventative maintenance, and watch for anomalies that might indicate equipment failures or maintenance needs.

The Breakthrough Effect

Even though the elements and conditions may exist to support a tipping point for IBs, their proliferation in the commercial sector is far from rampant. Clearly, a catalyst is missing that could spark a tipping point. In January 2023, Systemiq published their report, *The Breakthrough Effect: How to Trigger a Cascade of Tipping Pints to Accelerate the Net Zero Transition*.[74] The report uses the examples of three "super-tipping points" that could trigger a cascade of tipping points to drive the rapid adoption of zero-emission solutions and a drastic reduction in global emissions. While Gladwell describes the demand-side conditions that can foment tipping points, the breakthrough effect expounds on supply-side factors. In their examination, the authors suggest the conditions and drivers that can propel socio-economic tipping points to reach a mass market state. When examining the historic adoption of infrastructure and energy systems in the U.S. and U.K., these systems all exhibited tipping points where reinforcing feedback loops drove exponential growth in adoption along an S-curve. Figure 19 shows examples of the S-curve adoption that is typical of a technology transition.

[74] M. Meldrum, L. Pinnell, K. Brennan, M. Romani, S. Sharpe, and T. Lenton, The Breakthrough Effect: How to Trigger a Cascade of Tipping Pints to Accelerate the Net Zero Transition, London, England: Systemiq Ltd., January 2023. https://www.systemiq.earth/wp-content/uploads/2023/01/The-Breakthrough-Effect.pdf

Figure 19. S-Curve Adoption of Infrastructure and Energy Systems in the U.S. and U.K.[75]



Three enabling conditions are typically at play that support increased deployment of the new system or technology:

1. Affordability – Often, a rapid increase in deployment occurs when the relative affordability of the new solution passes a certain threshold. As the production of emerging technologies or systems increase, sharp decreases in costs often result, making the new solutions cost-competitive with legacy technologies.
2. Attractiveness – Along with cost, the improved performance or increased functionality of the new solutions will attract further deployment to help trigger a tipping point. In fact, the increased utility of the added capabilities of the new solutions can overcome early stage cost disadvantages of the emerging technology.
3. Accessibility – Emerging technologies may require supporting infrastructure to be in place before large-scale adoption can take place. For systems that share the supporting infrastructure, synergies are possible that can enhance the new solutions to bring capabilities beyond the previously segregated legacy solutions.

The combination of enabling conditions with reinforcing (or positive) feedback loops can result in a tipping point that pushes adoption rates along the exponential growth path of the S-curve. A reinforcing feedback loop is one in which an increase in a variable affects the system in such a way that causes the further increase of that variable. In the case of an emerging technology's adoption, as deployment of the technology increases, production will increase which can lead to a reduction in costs which can lead to further deployment, and so on. Balancing (or negative) feedback loops resist change and act to counteract and inhibit the exponential growth of reinforcing loops. In the case of S-curve adoption, initial growth in the adoption rate of the new

[75] Ibid.

solution is slowed by the market strength and legacy infrastructure of the incumbent technologies and the inertia of the business models that support them. If a tipping point is reached, the reinforcing feedback loops dominate and unlock S-curve adoption until market saturation introduces another balancing feedback loop.

The Systemiq report identifies a number of important types of reinforcing feedback loops, which can often operate in concert:

- Learning by doing – As the technology is put into practice, familiarity, improvements, and innovations are made to enhance the product. Production is optimized, which lowers costs. These increased benefits feed greater deployment.
- Economies of scale – As the scale of production increases, fixed costs are spread over the higher volume of products. The unit cost of production decreases, which supports a greater rate of output.
- Technological reinforcement – As the new solution is put into practice, additional practices and technologies arise that increase the usefulness of the new solution.
- Network and coordination efforts – As the new solution becomes embedded into the overall system, integration with other technologies and practices is realized and further enhances the utility of the new solution and initiates upgrades to the other systems.
- Self-reinforcing expectations – As expectations on future market size trigger investment, when these expectations are met or are exceeded, further investments are triggered.
- Contagion of social norms – Also known as the Diffusion of Innovations, new technologies spread rapidly through social communication after passing the early adopter stage of niche appeal into mass (self-sustained) adoption.

Depending on the strength of the reinforcing feedback loops, a tipping point can be initiated and the adoption rate will proceed along the exponential growth of the S-curve.

The Breakthrough Effect describes tipping cascades in which a tipping point in one sector can trigger tipping points in other sectors. IBs involve many different sectors including lighting, HVAC, IT, fire, security, and life safety. Sensors and controls can overlap across these sectors, which can result in either redundancy or the opportunity for integration. If there is a potential for a tipping cascade, then there usually exist super leverage points that provide relatively low difficulty or cost opportunities that can foment a tipping point across more than one sector. For example, a tipping point in the deployment of intelligent technologies in security because of developments in occupancy sensing could result in a tipping point for HVAC and lighting as the occupancy information is used to refine building operation and maintenance. The proliferation of GEBs could also be a super leverage point as tipping points occur with EVs and their need for charging stations at buildings, or solar microgrids with battery energy storage systems that power buildings will necessitate intelligent building technologies and systems. It might be possible to identify super leverage points and determine strategies that can tip these leverage points to catalyze tipping points and tipping cascades.

Actions that Support Emerging Technology Adoption

Emerging technologies or practices normally follow a developmental path as they gain full adoption in the marketplace. During each phase of this development, Systemiq has identified a number of key actions that are needed to support the growth of this new technology or practice and possibly trigger a tipping point. Table 22 shows the progression of transitional phases that technologies and practices travel through in their development from concept to full market adoption. For each phase, specific actions from sector stakeholders are identified that can help propel the development to the next phase of adoption.

Table 22. Transitional Phases of the Adoption of New Technologies and Required Actions for Further Development.

