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Grid-interactive Efficient Buildings Technical Report Series

Lighting and Electronics

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Disclaimer

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List of Acronyms and Abbreviations

AC	alternating current
AV	audio and video
BTO	Building Technologies Office
DC	direct current
DER	distributed energy resource
DOE	U.S. Department of Energy
EIA	Energy Information Administration
GEB	grid-interactive efficient building
HVAC	heating, ventilation, and air conditioning (also heating, *ventilating*, and air conditioning)
ISO	independent system operator
IT	information technology
LED	light-emitting diode
MEL	miscellaneous electric load
OLED	organic light-emitting diode
PV	photovoltaic
R&D	research and development
RTO	regional transmission organization
SSL	solid-state lighting
T&D	transmission and distribution
TWh	terawatt hour
UPS	uninterruptible power supply
W	watts

Glossary

These definitions are for the purposes of the *Grid-interactive Efficient Buildings Technical Report Series*. They may be defined differently or more generally in other contexts.

Grid services	Services that support the generation, transmission, and distribution of electricity and provide value through avoided electricity system costs (generation and/or delivery costs); this report focuses on grid services that can be provided by grid-interactive efficient buildings.
Distributed energy resource (DER)	A resource sited close to customers that can provide all or some of their immediate power needs and/or can be used by the utility system to either reduce demand or provide supply to satisfy the energy, capacity, or ancillary service needs of the grid.
Load profile	A building's load profile describes when—time of day or hour of the year—the building is consuming energy (typically used to refer to electricity consumption but can also describe on-site fuel use); load shape and load curve are often used interchangeably, but all refer to the timing of energy use.
Energy efficiency	Ongoing reduction in energy use to provide the same or improved level of function.
Demand flexibility	Capability of DERs to adjust a building's load profile across different timescales; energy flexibility and load flexibility are often used interchangeably with demand flexibility.
Demand response	Change in the rate of electricity consumption in response to price signals or specific requests of a grid operator.
Demand-side management	The modification of energy demand by customers through strategies, including energy efficiency, demand response, distributed generation, energy storage, electric vehicles, and/or time-of-use pricing structures.
Grid-interactive efficient building (GEB)	An energy-efficient building that uses smart technologies and on-site DERs to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences in a continuous and integrated way.
Smart technologies for energy management	Advanced controls, sensors, models, and analytics used to manage DERs. GEBs are characterized by their use of these technologies.

Executive Summary

Through its grid-interactive efficient building (GEB) research, the U.S. Department of Energy (DOE) Building Technologies Office (BTO) seeks to build on existing energy efficiency efforts and develop technological capabilities to optimize the interplay between building loads and the electric grid. This effort builds on energy efficiency research and development (R&D) to also consider impacts of distributed energy resources (DERs), including demand response and energy storage to increase the flexibility of demand-side management. BTO's mission is to support R&D of emerging efficient technologies, techniques, and tools for both existing and new residential and commercial buildings. To help inform BTO's R&D portfolio and the greater building research community, BTO is publishing a series of technical reports to explore the potential of specific building technologies and capabilities to provide grid benefits. This report is part of that series, focusing on lighting and electronics technologies only. The scope of this report and the *GEB Technical Report Series* is intentionally focused on technological capabilities and potential of residential/commercial buildings to enable and deliver grid services. Accordingly, the GEB report series will not address in-depth topics related to policies, business models, market constraints, measurement and verification, or implementation/scaling challenges.

Building technologies have significant untapped potential to provide cost-effective grid services through advanced demand-side management strategies. This potential is significant in part because buildings are the primary users of electricity: 75% percent of all U.S. electricity is consumed within buildings (U.S. Energy Information Administration [EIA] 2018). Figure ES-1 shows the breakdown by major end uses for both residential and commercial buildings. Lighting comprises approximately 10% and 16% of residential and commercial electricity use from major loads annually. Electronics loads, specifically consumer electronics and information technology (IT) equipment, are relatively much larger in the commercial sector than the residential sector; these loads comprise 10% and 23% of annual residential and commercial electricity major load use.

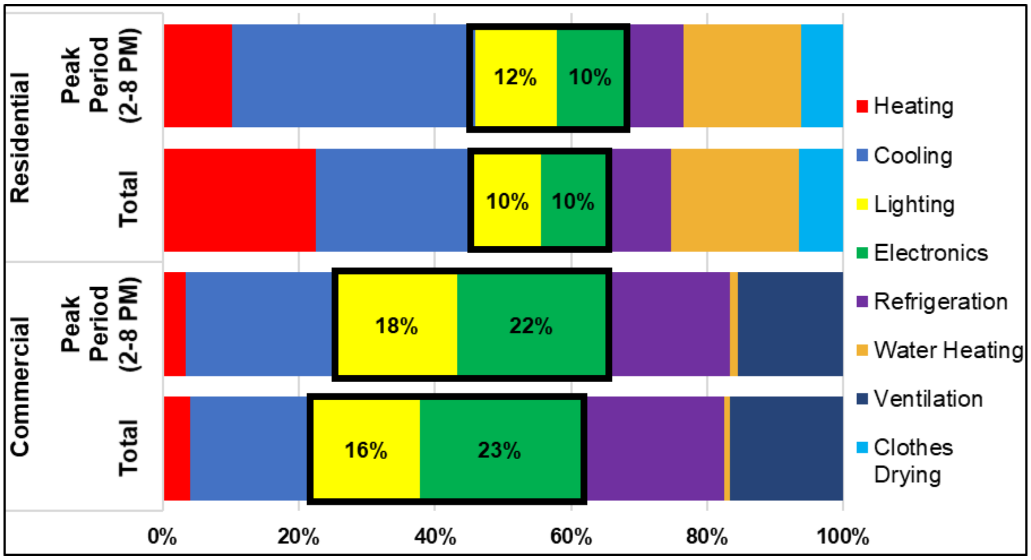

Figure ES-1. Total and peak period 2018 electricity consumption by major end use and building type[1]

Each colored bar represents a single end use. The end uses affected by technologies described in this technical report are outlined in black.

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[1] Data are generated using the Scout time-sensitive efficiency valuation framework (Satre-Meloy and Langevin 2019), which attributes annual baseline energy use estimates from the EIA's 2019 *Annual Energy Outlook* across all hours of the year using energy load shapes from ResStock (NREL) (https://www.nrel.gov/buildings/resstock.html) and the Commercial Prototype Building Models (https://www.energycodes.gov/development/commercial/prototype_models). Contributions of each end use to total peak period energy use were calculated with Scout using the energy savings from a measure representing 100% energy use reduction for the entire end use for one hour (e.g., 3–4 p.m.) during the peak period. The energy savings from each hour for a given end use were then summed across the peak period.

This report analyzes connected lighting systems and consumer electronics/IT equipment technologies, as outlined in Table ES-1. All lighting technologies are assumed to be lighting-emitting diode (LED) or organic LED (OLED) technologies. These technologies are analyzed in two separate sections and the evaluations are not meant to be comparable to each other or other building technologies.

Table ES-1. Connected Lighting and Consumer Electronics/IT Equipment Technologies

Technologies		Description
Connected Lighting	**Advanced Sensors and Controls**	Connected lighting systems utilizing advanced controls and algorithms to automatically modulate lighting levels or potentially other power-consuming lighting features (e.g., spectrum, reduced sensor or network communication interface power) in response to external grid/pricing signals.
	Hybrid Daylight Solid-State Lighting (SSL) Systems	Connected lighting systems that are enhanced by the integration of technologies to collect and redistribute daylight.
	SSL Displays	A system of connected lighting displays that eliminate the need for windows and skylights as sources of daylight.
Consumer Electronics/IT Equipment	**Continuous-Operation Electronics**	Stationary computing devices and electronic equipment used for computing, data storage, network supply, and related purposes that require constant power supply to operate. Examples: network equipment, set-top boxes, desktop personal computers, gaming consoles, servers, AV equipment.
	Battery-Powered Electronics	Computing devices and electronic equipment powered by an integrated rechargeable battery that require a charger connected to a power supply. Examples: laptops, smart phones, tablets, UPS battery backups.
	Electronic Displays	Electronic equipment with integrated lighting (OLEDs or LEDs) used for display purposes that require a constant power supply to operate. Examples: electronic billboards, video walls, computer monitors, TVs.