Phase	Description	Actions
Concept	Early stage development that requires prototyping to trial different possibilities to find a viable option.	This often requires publicly funded R&D programs along with private sector experimentation.
Solution Development	Proof of concept piloting through demonstrations and case studies often via public-private partnerships.	Strong public financial support is required to overcome the risk of investment for these breakthrough first-of-a kind commercial projects.
Niche Market	Early adopters create demand for the new technology to establish and grow the consumer base. Prosumers experiment with features to propel the use to wider applications.	Financing and consumer coalitions are required to build greater implementation. Shifts in policy can incentivize large scale production via subsidies and tax breaks or promote the growth of supporting public-private partnership infrastructure.
Mass Market	Once the technology has reached the early market adoption, demand for it outcompetes the incumbent technology and percent adoption has entered the steep part of the S-curve. As greater profits are realized, access to capital shifts from the old to new solutions.	During this stage, markets shift to favor the new solutions with new regulatory frameworks and schemes instituted to shift the phase-out of the legacy approaches.
Late Market	The new technology or practice has reached large-scale adoption and is being institutionalized as standard practice.	During this stage, new standards are set and enforced while the implications of the shift requires workforce retraining. The solution can also expand to new markets as

		the legacy approaches are expelled from remaining niches.

During the early phases, public funding is necessary to support development of emerging technologies. U.S. DOE has a number of funding programs that can be used in support of the development of technology solutions in the Concept, Solution Development, and Niche Market phases. These include:

1. The Advanced Research Projects Agency – Energy (ARPA-E) is intended to support Concept phase, early stage development of "high-potential, high-impact energy technologies that are too early for private-sector investment."[76]
2. The Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) funding opportunity that is issued on a regular basis with the purpose "to research and develop high-impact, cost-effective technologies and practices."[77] This funding can be used to support the development of technology solutions in the Concept and Solution Development phases.
3. The Small Business Innovation and Research (SBIR) and Small Business Technology Transfer (STTR) programs provide domestic small businesses funding "to explore their technological potential and provide the incentive to profit from its commercialization."[78] This funding should be applied to small businesses for the development of products and services in the Concept, Solution Development, and Niche Market phases.

Triggering a Minnesota Tipping Point

In Minnesota, market adoption of IBs is currently in the Niche Market phase where the chasm between the Early Adopters and the Early Majority needs to be bridged. The next challenge for IBs is to create a tipping point to move adoption to the Early Majority and beyond. The market segment of the Early Majority is characterized by those who need to be shown that the innovation has demonstrated both its effectiveness and value. They expect that the risks and challenges have been overcome and there is an established infrastructure to support its use and adoption.

While local chapters of professional organizations like ASHRAE[79] and the Association of Energy Engineers (AEEE)[80] and local trade associations like the Building Owners and Managers

[76] ARPA-E homepage. https://arpa-e.energy.gov/

[77] DOE Press Release, "BTO Releases BENEFIT 2022/23 Funding Opportunity for Innovations that Electrify, Optimize, and Decarbonize Building Operations," December 14, 2022. https://www.energy.gov/eere/buildings/articles/bto-releases-benefit-202223-funding-opportunity-innovations-electrify

[78] Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) homepage. https://www.sbir.gov/

[79] ASHRAE Minnesota Chapter homepage. https://mnashrae.org/

[80] Association of Energy Engineers Twin Cities Chapter homepage. https://aeetwincities.org/

Association (BOMA)[81,82] and NAIOP, the commercial real estate development association,[83] can provide valuable expertise and guidance, these special interest groups are focused on the specific needs and interests of their members. A coordinated network of practitioners, suppliers, vendors, and consumers is needed to trigger an IB tipping point in the region. Recently, the Twin Cities Chapter of the Building Intelligence Group (BIG-TC)[84] formed as a professional organization to support the growth and adoption of IBTs. Drawing from a membership that includes consultants, contractors, integrators, architects, engineers, various end-users, and service provider stakeholders involved in building management and automation, the Twin Cities chapter of BIG represents an organized group of early adopters who has established itself as a private sector resource and voice in the region. BIG-TC can be an important resource that provides the IB practitioners to serve as the connectors, mavens, and salespeople to support a tipping point. Appendix D: Building Intelligence Group provides more information about BIG and BIG-TC. With the backing of DOE and the commitment of the state and utilities, a concerted effort led by public-private partnerships is needed to provide R&D, demonstration projects, and incentive programs that will promote the adoption of IBTs and lead to the implementation of GEBs and CCs.

[81] BOMA Greater Minneapolis homepage. https://www.bomampls.org/

[82] Greater Saint Paul BOMA homepage. https://www.bomasaintpaul.org/

[83] NAIOP Minnesota Chapter homepage. https://www.naiopmn.org/Prod

[84] BIG-Twin Cities homepage. https://www.buildingintelligencegroup.org/twincities

Conclusions

IBs will play a significant role in the transition to a non-carbon energy future and the further development and increased market adoption of these IBTs and systems will be essential for this transformation. Currently, the market diffusion of IBTs are both in the early adoption stage with regard to IBs and in the innovation stage for their use in GEBs and connected communities. As these technologies continue to be developed and implemented, the practical considerations need to be identified and addressed to ensure that consumers will welcome and embrace these needed technologies. Innovations will not be adopted purely for the technical advantages that are offered. Ensuring that expectations are managed and met and that unintended consequences can be anticipated or minimized is vital to a smooth transition. The goal of this market analysis was to detail an important issue with IBTs: are the power requirements of IBTs understood and do the design, implementation, and use of IBTs justify the additional costs and complexity that IBTs carry? Finally, given the need and timeline for the transition to a non-carbon energy future, can private and public measures be administered that will accelerate market forces to promote and sustain a tipping point?

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Appendix A: Benefits of IBTs by Sector and Stakeholder

The non-energy benefits of IBTs vary by market sector and building stakeholder. The positive outcomes generated by IBTs for several major market sectors and stakeholders are listed below.

Positive Market Sector Outcomes

Health Care

- Enhanced Patient Experience
    - Intelligent buildings contribute to better patient experience by providing a comfortable and safe environment that puts enhanced levels of control in the hands of the patient and family.
- Improved Staff Productivity
    - Intelligent buildings streamline operations and automate routine tasks, allowing healthcare staff to focus more on their core mission of patient care. Automation of processes such as room scheduling and cleaning, equipment maintenance, and inventory management reduces administrative burdens, enhances staff productivity, and enables efficient resource allocation.
- Enhanced Safety and Security
    - Intelligent buildings integrate security systems, access controls, video surveillance, mobile duress, and emergency response mechanisms to enhance safety and security within healthcare facilities. This ensures the safety of patients, staff, and valuable assets while enabling rapid response to emergencies.
- Seamless Communication and Connectivity
    - Intelligent buildings include robust communication and connectivity infrastructure, supporting advanced healthcare technologies such as telemedicine, patient monitoring systems, electronic health records (EHR), and communication between staff members. This improves collaboration, information exchange, and overall efficiency in healthcare delivery.
- Infection Control and Patient Safety
    - Intelligent buildings can incorporate smart technologies for infection control, such as maintaining space pressure relationships, touchless entry systems, automated hand hygiene reminders, and cleaning reporting for accountability and compliance. These features contribute to reducing the spread of infections within healthcare facilities and safeguarding patient safety.

Higher Education

- Improved Comfort and Productivity

    - Intelligent buildings enhance occupant comfort and productivity within educational institutions. Integrated control systems allow for personalized climate control, adaptive lighting, and optimized indoor air quality. This creates a conducive environment for learning, studying, and working, resulting in improved student and staff satisfaction, well-being, and academic performance.
- Smart Space Utilization
    - Intelligent buildings enable higher education institutions to optimize space utilization through data-driven insights. Occupancy sensors and utilization analytics can help identify underutilized areas and enable effective space planning, improving operational efficiency and potentially reducing the need for new construction or expansion.
- Educational Opportunities
    - Intelligent buildings offer educational opportunities for students, providing them with exposure to state-of-the-art building technologies, energy management practices, and sustainability initiatives. Students can engage in research projects, gain hands-on experience with advanced systems, and develop skills relevant to the evolving field of intelligent buildings.

Public and Corporate Workplace

- Compliance and Certification Support
    - Intelligent buildings assist energy and sustainability managers in meeting regulatory requirements and achieving sustainability certifications, such as LEED (Leadership in Energy and Environmental Design) or Well Building. Intelligent building systems can generate reports and documentation required for compliance, simplifying the certification process.
- Occupant Engagement
    - Intelligent buildings facilitate collaboration and engagement with stakeholders, including building occupants, facility managers, and external partners. Energy and sustainability managers can leverage the system to communicate energy-saving tips, provide feedback, and encourage sustainable behaviors, fostering a culture of sustainability within the building.
- Automated Benchmarking and Target Setting
    - Intelligent buildings can automate the benchmarking process by comparing energy performance against industry standards, regulatory requirements, or historical data. Energy and sustainability managers can set targets for energy reduction, carbon emissions, or other sustainability metrics, track progress, and implement corrective actions as needed.
- Sustainability Performance Monitoring
    - In addition to energy management, intelligent buildings provide tools for monitoring and managing other sustainability aspects, such as water usage, waste management, indoor air quality, and renewable energy integration. Energy and sustainability managers can track and report on these metrics,

enabling them to implement strategies for improved sustainability performance and meet corporate social responsibility goals.

Laboratories/Life Sciences

- Enhanced Laboratory Safety and Compliance
    - Intelligent buildings can integrate safety systems, such as ventilation controls, fume hoods, and emergency response systems, to ensure a safe laboratory environment. Real-time monitoring and alerts help identify potential hazards, maintain compliance with regulatory requirements, and prevent incidents.
- Efficient Resource Management
    - Life sciences facilities consume significant resources, including energy, water, and gasses. Intelligent buildings enable precise monitoring and control of resource use, optimizing efficiency and reducing waste. This not only reduces operational costs but also aligns with sustainability goals.
- Reliable Infrastructure and Equipment Performance
    - Intelligent building's continuous monitoring and predictive maintenance capabilities ensure that critical infrastructure and laboratory equipment, such as incubators, freezers, and HVAC systems, are functioning optimally. This minimizes the risk of equipment failures, ensures data integrity, and supports uninterrupted research activities.
- Precise Environmental Control
    - Intelligent buildings provide advanced control systems for maintaining precise environmental conditions critical for life sciences research, such as temperature, humidity, and air quality. This control minimizes the impact of external fluctuations and provides stable conditions for experiments and sample storage.
- Data Integrity and Security
    - Intelligent buildings offer robust data management and security measures to safeguard critical research data. These include secure access controls, data backup systems, and cybersecurity protocols. Such measures protect intellectual property and sensitive information, ensuring data integrity and compliance with data protection regulations.
- Collaborative Research Environment
    - Intelligent buildings facilitate collaboration and communication among researchers, teams, and departments through integrated communication systems, shared data platforms, and collaboration spaces. This fosters innovation, knowledge sharing, and teamwork, enhancing research outcomes.
- Regulatory Compliance
    - Life sciences facilities must adhere to stringent regulations and quality standards. Intelligent buildings assist in meeting regulatory requirements by providing comprehensive data records, audit trails, and reporting capabilities, easing compliance processes and ensuring adherence to industry standards.

Multifamily and Hospitality

- Energy Efficiency
  - Intelligent buildings provide advanced energy management systems, allowing multifamily property owners to optimize energy consumption across multiple units. This leads to reduced energy waste, lower utility costs, and improved energy efficiency for the entire property.
- Enhanced Comfort and Convenience
  - Intelligent buildings allow for personalized climate control, lighting automation, and smart home features in individual units. This enhances the comfort and convenience of residents, contributing to tenant satisfaction, higher occupancy rates, and potential rent premiums.
- Remote Monitoring and Management
  - Intelligent buildings enable remote monitoring and management of systems and equipment. Property owners and managers can access real-time data, receive alerts, and adjust from anywhere, enhancing operational efficiency and enabling quick response to issues or emergencies.
- Enhanced Maintenance and Asset Management
  - Intelligent buildings facilitate predictive maintenance and asset management. Remote diagnostics, real-time monitoring, and automated alerts help property owners and managers proactively address maintenance needs, reduce equipment downtime, and extend the lifespan of building systems.
- Tenant Engagement and Satisfaction
  - Intelligent buildings enable interactive platforms and communication channels between residents and property management. This fosters tenant engagement, facilitates service requests, and allows for the dissemination of important information, enhancing overall tenant satisfaction and loyalty.