The analysis for this report began with characterization of key state-of-the-art technologies in lighting and consumer electronics/IT equipment, which were then evaluated based on their ability to provide grid services. The analysis considered the following demand-side management strategies:

- **Efficiency**: the ongoing reduction in energy use while providing the same or improved level of building function.[2]
- **Load Shed:** the ability to reduce electricity use for a short time period and typically on short notice. Shedding is typically dispatched during peak demand periods and during emergencies.
- **Load Shift:** the ability to change the timing of electricity use. In some situations, a shift may lead to changing the amount of electricity that is consumed. Load shift in the *GEB Technical Report Series* focuses on intentional, planned shifting for reasons such as minimizing demand during peak periods, taking advantage of the cheapest electricity prices, or reducing the need for renewable curtailment. For some technologies, there are times when a load shed can lead to some level of load shifting.

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[2] This would have the greatest impact for the grid during high-cost periods and also minimize utilization of costly generation resources.

- **Modulate:** the ability to balance power supply/demand or reactive power draw/supply autonomously (within seconds to subseconds) in response to a signal from the grid operator during the dispatch period.

The technologies were qualitatively ranked as having high, medium, or low potential to provide grid services based on a number of criteria; they are summarized in Table ES-2.

Table ES-2. Evaluated Grid Service Potential of Each Technology

Category	High Potential	Medium Potential	Low Potential
Connected Lighting Systems	• Advanced Sensors and Controls	• Hybrid Daylight SSL Systems	• SSL Displays
Consumer Electronics/IT Equipment	• Continuous-Operation Electronics	• Battery-Powered Electronics	• Electronic Displays

In Section 2, the grid-responsive connected lighting system technologies considered to have medium or high grid service potential (advanced lighting sensors and controls as well as hybrid daylight SSL systems) are evaluated according to their system attributes, including energy performance, resilience, usability, cost, and human health impacts. Each of these technologies is analyzed with respect to these system attributes, but not all attribute-technology combinations were found to have significant benefits or challenges. This exercise led to a list of relevant benefits and challenges that helped frame the R&D opportunities that enable lighting to provide grid services. Similar, in Section 3, challenges and R&D opportunities are discussed to enable consumer electronics/IT equipment to provide grid services and/or to address market barriers. The R&D opportunities were developed based on the benefits and challenges of each technology and input from researchers and laboratories. The R&D opportunities uncovered in this report are summarized in Table ES-3. Additional discussion of R&D opportunities related to controls and sensors is available in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.[3]

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[3] See Section 1 for a link to this report and to the other GEB reports.

Table ES-3. Summary of GEB Lighting and Electronics R&D Opportunities

Technology	Challenges	R&D Opportunities
All Connected Technologies	Interoperability	• Support the development and adoption of standardized semantic and syntactic specifications for connected devices and software systems
	Cybersecurity	• Support the adoption of secure system architectures and cybersecurity best practices
	Cost	• Develop manufacturing processes that have low capital costs or can use existing manufacturing equipment with minimal investment • Develop materials and technologies compatible with scalable manufacturing methods that enable increasing production volumes
Advanced Lighting Sensors and Controls	Demand Response Protocols and Control Algorithms	• Quantify the demand flexibility potential of lighting manipulations in various building types, designs, activities, and conditions • Determine the optimal communication protocols and control algorithms for maximizing grid services provided (shedding and modulating) and minimizing occupant impact • Develop novel control algorithms that leverage data and machine learning capabilities to customize strategies • Determine the impact to occupants from lighting systems providing grid services through demand flexibility (productivity, comfort, etc.)
	Sensors Integration	• Optimize techniques, design, and methods for embedding sensors directly in lamp/luminaires to enable multiple methods of control • Improve signal-processing techniques to reduce the error margin within the sensing range and increase the task-specific ability of the sensors
Hybrid Daylight SSL Systems	Efficiency of Light Guiding Materials	• Improve design of hybrid daylight SSL systems and materials to minimize daylight transmitting losses
	High Cost	• Develop higher-efficiency daylight-transmitting systems at lower costs to decrease technology payback periods
	Integration with SSL Systems	• Optimize the design of hybrid daylight SSL systems to ensure that lighting levels/spectrum are consistent and that transitions from daylight to electric light are seamless • Conduct field validation studies that inform design and foundational science • Develop models to improve insights into efficiency and other value propositions for established and emerging applications
	Load Modulation Benefit Quantification	• Develop hybrid daylight system prototypes that are designed to autonomously respond to grid signals within seconds • Identify the use cases and measure/verify the potential load modulation benefits
	Demand Response Protocols	• Develop demand response protocols and integrated controllers that enable the lighting system to switch between daylight and electrical lighting seamlessly in response to grid signals
Consumer Electronics/IT Equipment	Communication	• Develop control intelligence for electronics with the long-term vision of autonomous control
	Consumer Impact	• Integrating control logic into existing algorithms to enable users to set energy rate and efficacy preferences • Research on the relationship of consumer preferences to product functionality limitations

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1 Introduction

To help inform the building research community and advance the U.S. Department of Energy (DOE) Building Technologies Office's (BTO's)[4] research and development (R&D) portfolio, BTO has published a series of technical reports that evaluate the opportunities for grid-interactive efficient buildings (GEBs)[5]. This GEB report covers lighting and electronic technologies. In addition to this report, an overview report and three other GEB reports were published in 2019 as part of the *GEB Technical Report Series*, covering major relevant building technology areas with significant potential for energy flexibility:

- *Overview of Research Challenges and Gaps*[6]
- *Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration*[7]
- *Lighting and Electronics* (this report)
- *Windows and Opaque Envelope*[8]
- *Whole-Building Controls, Sensors, Modeling, and Analytics*[9]

The *Overview of Research Challenge and Gaps* report serves as an introduction to these technical reports and is intended to provide background on core concepts of GEBs. It addresses how flexible building loads can be integrated and controlled to benefit consumers, the electric grid, and society more broadly.

The GEB technical reports evaluate state-of-the-art and emerging building technologies that have the potential to provide grid services. These reports also identify major research challenges and gaps facing the technologies as well as opportunities for technology-specific R&D. The *GEB Technical Report Series* will help inform and guide BTO's R&D portfolio and serve as a foundational resource for the larger building research community. On-site behind-the-meter generation, batteries, and electric vehicles are also an important part of the distributed energy resource (DER) optimization strategy for buildings. In general, the component technology reports do not focus on distributed generation or batteries, but the *Whole-Building Controls, Sensors, Modeling, and Analytics* report discusses how a building can optimize across all DERs.

1.1 Strategy and Vision

BTO's mission supports the R&D, validation, and integration of affordable, energy-saving technologies, techniques, tools, and services for U.S. buildings (existing and new, residential and commercial). In support of this mission, BTO is developing a GEB strategy that aims to optimize energy use across DERs to advance the role buildings can play in energy system operations and planning. The GEB strategy supports broader goals, including greater affordability, resilience, sustainability, and reliability, recognizing that:

- Building end uses can be dynamically managed to help meet grid needs and minimize electricity system costs, while meeting occupants' comfort and productivity requirements;
- Technologies such as rooftop photovoltaics (PV), battery and thermal energy storage, combined heat and power, and other DERs can be co-optimized with buildings to provide greater value, reliability, and resiliency to both utility customers and the overall electricity system; and

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[4] For more information, see: https://www.energy.gov/eere/buildings/building-technologies-office.

[5] For more information, see: https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings.

[6] Available online here: https://www.nrel.gov/docs/fy20osti/75470.pdf.

[7] Available online here: https://www.nrel.gov/docs/fy20osti/75473.pdf.

[8] Available online here: https://www.nrel.gov/docs/fy20osti/75387.pdf.

[9] Available online here: https://www.nrel.gov/docs/fy20osti/75478.pdf.

- The value of energy efficiency, demand response, and other services provided by behind-the-meter DERs can vary by location, hour, season, and year.