Retail

- Energy Cost Savings
  - Retail chains' portfolios of stores often have large energy footprints. Intelligent buildings optimize energy consumption through advanced energy management systems, real-time monitoring, and automated controls. This leads to significant energy cost savings by identifying inefficiencies, reducing energy waste, and implementing energy-saving measures.
- Enhanced Customer Experience
  - Intelligent buildings offer technologies to improve the customer experience in retail stores. This includes features like smart lighting, personalized climate control, indoor wayfinding, and location-based services. These enhancements create a comfortable and convenient shopping environment, leading to increased customer satisfaction and loyalty.
- Data-Driven Decision Support

    - Intelligent buildings generate vast amounts of data on energy use, customer behavior, and operational patterns. Retail chains can leverage this data for data-driven decision-making, such as optimizing store layouts, analyzing customer footfall, and tailoring marketing strategies. This helps drive revenue growth, improve operational performance, and enhance customer engagement.
- Remote Monitoring and Management
    - With intelligent buildings, retail chains can remotely monitor and manage multiple stores from a centralized location. This allows for efficient troubleshooting, maintenance planning, and proactive problem-solving. Remote access to building systems also reduces the need for onsite visits, saving time and resources.
- Security and Asset Protection
    - Intelligent buildings provide integrated security systems, including video surveillance, access control, and alarm systems, ensuring the safety and protection of assets within big box retail stores. Real-time monitoring and alerts enable quick response to security threats, reducing the risk of theft, vandalism, or unauthorized access.

Positive Building Stakeholder Outcomes

Building Owner

- Streamlined portfolio management
- Increased sale value of the building
- Attract buyers
- Scalability and flexibility
- Future-readiness
- Meet corporate Energy, Sustainability, Governance (ESG) goals
- Data-driven insights and decision support
- Decreased operating costs

Building Operator

- Remote monitoring and control
- Mobility
- Enhanced energy management
- Predictive maintenance
- Streamlined operations and automation
- Data analytics and insights
- Compliance and reporting
- Do more with less

Building Occupant

- Improved occupant satisfaction
- Enhanced comfort and personalization
- Safety and well-being
- Improved productivity
- Improved indoor air quality
- Smart amenities and services
- Occupant engagement and communication
- Flexibility and adaptability

Energy and Sustainability Manager

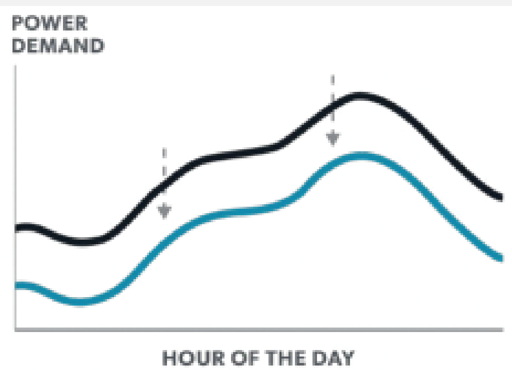
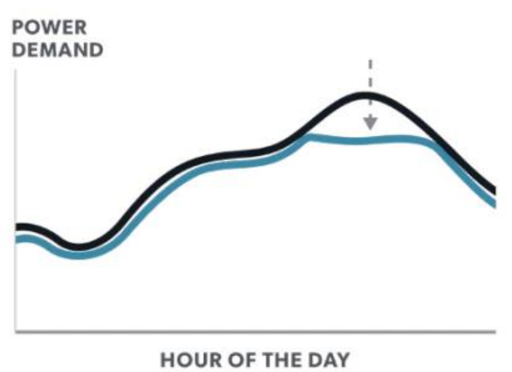
- Comprehensive energy monitoring and reporting
- Advanced energy analytics
- Automated benchmarking and target setting
- Sustainability performance monitoring
- Compliance and certification support
- Collaboration and stakeholder engagement
- Continuous improvement and optimization
- Demonstrate tangible results in terms of energy efficiency, cost savings, and environmental impact reduction

Appendix B: Grid-Interactive Efficient Buildings and Connected Communities

Grid-Interactive Efficient Buildings

The U.S. Department of Energy (DOE) defines GEBs as "energy-efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way."[85] Table 23 shows how GEBs can benefit the grid.

Table 23. Grid Benefits of GEBs.

Load Impact		Example Measure	Example Benefit
Efficiency		Building has an insulated, tight envelope and an efficiency HVAC system to reduce heating/cooling energy needs	Reduced costs of burning fuel to satisfy energy demand and reduced emissions associated with lower fuel use
Shed Load		Building dims lighting system by a preset amount in response to grid signals while maintaining occupant visual comfort levels	Reduced investment in generation and transmission capacity due to lower peak demand

[85] A. Satchwell, M.A. Piette, A. Khandekar, J. Granderson, N. Mims Frick, R. Hledik, A. Faruqui, L. Lam, S. Ross, J. Cohen, K. Wang, D. Urigwe,D. Delurey, M. Neukomm, and D. Nemtzow. 2021. A National Roadmap for Grid-Interactive Efficient Buildings. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Building Technologies Office. https://eta-publications.lbl.gov/sites/default/files/a_national_roadmap_for_gebs_-_final_20210517.pdf

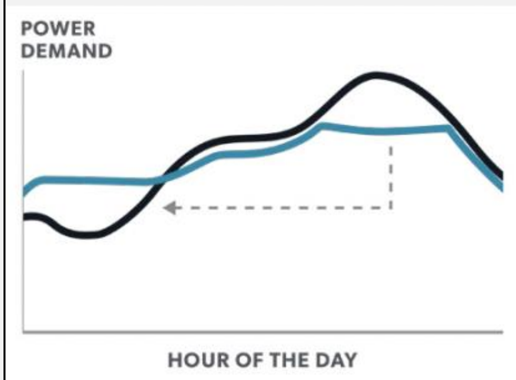
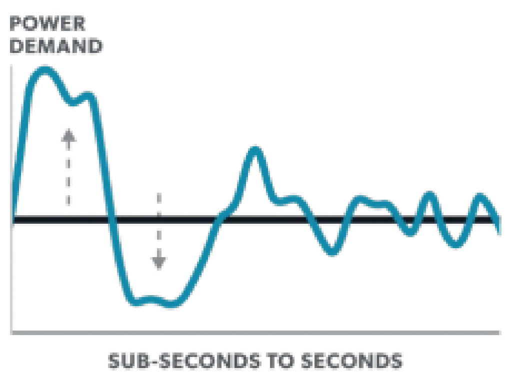
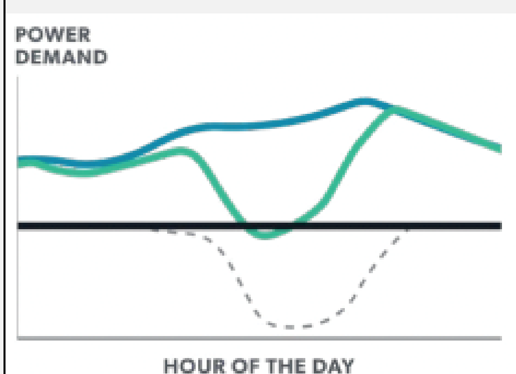
Shift Load		Connected water heaters pre-heat water during off-peak periods in response to grid signals.	Reduced energy costs due to shifting consumption to cheaper hours of the day; avoided curtailment of renewables during off-peak periods
Modulate		Batteries and inverters autonomously modulate power draw to help maintain grid frequency or control system voltage	Reduced ancillary services costs, improved integration of variable generation resources (e.g., wind, solar)
Generate		Rooftop solar PV exports electricity to the grid	Reduced T&D losses due to on-site consumption; avoided need for grid-scale generation

Table 24 describes the main features that will enable GEB technology integration.

Table 24. Key Features for Enabling GEB Technology Integration.

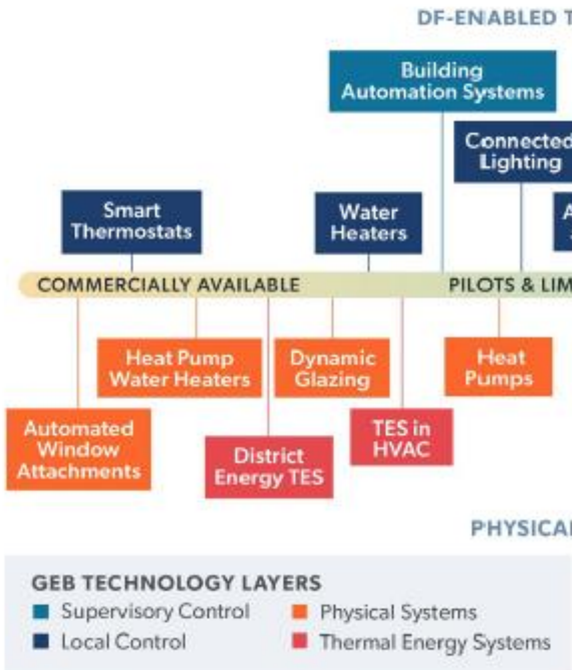
GEB Integration Layers	Large Commercial
Physical systems, hardware, and equipment	Insulated and tight envelope; Persistent and flexible loads; Dynamic façade, HVAC, lighting; Miscellaneous electric loads

Sensing (temperature, air flow, energy use, occupancy, light level)	Granular, distributed sensing for predictable and reliable building and grid service delivery; state of charge sensing for active or passive thermal storage
Local communication and control	End-user controls, such as thermostats or heat-pump water heaters (HPWH), capable of interacting with supervisory control and adjusting setpoints based on external input
Supervisory communication and control	BASs and energy management information systems are software and applications that provide predictive integrated control. Smart devices may be capable of providing their own predictive control capabilities.

DOE has defined the demand flexible (DF)-enabled technology pipeline for each of these GEB layers, as shown in Figure 20.[86] For commercial buildings, supervisory control technologies (shown in teal) are provided by the BAS (a commercially available tool according to the timeline in Figure 20**Error! Reference source not found.**) and multi-building control (which is shown t owards the in-development stage). Local control technologies (shown in the dark blue boxes) are commercially available for smart thermostats and water heaters with increased availability for connected lighting systems. Appliances and miscellaneous electric loads (MELs) currently have more limited availability and in many cases are still in development. Many physical systems (shown in orange) such as heat pump water heaters are commercially available. Thermal energy systems (denoted by the red boxes) tend more toward the limited availability/in development stages.

[86] Ibid.

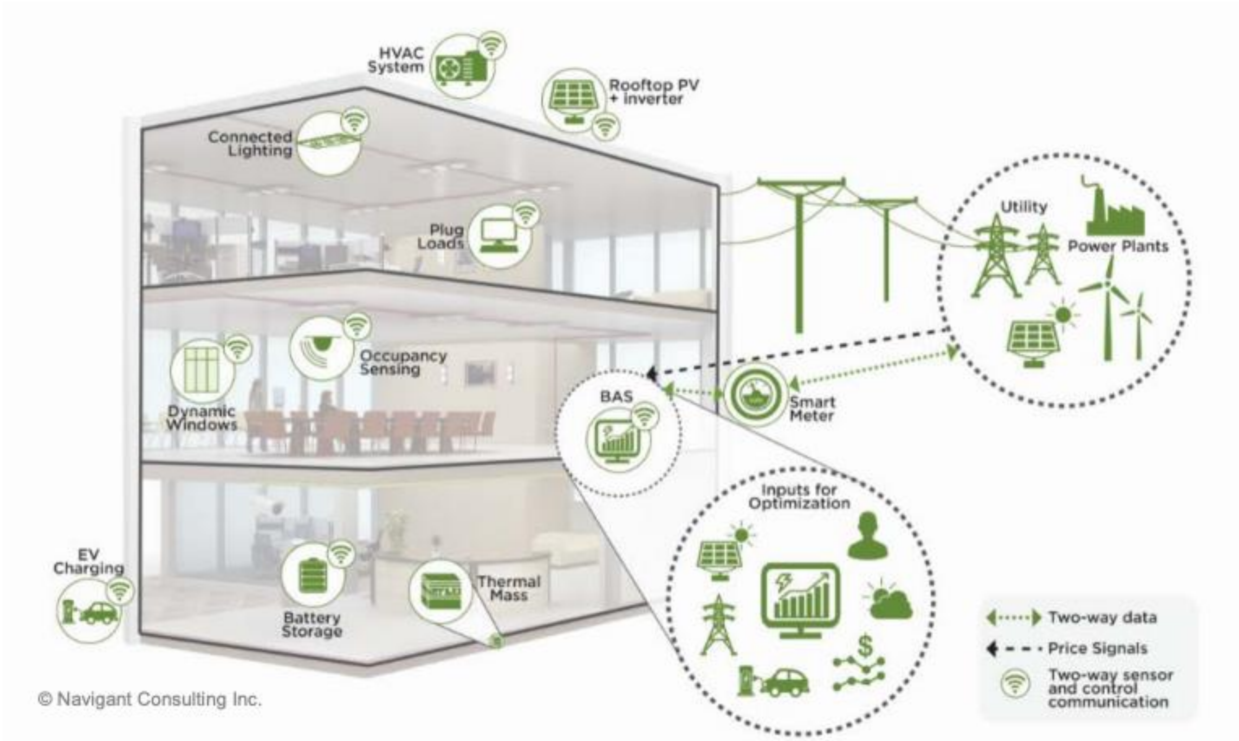
Figure 20. Technology Pipeline Examples for Each GEB Layer.