A key part of this strategy will include utilizing smart technologies (sensors, actuators, controllers, etc.) for building energy management. This is a core area of technological investment for BTO. Integrating state-of-the-art sensors and controls throughout the commercial building stock has the potential to save as much as an estimated 29% of site energy consumption through high-performance sequencing of operations, optimizing settings based on occupancy patterns, and detecting and diagnosing inadequate equipment operation or installation problems (Fernandez et al. 2017). In addition, state-of-the-art sensors and controls can curtail or temporarily manage 10%–20% of commercial building peak load (Kiliccote et al. 2016; Piette et al. 2007). Accordingly, these strategies are available and necessary for implementing flexible, grid-interactive strategies to optimize building loads within productivity or comfort requirements.

BTO's GEB vision involves the integration and continuous optimization of DERs for the benefit of the buildings' owners, occupants, and the electric grid. As shown in Figure 1, the example GEB utilizes analytics supported by sensors and controls to optimize energy use for occupant patterns and preferences, utility price signals, weather forecasts, and available on-site generation and storage. In the building depicted in Figure 1, a suite of advanced building technologies—including the HVAC system, connected lighting, dynamic windows, occupancy sensing, thermal mass, and distributed generation and battery storage—are optimized to meet occupant and grid needs. In many buildings, smaller sets of existing technologies could be integrated and controlled.

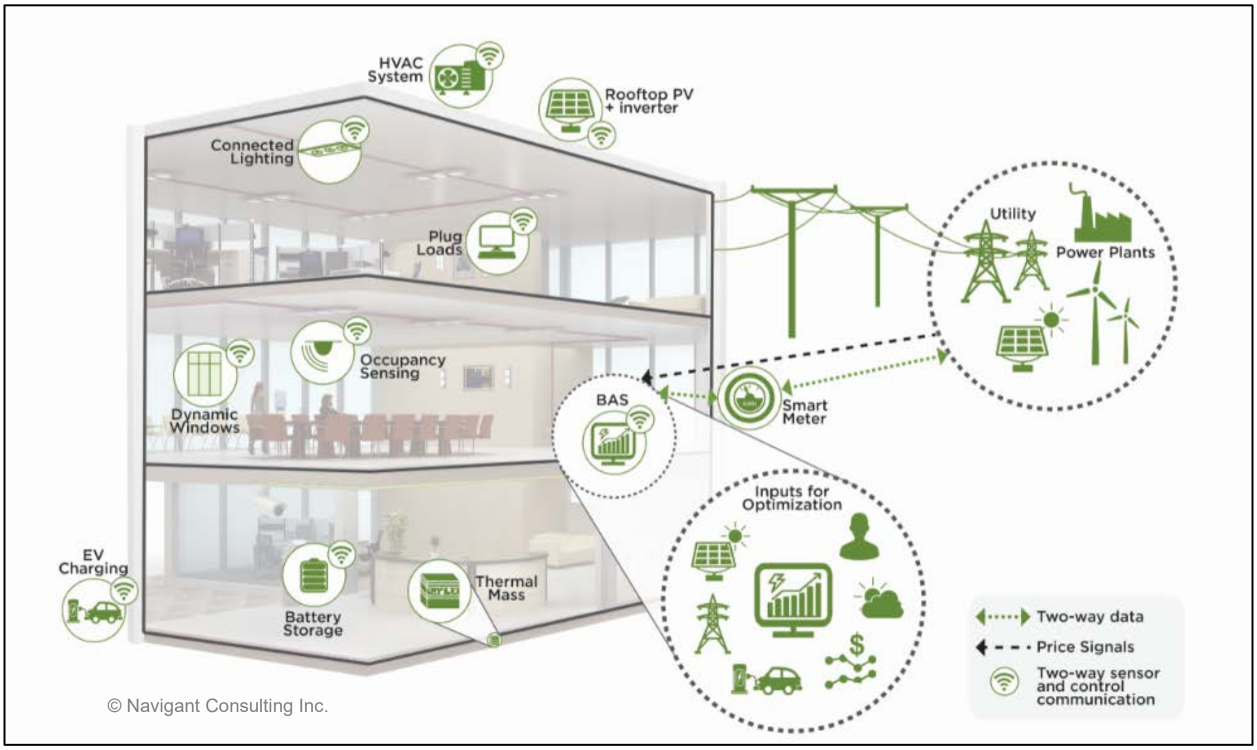
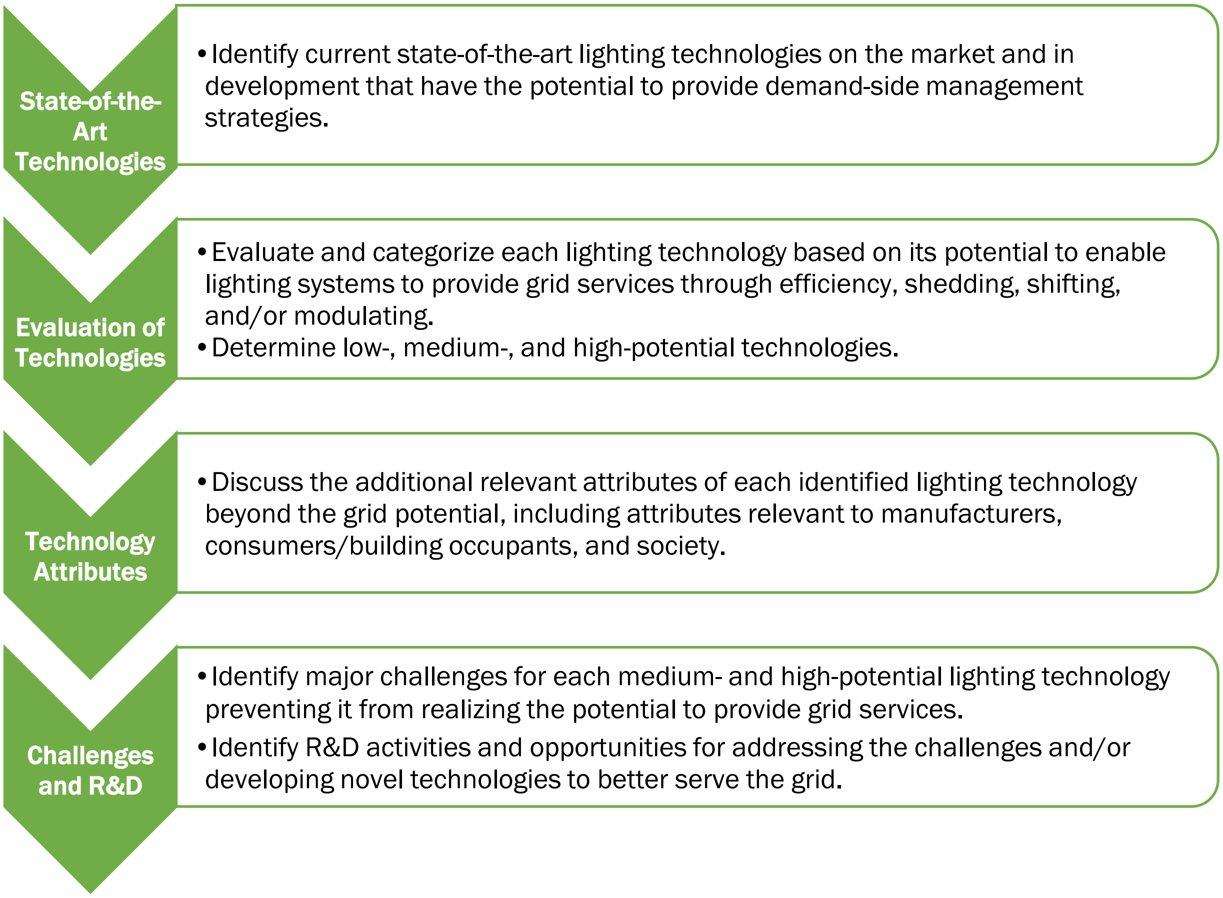


Figure 1. Example grid-interactive efficient commercial building

The building automation system utilizes analytics supported by sensors and controls to optimize energy use for occupant patterns and preferences, utility price signals, weather forecasts, and available on-site generation and storage.