IBs feature the sensors, controls, and building system integration necessary for the building to achieve the demand flexibility required for grid interactivity. For example, two-way communication between the building and the grid will allow the grid to send signals to the supervisory systems to modify building operation in response to grid needs. By managing the power loads of buildings through efficiency, load shedding, shifting, modulating power, and even energy generation, IBs will be an essential clean and flexible energy resource. Figure 21 shows an example of how an IB can serve as a GEB.[87] Within the building, the IB elements would be the HVAC system, connected lighting, plug loads, dynamic glazing, occupancy sensing, and the BAS. The GEB elements (which would incorporate the intelligent building elements) include the rooftop PV + inverter, battery storage, EV charging, smart meter, additional inputs for optimization with the BAS, and the communications with the grid.

[87] C. Harris. 2019. Grid-interactive Efficient Buildings Technical Report Series. Windows and Opaque Envelope. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. https://www.nrel.gov/docs/fy20osti/75387.pdf

Figure 21. Example of a GEB.



Connected Communities

In a multi-building application of GEBs, DOE has been fostering the development of Connected Communities (CCs).[88] In 2021, DOE invested $61 million for ten CC projects to equip over 7,000 buildings with smart controls, sensors, and analytics to demonstrate how CCs can reduce energy cost use, costs, and GHG emissions.[89] CCs are defined as "a group of contiguous or non-contiguous buildings that incorporates central controls to manage multiple DERs at the multi-building scale, enabling communication to and from the grid for optimized and coordinated operations and dispatch."[90] Figure 22 shows how a collection of GEBs with DERs create synergies for greater resiliency, efficiency, and load flexibility.

[88] DOE Solar Energy Technologies Office Connected Communities Funding Program webpage. https://www.energy.gov/eere/solar/connected-communities-funding-program

[89] DOE Press Release, "DOE Invests $61 Million for Smart Buildings that Accelerate Renewable Energy Adoption and Grid Resilience," October 13, 2021. https://www.energy.gov/articles/doe-invests-61-million-smart-buildings-accelerate-renewable-energy-adoption-and-grid

[90] V. Olgyay, S. Coan, B. Webster,and W. Livingood. 2020. Connected Communities: A Multi-Building Energy Management Approach. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-75528. https://www.nrel.gov/docs/fy20osti/75528.pdf

Figure 22. The Value Added of Connected Communities.[91]

CCs can provide utilities with the grid flexibility needed to help reduce GHG emissions. DOE expects that CCs will help to attain a carbon-free electricity system by 2035 and zero-carbon energy sector by 2050.

[91] PLMA, *PLMA Load Management Dialogue – US Department of Energy's Future Connected Communities: Validating Buildings as a Grid Resource presentation*, April 2, 2020. https://www.peakload.org/assets/dr-dialogue/PLMA%20Dialogue%20April%202%20slides%20040220.pdf#page=6

Appendix C: Commercially Available and Experimental PCS Chairs

For commercial buildings, office chairs with heating and cooling capabilities are the most relevant, but interesting products in both the outdoors and entertainment segments can provide some inspiration for the future of smart commercial buildings. In general, heating functions are more commonly available than cooling functions in office chairs, with several models of office chairs available that offer heating or heating and massage features. Cooling functionality tends to be achieved by convection, and thus requires a breathable material (typically a textile mesh) as part of the seat or back, which is not always used in high-end office furniture.

Office Chairs

The X-Chair brand of office chairs offers an optional heating and cooling device called the “Elemax” that replaces the standard lumbar support panel.[92] A small control panel is integrated along the right side of the back of the device and allows the user to access heating, cooling, and massage functions. Power is provided by an integrated rechargeable battery. Cooling is provided by a pair of small fans that draw air over the user’s lower back. Heating up to a maximum temperature of 55°C is provided by conduction to the user’s lower back and automatically shuts off after 15 minutes. The battery can provide seven heating cycles between charges.

Outdoor Chairs

Magellan Outdoors offers a folding camp chair with heating and cooling functionality.[93] Power is provided by a rechargeable 5 V battery pack that is tucked into a pocket near the arm of the chair. Either a small fan in a mesh pocket in the backrest or a heating coil integrated into the seat, but not both simultaneously, can be plugged into the battery to provide cooling or heating respectively. This product takes advantage of the fact that breathable mesh materials are typical for camp chairs to integrate cooling function. It also capitalizes on the fact that camp chairs are typically used outside where the thermal environment is typically uncontrolled.