1.2 Report Approach and Scope

This report focuses on lighting technologies and electronics that have the potential to provide grid services. These technologies are analyzed in two separate sections, and the evaluations are not meant to be comparable to each other or other building technologies. Section 2 covers lighting technologies only; the report approach for the lighting section is summarized in Figure 2. First, relevant state-of-the-art lighting technologies are identified. Then, these lighting technologies are evaluated according to their potential ability to provide grid services (see Section 1.3) through four demand-side management strategies: energy efficiency, load shed, load shift, and modulating load. Based on the potential to provide these grid services, each technology will be classified as low, medium, or high potential. Then, technology attributes are discussed for each identified GEB lighting technology, including energy performance, resilience, usability, cost, and human health impacts. Finally, R&D activities and opportunities are identified based on current technological challenges facing the identified high- and medium-potential GEB technologies.



State-of-the-Art Technologies

- Identify current state-of-the-art lighting technologies on the market and in development that have the potential to provide demand-side management strategies.

Evaluation of Technologies

- Evaluate and categorize each lighting technology based on its potential to enable lighting systems to provide grid services through efficiency, shedding, shifting, and/or modulating.
- Determine low-, medium-, and high-potential technologies.

Technology Attributes

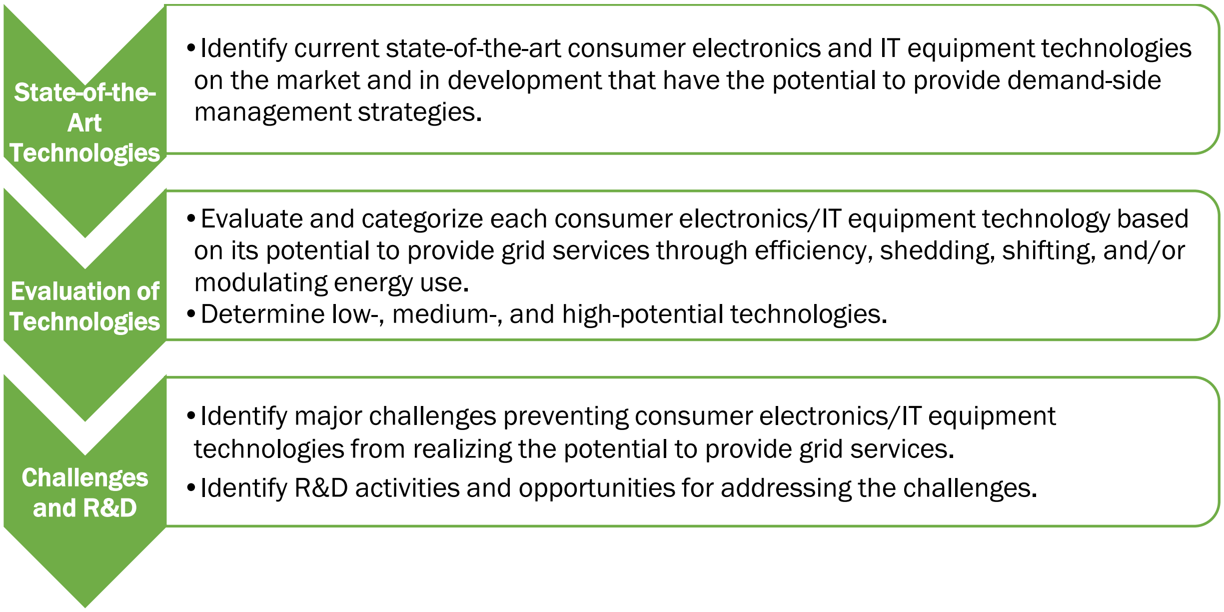
- Discuss the additional relevant attributes of each identified lighting technology beyond the grid potential, including attributes relevant to manufacturers, consumers/building occupants, and society.

Challenges and R&D

- Identify major challenges for each medium- and high-potential lighting technology preventing it from realizing the potential to provide grid services.
- Identify R&D activities and opportunities for addressing the challenges and/or developing novel technologies to better serve the grid.

Figure 2. Lighting section approach

Section 3 covers consumer electronics and information technology (IT) equipment technologies only. This section approach, similar to the lighting section, is summarized in Figure 3. First, relevant state-of-the-art consumer electronics and IT equipment technologies are identified. Then, these technologies are evaluated according to their potential ability to provide grid services (see Section 1.3) through four demand-side management strategies: energy efficiency, load shed, load shift, and modulating loads. Each technology is then classified as having low, medium, or high potential to provide these grid services. Finally, challenges and R&D opportunities are identified for all grid-responsive electronics technologies.



- Identify current state-of-the-art consumer electronics and IT equipment technologies on the market and in development that have the potential to provide demand-side management strategies.
- Evaluate and categorize each consumer electronics/IT equipment technology based on its potential to provide grid services through efficiency, shedding, shifting, and/or modulating energy use.
- Determine low-, medium-, and high-potential technologies.
- Identify major challenges preventing consumer electronics/IT equipment technologies from realizing the potential to provide grid services.
- Identify R&D activities and opportunities for addressing the challenges.

Figure 3. Electronics section approach

The scope of the *GEB Technical Report Series* is intentionally focused on technological capabilities and the potential of residential/commercial buildings to enable and deliver grid services. The GEB report series will not address in depth the following topics that, while important in practice, are considered out of scope: utility programs and policies, business models and value streams, potential future grid services/resource mixes, technology adoption and market constraints, product measurement and verification, commissioning, and implementation and scaling challenges. However, BTO recognizes that many of these topics represent significant barriers that must be addressed in future work and research to realize its vision of GEBs. Further, the technology scope is limited to lighting, consumer electronics/IT equipment, and embedded sensors and controls, as shown in Figure 4. Some of the external controls and sensors will be covered in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

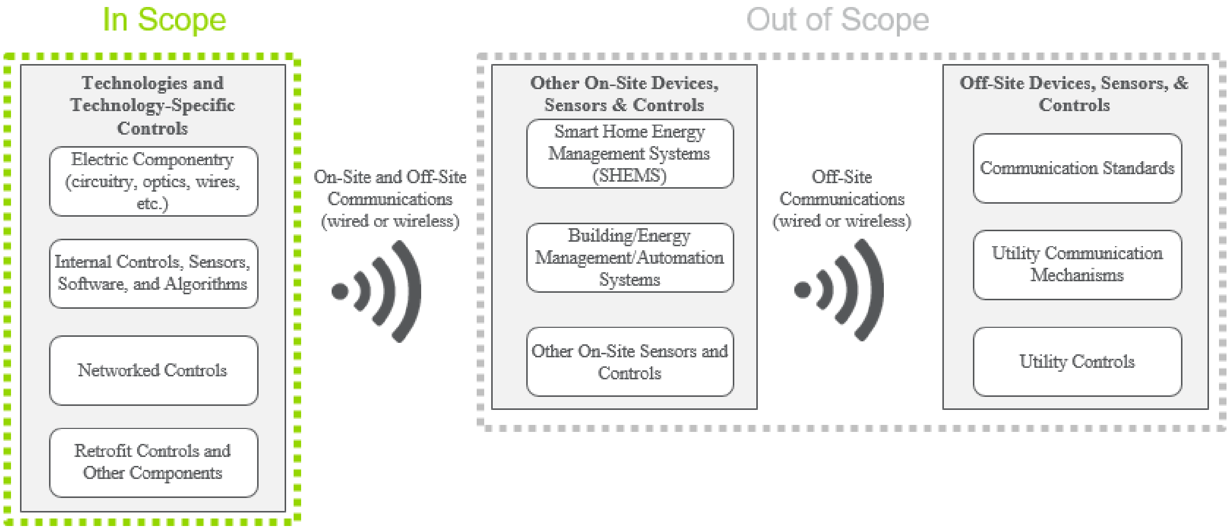


Figure 4. Report technology scope definition

1.3 Grid Services Provided by Buildings

This report characterizes connected solid-state lighting (SSL) and consumer electronics/IT equipment technologies to help identify R&D opportunities to improve the demand flexibility for these technologies and the associated ability to provide grid services. Depending on the market and the grid need, that could be for only a few days per year (e.g., reliability-based demand response), or it could be on a daily, hourly, or even continuous basis. Table 1 summarizes seven different grid services that may be provided by building technologies.