Gaming Chairs

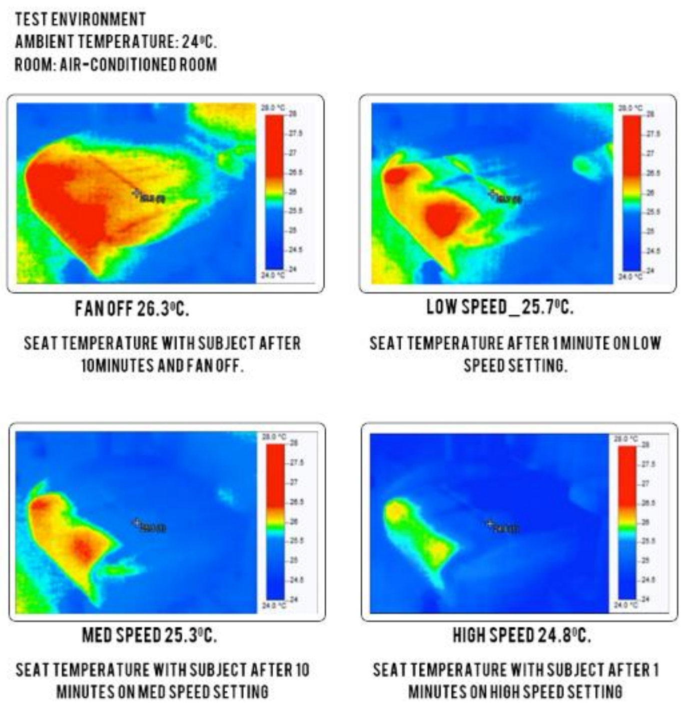
While office chairs seem to focus on heating functionality, chairs designed for competitive gaming seem to focus on cooling, presumably to keep gamers comfortable during intense and

[92] X-Chair “ELEMAX™ Cooling, Heat & Massage Unit” webpage. ://www.xchair.com/elemax-unit.html

[93] Academy Sports + Outdoors “Magellan Outdoors Cooling and Heating Folding Chair“ webpage. https://www.academy.com/p/magellan-outdoors-cooling-and-heating-folding-chair

highly engaging game play. The X Comfort Air chair from Thermaltake[94] uses an array of four small fans to draw air through the seat. While the seat itself is made from PVC faux-leather, ventilation holes and a mesh layer beneath the covering allow airflow to reach the occupant. The three-speed fans allow the user to match the cooling effect to their specific thermal needs. Thermal images demonstrate that the fans can reduce the seat surface temperature by up to 1.5°C in a 24°C ambient environment. Maximum airflow is claimed as 21.3 cfm. Controls are located beneath the seat. The DC power input for the fans is part of the control box. Figure 23 shows thermal images of the cooling effect obtained by the fans of the X Comfort Air Chair.

Figure 23. Thermal Images of Cooling Impact of X Comfort Air Chair.



Add-On Heating and Cooling Pads

In addition to chairs designed to be used with heating and cooling functions, heating and cooling seat cushions are marketed as products that can turn any seat into a PCS chair. Usually targeted toward automotive seats and office chairs, devices such as the SNAILAX heating pad and cooling cushion[95] provide cooling via convection with fans and heating via conduction with

[94] Thermaltake "X Comfort Air professional gaming chair" webpage. https://www.thermaltakeusa.com/x-comfort-air-black.html

[95] SNAILAX "Vibration Heated Car Seat Cushion" webpage. https://www.snailax.com/collections/vibration-heated-car-seat-cushion/products/3d-cooling-and-heating-seat-cushion-exclusive-at-snailax

resistive elements. Some models can operate on both 12 VDC and 110 VAC for use in the car or in a building.

Experimental Cooling Chairs

While all the commercially available chairs with cooling used air movement across the user's clothing or body to achieve the cooling effect, the Linus Tech Tips team designed and tested a prototype water-cooled gaming chair[96] that uses a 300 W Peltier chiller to cool water circulating through tubing in the back and seat. While this device was not intended to be commercialized, it is an interesting example of a cooling chair that can provide a heat sink at a temperature lower than the ambient room temperature.

[96] Linus Tech Tips "ULTIMATE Water Cooled Gaming Chair!!" YouTube video. https://www.youtube.com/watch?v=2pXrfHUjzmM

Appendix D: Building Intelligence Group

Through the efforts of local practitioners, the Twin Cities Intelligent Buildings Working Group was established on February 22, 2018 and soon expanded into the Building Intelligence Group of the Twin Cities (BIG-TC). BIG-TC members meet regularly for networking and education with the goal of advancing adoption of IBs. As members from outside the region began to take part in BIG-TC activities, other local chapters began to form and collaborative events took place. Soon this resulted in a tipping point that led to the formation of a network of local chapters of IB practitioners and enthusiasts under the umbrella association of the Building Intelligence Group (BIG).[97] These local chapters can serve as an important resource in the development and growth of IBs.

The Building Intelligence Group (BIG) incorporated as a 501(C)(3) non-profit and elected its first Board of Directors in January 2021. BIG is an entirely volunteer-led organization built on crowdsourcing and collaboration. Because of its emphasis on including cross-functional stakeholders from every industry, discipline, and trade, BIG brings people together at a local, grassroots level like no other organization. IBs are predicated on tearing down the silos between traditional building systems, and similarly BIG was created to tear down the silos between traditional associations, enabling a level of collaboration and community that was previously absent in the industry. By virtue of BIG's unique mix of practitioners, the Law of the Few personas of Connectors, Mavens, and Salespeople are well represented.

Connectors

The collaborative nature of BIG appeals to the Connectors whose networks extend beyond IBs into the many adjacent practices, products, and technologies that intersect with IBs. Connectors may also belong to other associations, often eager to facilitate connections and cross-disciplinary knowledge exchange to strengthen the BIG community and extend its potential thought leadership influence.

Mavens

BIG is rich with a wide assortment of subject matter experts in their given and varied fields of practice. As BIG members, these Mavens are excited to share their individual vision and specialized knowledge with each other in order to learn more about how their specialties intersect and to conceive of how new approaches can be created through unique and novel assemblage of constituent components-the goal being a sum that is greater than its parts.

Mavens seek to educate end-users and Buyers about the "art of possible" and give them the tools to make educated decisions. The free exchange of ideas among like-minded people with different backgrounds helps to highlight and ignite the innovations that today seem like science fiction but tomorrow will seem commonplace. Mavens help achieve BIG's goal of making the

[97] Building Intelligence Group homepage. https://www.buildingintelligencegroup.org/

adoption of IBs a mainstream requirement rather than the optional value add as it's often been perceived as.