Table 1. Grid Services Definitions

For more information on these grid services, see the *Overview of Research Challenges and Gaps* report.

Grid Services		Potential Avoided Costs
Generation Services	Energy	Power plant fuel, operation, maintenance, and startup and shutdown costs
	Capacity	Capital costs for new generating facilities and associated fixed operation and maintenance costs
Ancillary Services	Contingency Reserves[10]	Power plant fuel, operation, maintenance, and opportunity costs associated with providing contingency reserves
	Frequency Regulation	Power plant fuel, operation, maintenance, and opportunity costs[11] associated with providing frequency regulation
	Ramping	Power plant fuel, operation, maintenance, and startup and shutdown costs
Delivery Services	Non-Wires Alternatives[12]	Capital costs for transmission and distribution equipment upgrades
	Voltage Support	Capital costs for voltage control equipment (e.g., capacitor banks, transformers, and smart inverters)

The grid services listed in Table 1 can be delivered via four different mechanisms: efficiency, load shedding, load shifting, and load modulation (i.e., frequency regulation or voltage support). These strategies are discussed in more depth in Section 2.3.1 and in the *Overview of Research Challenges and Gaps* report. The ability of lighting and consumer electronics/IT equipment technologies to deliver value hinges on the existence of the necessary communications infrastructure to connect utilities directly to the end-use loads or to the technologies/building energy control systems. Because efficiency is already a well-known and well-researched area for lighting and consumer electronics/IT equipment, this report will primarily focus on the ability of these technologies to provide grid services beyond efficiency alone (shedding, shifting, and modulating). However, in most circumstances today, the greatest grid benefit that lighting and consumer electronics/IT equipment can provide is energy efficiency.

1.4 Lighting and Electronics Grid Services Potential

The technologies covered in this report affect lighting and electronics loads in residential and commercial buildings. The total energy use and daily peak energy use of these technologies can be used to approximate the relative potential of these technologies to impact the grid through manipulations in their demand (i.e., the grid service potential). In 2018, lighting loads used approximately 91 terawatt-hours (TWh) and 140 TWh site electricity annually in residential and commercial buildings (Figure 5), respectively, comprising 10% and 16% of residential and commercial electricity use from major loads during this period (Figure 6). During the peak

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[10] This includes reserves products with various timescales, including spinning reserves, nonspinning reserves, and other particular reserves products that exist in some regions.

[11] For example, not selling power in order to be ready for up-regulation.

[12] Also referred to as deferred transmission and distribution upgrades.

period, assumed to be 2–8 p.m., the lighting loads use 33 TWh and 47 TWh of site electricity annually in residential and commercial buildings, respectively, comprising about 12% and 18% of residential and commercial electricity use from major loads during this period.

Electronics loads, specifically consumer electronics and IT equipment, are relatively much larger in the commercial sector than the residential sector. Electronics use approximately 88 TWh and 210 TWh site electricity use in residential and commercial buildings (Figure 5), respectively, comprising 10% and 23% of residential and commercial electricity use from major loads during this period (Figure 6). During the peak period (2–8 p.m.), the electronics loads use 27 TWh and 58 TWh of site electricity annually in residential and commercial buildings, comprising about 10% and 22% of residential and commercial electricity use from major loads.

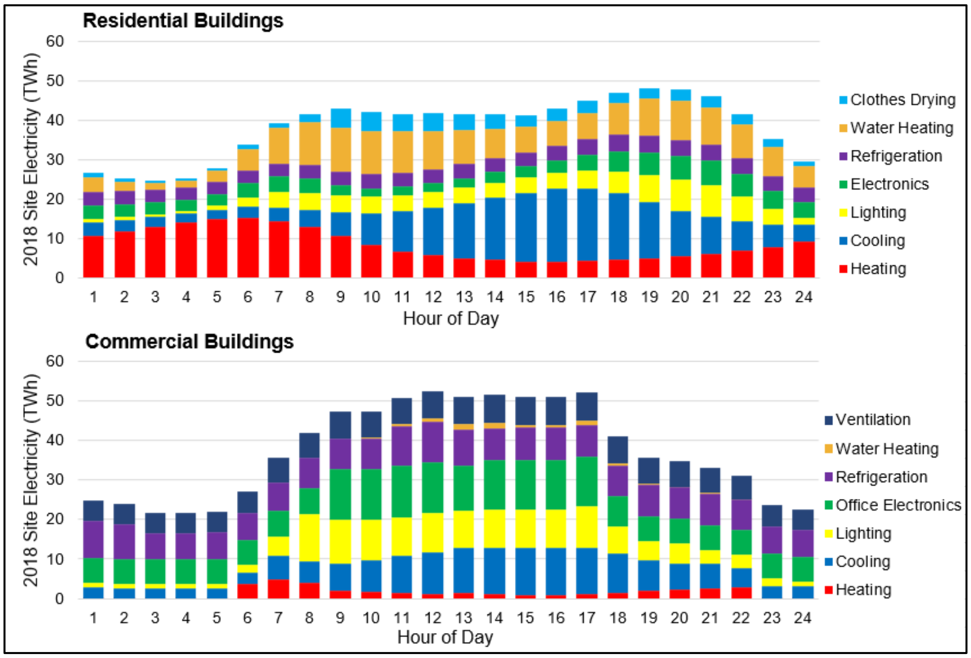

Figure 5. Hourly electricity use in residential and commercial buildings[13]

Total hourly electricity use in TWh in U.S. residential buildings (top) and commercial buildings (bottom), broken out by major electric end use for 2018. Each colored bar represents a single end use, and bar labels indicate the total site electricity use that occurs during each hour across the course of the year.

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[13] Data are generated using the Scout time-sensitive efficiency valuation framework (Satre-Meloy and Langevin 2019), which attributes annual baseline energy use estimates from the EIA's 2019 *Annual Energy Outlook* across all hours of the year using energy load shapes from ResStock (NREL) (https://www.nrel.gov/buildings/resstock.html) and the Commercial Prototype Building Models (https://www.energycodes.gov/development/commercial/prototype_models). Energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes. Contributions of each end use to total peak period energy use were calculated with Scout using the energy savings from a measure representing 100% energy use reduction for the entire end use for one hour (e.g., 3–4 p.m.) during the peak period. The energy savings from each hour for a given end use were then summed across the peak period.

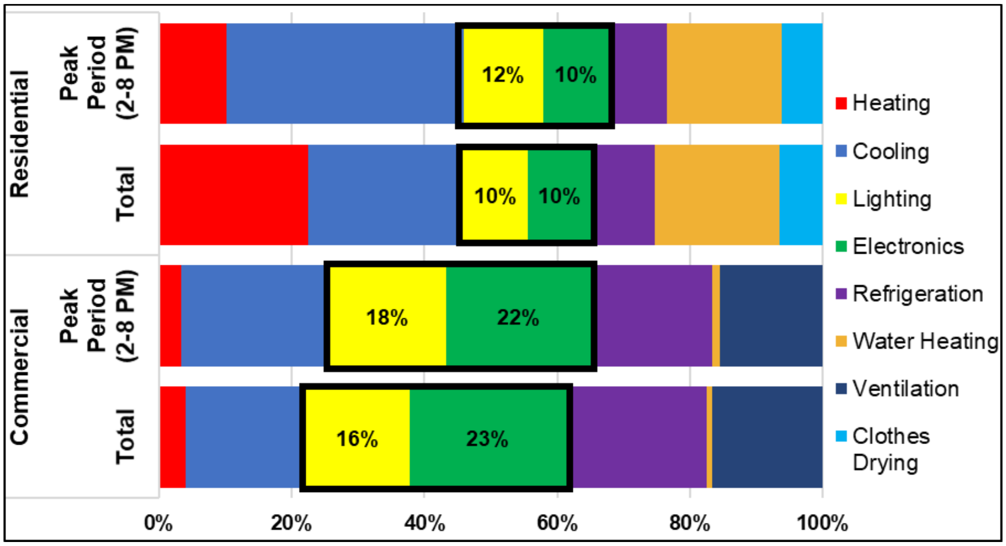

Figure 6. Total and peak electricity use by major end use and building type[14]

Total and peak period (2–8 p.m.) electricity use broken out by major electric end use in commercial buildings (top image) and residential buildings (bottom image) for 2018. Each colored bar represents a single end use and the end uses affected by technologies described in this technical report are outlined in black; the percentage contributions of the affected end uses to total and peak period electricity use are also shown.

Figure 7 shows the lighting and electronics load profiles in buildings (the national aggregate annual hourly energy use). In general, lighting and electronics loads have similar daily use patterns. In the commercial sector, lighting and electronics loads peak between 8 a.m. and 5 p.m., corresponding with typical office hours. In the residential sector, lighting and electronics loads generally peak later in the day between 6 p.m. and 10 p.m. In addition, lighting and electronics building loads are both completely electric loads with similar grid service capabilities. The greatest opportunity for demand-side management in lighting and electronics is through energy efficiency improvements; load shedding and fast load modulation are additional emerging opportunities for demand response and/or building peak demand-side management. However, load shifting for lighting and electronics is generally not possible without the addition of electricity storage technologies.

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[14] Data are generated using the Scout time-sensitive efficiency valuation framework (Satre-Meloy and Langevin 2019), which attributes annual baseline energy use estimates from the EIA's 2019 *Annual Energy Outlook* across all hours of the year using energy load shapes from ResStock (NREL) (https://www.nrel.gov/buildings/resstock.html) and the Commercial Prototype Building Models (https://www.energycodes.gov/development/commercial/prototype_models). Contributions of each end use to total peak period energy use were calculated with Scout using the energy savings from a measure representing 100% energy use reduction for the entire end use for one hour (e.g., 3–4 p.m.) during the peak period. The energy savings from each hour for a given end use were then summed across the peak period.

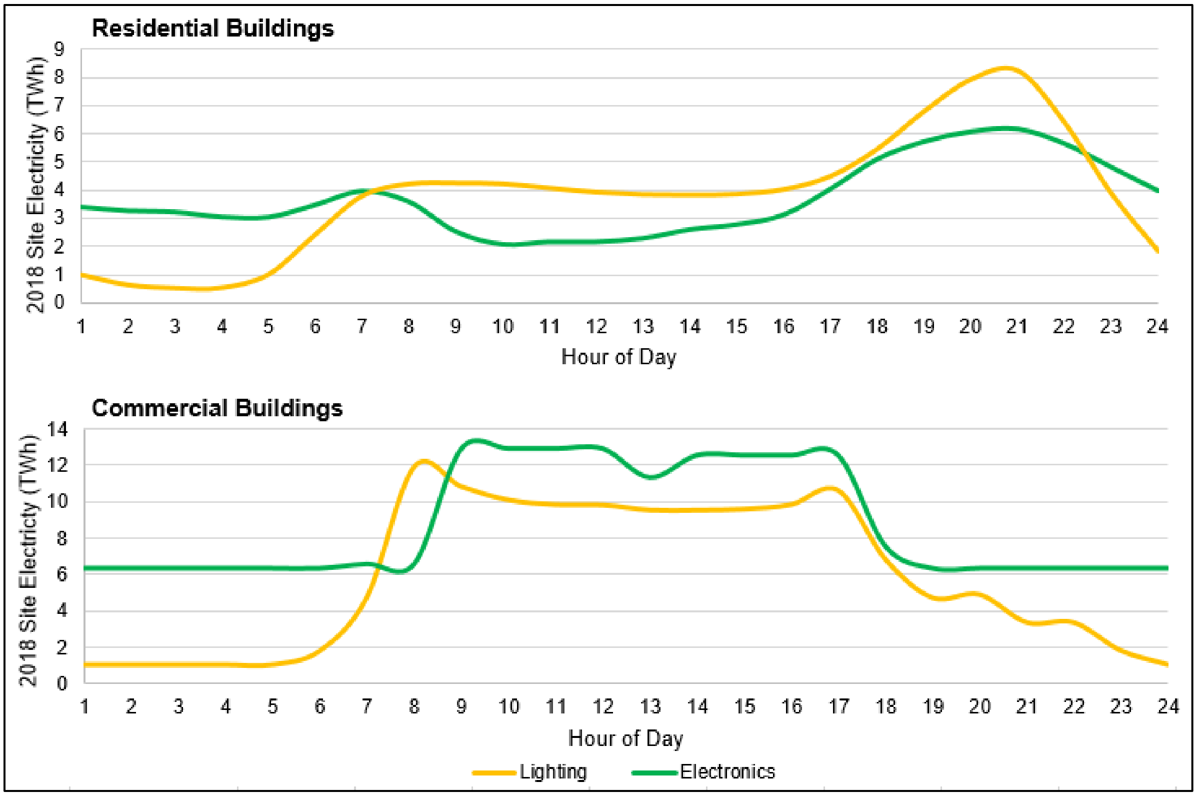

Figure 7. Lighting and electric load profiles in residential and commercial buildings[15]

Total hourly electricity use in TWh in U.S. residential buildings and commercial buildings combined, broken out by lighting and electronics electric end use for 2018.

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[15] Data are generated using the Scout time-sensitive efficiency valuation framework (Satre-Meloy and Langevin 2019), which attributes annual baseline energy use estimates from the EIA's 2019 *Annual Energy Outlook* across all hours of the year using energy load shapes from ResStock (NREL) (https://www.nrel.gov/buildings/resstock.html) and the Commercial Prototype Building Models (https://www.energycodes.gov/development/commercial/prototype_models). Energy load shapes for the commercial sector do not currently account for scheduling diversity across the stock of a given commercial building type in a given region, which would yield smoother utility-scale load shapes than those shown in this report. Ongoing efforts to collect residential and commercial end-use load shape data that better represent this scheduling diversity (https://www.nrel.gov/buildings/end-use-load-profiles.html) will be incorporated in future iterations of the residential and commercial load shapes. Contributions of each end use to total peak period energy use were calculated with Scout using the energy savings from a measure representing 100% energy use reduction for the entire end use for one hour (e.g., 3–4 p.m.) during the peak period. The energy savings from each hour for a given end use were then summed across the peak period.

2 Lighting

2.1 Current Grid-Responsive Lighting

Currently, penetration of grid-responsive lighting is low—it was estimated to be used in only 4% of commercial buildings according to the 2012 Commercial Buildings Energy Consumption Survey (EIA 2012), and it is essentially nonexistent in the residential sector. A 2018 survey of 155 U.S. utilities found that only 8 utilities reported that commercial and industrial customers enrolled in automated demand response utilized lighting, compared to 23 utilities that utilized HVAC (Chew et al. 2018).[16] Automated demand response for lighting is done today primarily by configuring connected lighting systems to dim light levels in commercial and industrial buildings. A large portion of the grid-responsive lighting today can be attributed to the 2016 building code in California's Title 24, which requires that all buildings larger than 10,000 ft^2 (new construction and building alterations) must be capable of automated wattage reduction of 15% in response to demand response signals (Pacific Gas and Electric Company 2016). In general, lighting is underutilized in automated demand response programs in the United States (Jackson 2017). Generally, automated demand response vendors and contractors are focused on large commercial and industrial loads. As such, there are few lighting system products equipped with automated demand response features. In 2017, only 6 products out of 128 total OpenADR-compliant[17] products were offered for lighting control systems (Jackson 2017).