Salespeople

In Gladwell's assessment, Salespeople are purveyors of ideas and are not limited to people with positions as salespeople. For the purpose of BIG, the association chose to be thoughtful of how to incorporate people with positions in sales. BIG was deliberate about determining at what capacity to include Salespeople in the organization, not wanting meetings to become overrun with corporate advertisements that would create an environment that is potentially hostile to attracting end-users and diluting educational opportunities. BIG chose to welcome Salespeople as all participants are welcomed, as individuals representing their own interests and ideas about intelligent buildings rather than as representatives for the companies for whom they work. This has produced an atmosphere conducive to true collaboration, even among individuals who work for competitor companies.

All are encouraged to work together in the best interest of the end-users. Recognizing that a rising tide lifts all ships, progress can be made through collaboration of non-traditional partners. Relationships created through the BIG community have tended to open doors to business opportunities that may have otherwise been undiscovered, which is a secondary benefit of BIG and necessary to the advancement of the industry, despite not being the primary goal of BIG.

Collaboration

The IB industry is not a single monolith, but rather an amalgamation of industries, products, and services that can be brought together, often in a bespoke manner, to produce a resulting outcome that can be described as an intelligent building. Despite the concept of smart and intelligent buildings existing for over four decades, the IB community has remained somewhat nascent until recently, lacking any centralized leadership or unified vision about what an intelligent building is, or even how it is defined.

Independent thought leaders like Ken Sinclair of AutomatedBuildings.com have been writing and publishing about the controls and intelligent buildings industries for over 30 years. Realcomm is celebrating the 25th year of its annual real estate and intelligent buildings conference that has successfully brought together practitioners, end-users, and salespeople with a similar education, networking, and industry promotion mission as BIG. Other examples include the Continental Automated Buildings Association (CABA) whose focus tends to be producing research and analysis of the industry. And, of course, many podcasts and blogs from independent as well as corporate voices have existed to serve niche communities within the IB industry.

However, it seems that in the past half-decade that there has been greater momentum around galvanizing IB communities around a central vision and core mission to drive awareness and adoption of IBs. James Dice is leading the online community called Nexus Labs that includes members from around the world. Nexus Labs' community-based approach and values of promoting energy efficient IBs that benefit the planet and the owner/operators aligns well with the mission of the Building Intelligence Group and both organizations have partnered to host collaborative programs. The Coalition 4 Smarter Buildings (C4SB) is focused on educating lobbyists on how policies for energy efficiency, carbon reduction, and ESG reporting could be enacted. C4SB is also creating tools for specifying intelligent buildings around a model that diverges from the traditionally common vertically integrated technology and services stack.

BIG has engaged in collaboration with industry associations and has found strong alignment, both formal and informal, with other leading voices in the IB community including the Coalition 4 Smarter Buildings (C4SB), Nexus Labs, CABA, RealComm, and others. These organizations' approaches to solving the common challenges of awareness and adoption are different but well aligned.

Many members of the BIG also belong to the USGBC, ASHRAE, and/or the association groups that represent their various industries. BIG does not compete with these groups and offers a complimentary experience. Because IBs are a broad topic encompassing many different subjects and offering a great variety of benefits and outcomes, the intersection of BIG and other industries is vast.

The Twin Cities chapter of BIG has explored the intersections with other industries and associations. For instance, in May 2020 BIG collaborated with the Association of Energy Engineers (AEE) for a joint event to present on Building Intelligence Around Energy as it relates to GEBS. BIG is open, both locally and nationally, to partnering with other organizations and has explored joint programs with USGBC and the Well Building Standard. The organization will continue to be mindful of related organizations where a partnership will be mutually beneficial.

Recruitment and Research

Affiliating with similar organizations is a great way to spread awareness of the Building Intelligence Group and its mission. Cross-promotion drives attendance and membership. However, much of BIG's growth can be attributed to word-of-mouth and the viral nature of networking especially in the era of social media. BIG chapter leaders across the country learn about BIG through other associations or through their social networks, and if there isn't already a chapter in their area BIG provides the support to launch a local chapter. These chapters soon grow to include the diversity of thought that is the hallmark of BIG. While an active recruitment drive has not yet occurred, plans are in the works to begin actively recruiting members as more chapters form to support local discussions.

BIG is not presently set up as an organization capable of speaking with a singular voice or conducting independent research. However, individual members of BIG may participate in research for which the BIG community may be engaged as potential contributors. BIG members may be polled for survey data and may participate as subjects in research being conducted by other BIG members or affiliates. Surveys can be administered to the national organization or targeted to individual chapters. BIG's collaborations could extend to research opportunities with other organizations.

BIG members and the companies they work for sometimes lead research. BIG intends to be a repository for the research and published data on IBs, and we can work collaboratively along with others in the industry to promote awareness of studies both published and in progress, along with the help of our collaborative organizations.

The BIG Tipping Point

What has made it possible for BIG to tip from being a monthly meet-up in the Twin Cities to becoming a national nonprofit with many local chapters? To begin with, BIG meets an otherwise unmet need to gather locally with cross-functional peers and industry leaders. This hunger is apparent as ever more leaders step up across the country to found local BIG chapters. Many new chapters were poised to launch in 2020, just as pandemic lockdowns made gathering for social events difficult or impossible. BIG shifted to hosting virtual events that were joined by folks across the country and internationally. This kept the momentum alive, and when lockdown restrictions were lifted even the historic pandemic wasn't enough to suppress the pent-up demand for local, in-person collaboration that propelled several chapters into being within a year of social restrictions being lifted.

Tipping points require a critical mass to gain the momentum to go from a spark to a fire. BIG has achieved critical mass by adding local chapters and attracting members through collaborations with other associations and thought leaders. Like kernels of popcorn, the rate of new chapter formation is following a logarithmic curve. And like a snowball rolling down hill, as BIG chapters increase and the membership becomes more massive, the surface area for attracting more attention and members grows as well.

Having a core structure with an elected board and by-laws helps keep the association on-target and on-message to ensure the culture and values remain even as BIG grows. The crowdsourced work accomplished in the early days of BIG, even before the association’s incorporation as a nonprofit, has helped the organization define and retain its identity and will be critical to ensure a consistent vision as the group scales. The tipping point starts with a vision, and relies on all of those involved to play their parts. Without the Connectors, Mavens, and Salespeople, BIG may never have become what it is today, and may not have developed the potential to be what it is to become.