Lighting has historically not been targeted for demand response for several key reasons. In contrast to other building technologies, such as HVAC systems or appliances, lighting systems cannot be natively shifted and are generally considered critical loads in occupied spaces—they must remain on at all times for occupant safety, productivity, and comfort (or be provided through significant daylighting). When buildings are occupied, lighting systems cannot be completely turned off during a demand response event. Further, without additional technologies such as batteries or significant daylighting, the magnitude of lighting output manipulation is greatly restricted. Although dimming will reduce the lighting load, the dimmable amount is also limited to levels that will not compromise occupant productivity, comfort, or safety. Though some research has been done on this topic (see discussion in Section 2.4.1.3), generally, more research is needed to better determine appropriate dimming levels in different contexts (building type and design, occupational use and patterns, geographic location and season, etc.) so that occupant comfort, productivity, and well-being are not affected. In addition, lighting is only valuable as a demand response resource when aggregated across the whole building, as the average light-emitting diode (LED) wattage in buildings is very small—only 19 watts (W) per lamp for commercial buildings in 2015 (Buccitelli et al. 2017). Hence, large commercial buildings are generally the most viable market for grid-responsive lighting. However, smaller commercial or residential buildings can work with demand aggregators to participate in grid service markets.

In addition to demand response, connected lighting systems with grid-responsive capability may also be utilized for building peak demand-side management. In large commercial and industrial facilities utilizing time-of-use rates, demand charges are applied to utility bills based on the highest 15 minutes of electricity demand each month. These demand charges often comprise significant portions of utility customer bills. Reducing the peak energy use of a building or shifting energy use to off-peak hours reduces customer bills and often helps reduce the larger grid peak periods as well. Connected lighting technologies can provide building peak demand-side management through load shedding (traditionally, dimming) during peak hours.

2.2 Current Lighting State-of-the-Art

Technological advances are increasing the capability and potential for lighting to provide automated demand response and building peak demand-side management (i.e., billing demand charges in large commercial buildings). Lighting (as well as HVAC and other building systems) is rapidly evolving to become more

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[16] Not all utilities that have automated demand response programs responded to this survey question.

[17] OpenADR is a nonproprietary, open standardized demand response interface that allows electricity providers to communicate directly to customers. For more information, see: https://www.energy.gov/sites/prod/files/2014/05/f16/OpenADR%20DOE.pdf.

intelligent and connected. Further, although lighting controls were originally designed to be bolted onto static (nonconnected) lighting devices to enable changes to their light output based on schedules, occupancy, or daylighting sensing, today's connected lighting systems can now provide additional capabilities. The incorporation of more modern network interfaces, intelligence, and sensor advancements has paved the way for increased data collection and analytics enabling connected lighting systems to potentially provide increased productivity, occupant health and well-being, energy savings, security, enhanced control, demand response, building peak demand-side management, and/or sharing data with HVAC or the building automation system. Artificial intelligence and machine learning in connected lighting systems can also be used to both optimize the lighting needs based on occupancy patterns and predict maintenance needs (Maxwell et al. 2017).

The development and integration of new technologies may enable new ways for connected lighting systems to reduce, shed, and modulate lighting loads. This section provides an overview of state-of-the-art connected lighting system technologies. As discussed in the following section (Section 2.2.1), connected lighting systems are the foundational technology that will enable grid services beyond traditional energy efficiency, therefore all technologies explored and discussed in this report are framed in the context of this capability. However, it should be noted that in most cases, the greatest grid benefit that lighting can provide is through deploying traditional energy efficiency measures first, including, but not limited to, upgrading to the most efficient LEDs/OLEDs available and utilizing well-known adaptive lighting strategies (e.g., occupancy or vacancy control, daylight optimization, and task tuning).

2.2.1 Connected Lighting Systems

All technologies explored and discussed in Section 2 of this report are framed in the context of connected lighting systems, which offer opportunities to reduce consumption during peak times and provide additional grid services, such as fast response services. Connected lighting systems[18] comprise SSL sources (e.g., LED lamps and/or luminaires), network communication interfaces, as well as sensors and controllers integrated into a system. Network communication interfaces, sensors, and controllers can either be integrated within the light source or in other standalone devices within the system. Only SSL technologies are considered in this report because they are currently the most efficient lighting technology on the market, and as mentioned, energy efficiency is generally the most valuable grid service that lighting can provide. Additionally, only lighting *systems* are considered in this report because lighting is only valuable to the grid when individual lamps and luminaires are aggregated in the building. Finally, only *connected* lighting technologies are considered in this report because their communication and control capabilities are essential for providing grid services beyond traditional energy efficiency.

2.2.2 Selection of Current State-of-the-Art Technologies

Connected lighting systems can respond automatically and in aggregate to grid signals. They can reduce or modulate lighting loads or shift the lighting power source from the electric service to a reserve battery. In addition, daylighting technologies also offer opportunities for decreasing lighting loads during the day when daylight can supplement electric lighting.

In this section, we identify and characterize three types of connected lighting systems: systems with advanced sensors and controls, hybrid daylight SSL systems, and SSL displays. These three connected lighting systems are discussed in greater detail in Table 2. Prior to selecting these three technologies as the focus of the report, a broad suite of lighting technologies—including lighting technologies in existence, proposed, or theoretical—were considered. The additional technologies considered are summarized in this section. In general, technologies that were evaluated in this report each had to satisfy these criteria: (1) it must have the potential to

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[18] Within the lighting industry, various terms are used to describe lighting systems that offer control savings through sensor-enabled intelligence. The DesignLights Consortium uses the term "networked lighting controls," while DOE uses "connected lighting systems." In addition, there are several terms such as advanced lighting controls, luminaire-level lighting controls, integrated lighting controls, external systems integration, and energy monitoring that describe the features and capabilities of these lighting systems. In this paper, the terms "networked" and "connected" are deemed synonymous, consistent with how these terms are typically treated within the lighting industry. For ease, this report refers to these products collectively as connected lighting systems.

provide grid services *beyond* energy efficiency (through shedding, shifting, and/or modulating loads), (2) there must be some supporting research available on the technology, and (3) there must be potential for it to have a meaningful impact on the grid (primarily general illumination lighting).

Based on available research and consultation with SSL and connected lighting researchers and experts, the following technologies were eliminated from consideration in this report:

DC Lighting Systems. DC lighting refers to connected lighting systems that are powered by direct current (DC) rather than alternating current (AC). LEDs are inherently DC electronic devices and therefore can operate from DC electric generation sources, eliminating the need to convert AC to DC within each LED luminaire or lamp. This provides additional energy efficiency gains by reducing the 10%–15% energy loss in the conversion (Hutchinson 2018). DC lighting systems are also well suited for connections with distributed generation (solar PV panels or microturbines) or distributed batteries, both of which naturally supply DC power. An example of DC lighting system technology is Power over Ethernet, which can reliably transport data and low-voltage DC current to power LEDs. Power over Ethernet LEDs are also well suited to send and receive grid signals from the utility as the ethernet cables provide reliable data transfer. Though this technology provides some demand-side management strategies, DC technologies are covered in the *Overview of Research Challenges and Gaps* report and will not be discussed in this report.

Integrated Batteries. The term integrated batteries refers to connected lighting systems utilizing an integrated rechargeable battery, such as lithium-ion, to provide several hours of off-grid lighting power that automatically recharges when needed. The battery could be integrated into the luminaire or somewhere else in the lighting system, depending on the system architecture. Though this technology provides substantial demand flexibility through shifting and modulating, battery-integrated technologies are covered in the *Overview of Research Challenges and Gaps* report and will not be discussed in this report.

Fluorescent Lighting. As mentioned previously, all lighting technologies discussed in this report are assumed to be subsets of connected lighting systems, which means that DOE is not including lighting technologies (such as fluorescent lighting) that are typically less efficient than SSL.

Laser Diode Lighting. A laser diode is a semiconductor device like an LED, though the laser beam created at the diode junction produces higher intensity (lumen) lighting output in a much smaller, focused spot. The stimulated emission mode of the laser diode eliminates current density droop that reduces the efficiency of LEDs at high current densities. This allows laser diodes to maintain their wall-plug efficiencies at higher current density operation, unlike LEDs (Pattison et al. 2019). However, the wall-plug efficiency of blue laser diodes is much lower than LEDs—currently 30%–40% for laser diodes compared to 60%–70% for high-performance LEDs (Pattison et al. 2019). Today, laser diodes are finding commercial success in specialty lighting purposes (directional, automotive, display, etc.),[19] but more research is needed to raise the laser diodes' wall-plug efficiency to allow them to move into general illumination applications. Because of their limited applications today, this technology is not evaluated in this report.

Task-Ambient LED Lighting System. A task-ambient LED lighting system consists of an ambient connected lighting system complemented with task-specific lighting in occupied work areas, which reduces lighting requirements from overhead ambient fixtures. For instance, desktop lighting can be used to light cubicles/offices when they are occupied. In a recent meta-analysis study, Lawrence Berkeley National Laboratory reported lighting energy savings of 36% from utilizing task LED lighting and occupancy sensors and controls relative to a traditional LED lighting system (Williams et al. 2011). Though this technology does provide increased energy efficiency, there is minimal opportunity for additional grid services through shedding

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[19] For more information about SLD Laser, see: https://www.sldlaser.com/about.

or modulating. Because task lighting is already minimizing lighting energy use to levels that are needed for tasks, any further alterations in lighting level would likely be disruptive to occupants.

OLEDs and Organic Photovoltaic Integrated Windows. This technology consists of transparent OLEDs and organic photovoltaic glazing integrated into a window with daylighting sensors and controls that can generate electricity and provide supplemental lighting when daylighting is unavailable. Though both OLED-integrated windows and photovoltaic glazing for windows exist separately as commercial technologies, they have never been combined into a single product. Further, without the addition of a battery, only limited potential exists to shift and modulate loads through power generation from the organic photovoltaics. Also, there is no known research available on technological capabilities and efficiency of integrated OLEDs and organic photovoltaics in windows. However, photovoltaic glazing for windows is discussed in further detail in the *Windows and Opaque Envelope* report.[20]

Lighting Design/Redesign. Lighting design/redesign is the concept of designing lighting use to maximize energy efficiency. This concept encompasses a variety of techniques that can be used in the design process, including installing task lighting, maximizing daylighting through windows/skylights, using light wall colors, and matching the amount and quality of light needed to perform functions.[21] Because this concept is focused on building design rather than a lighting technology, this is considered out of scope for this report.

Spectral Tunable LED Controls. This technology consists of connected LED lighting systems with the capability to shift color spectrum either as needed by occupants or automatically to support circadian rhythms. In general, this technology is included within “advanced sensors and controls” for lighting systems. Although spectral tunable LED controls have the technological capability to provide grid services, including shedding and modulation, the potential is constrained by occupant health needs. In other words, if this lighting system is used to provide health benefits (supporting circadian rhythms), there is little to no capability to provide grid services such as shedding. Accordingly, this technology will not be discussed in detail.

Horticulture LED Lighting System. A horticulture LED lighting system is simply a connected lighting system designed for indoor plant cultivation (including for supplemented greenhouses, sole-source indoor farms, and vertical farms). LEDs offer advantages over other lighting technologies because of the increased efficiency and ability for spectral tuning (Stober et al. 2017). Generally, lighting demand in these facilities is substantial (about 50% of electricity consumption) and the system is often operated for more than 12 hours a day, depending on plant type, growth phase, etc. Because plants are sensitive to changes in lighting output, there is little to no potential for horticulture lighting to provide modulation or shedding services. However, in indoor farms with no supplemental lighting from daylight, there is potential to shift the hours of operation to align with off-peak periods (including time-of-use pricing structures) or periods of high variable renewable energy generation (e.g., to be paired with wind energy at night or solar output during the day) depending on the regional grid needs. However, because of the daily, alternating light and dark photoperiod requirements in these facilities to maximize plant growth, there is little additional short term shifting available on a daily/hourly basis. Though the lighting energy consumption from these facilities is significant—DOE estimates about 5.9 TWh of site electricity in 2017—it represents only a fraction of the lighting energy consumed in the residential and commercial building sectors (Stober et al. 2017). In addition, there is no additional technological capability needed to perform this shifting—it is simply a market and policy issue that is out of scope for the report.

2.2.3 State-of-the-Art Connected Lighting Technologies

This section includes a description (Table 2) of each connected lighting system technology that was evaluated, including how it enhances the ability of connected lighting systems to provide grid services, the current

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[20] See Section 1 for a list of report links.

[21] For more information, see the U.S. Department of Energy’s “Lighting Design” web page: https://www.energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/lighting-design.

performance levels, the development phase, the applicable building sector and market, and the growth potential and projections. These technologies all enable connected lighting systems to deliver additive and complementary grid services. In addition, this report does not discuss lighting technology R&D options that would solely impact efficiency, such as improved SSL devices, materials, architectures, down converters, power electronics, light extraction, or advanced fabrication technologies. Although advances in these lighting R&D technologies have the potential to provide significant energy savings, this report focuses on the ability to provide additional grid services. For more information on energy efficiency R&D opportunities in lighting, refer to the 2018 Solid-State Lighting R&D Opportunities report (Pattison et al. 2019). It is also important to note that R&D advancements to sensor and control technologies and data analytics, while essential to the realization of grid benefits from lighting, are discussed at greater lengthen in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

Table 2. State-of-the-Art Lighting Technologies

<table>
<tr><th colspan="2">Advanced Sensors and Controls</th></tr>
<tr><td>Overview</td><td>Advanced sensors and controls enhance connected lighting systems with an improved ability to use algorithms to automatically modulate lighting levels or potentially other power-consuming features (e.g., spectrum, reduced sensor or network communication interface power) in response to external grid/pricing signals. The control algorithms may be embedded in a light source, in a gateway, or in the cloud. Technologies include advanced concepts for control integration, interoperability with grid/pricing signal protocols, application program interfaces, luminaire-level energy use reporting, and adaptive algorithms for optimized performance (including artificial intelligence and machine learning). These technologies would enable deeper interaction with both the grid and building-level sensors and controllers to reduce lighting loads and potentially provide quick response services, such as contingency reserves and frequency regulation. However, these capabilities are limited in scope because of lighting's necessity for occupant productivity, comfort, and safety. In addition, because each individual LED luminaire or lamp represents a small load, many luminaires (and likely lighting systems) would need to be aggregated to provide valuable service to the grid.


Figure 8. Example diagram of an advanced sensor and control lighting system
Source: Bonneville Power Administration (N.D.)</td></tr>
<tr><td>Applicable Market</td><td>The primary market is commercial buildings; however, this technology can apply to both new construction and retrofits for commercial or residential buildings. Installation costs may be prohibitively high for some commercial and many residential buildings.</td></tr>
<tr><td>Growth Potential</td><td>The market for connected lighting systems with advanced sensors and controls is expected to see rapid growth over the next 20 years. In the commercial sector, connected lighting systems are expected to account for 34% of lighting in the commercial sector and 12% of lighting in the residential sector by 2035 (Penning et al. 2016). The major market drivers include increased energy and cost savings, data and analytic capabilities, and increased adoption of smart home technologies. Connected lighting systems with advanced sensors and controls are typically purchased by the end user and utilities may offer rebates or incentives.</td></tr>
</table>

Hybrid Daylight SSL Systems	
Overview	Hybrid daylight SSL systems are connected lighting systems that are enhanced by the ability to collect and redistribute zero energy daylighting. Daylighting technologies include optimization of window and skylights as well as daylight concentrating systems, including solar collectors (often a mirrored lens with a sun tracker), beam splitters to filter out nonvisible light, and a light guiding and diffusing system to distribute the daylight in the building (e.g., fiber-optic cables, piping, mirrors, etc.). Photosensors and controllers are used to ensure real-time and automatic light modulation to maintain lighting levels and spectrum based on daylight availability. This system can also be combined with solar PV cells and electricity storage to generate electricity with the nonvisible light rays (ultraviolet and infrared), store it, and power the LEDs as needed (Tsuei et al. 2010). The primary benefit of the system is lighting energy savings, though load shedding and modulation for demand response are additional capabilities.  **Figure 9. Example hybrid fiber-optic lighting system (shown: the Heliobus[22] light guide system)** Source: Mayhoub (2014)
Applicable Market	The primary market is commercial new construction; however, this technology can apply to both new construction and retrofits for commercial and residential buildings. Depending on the system design, installation costs may be prohibitively high for many commercial retrofit applications as well as new construction or retrofits for residential buildings.
Growth Potential	Hybrid fiber-optic daylighting systems integrated with electric lighting systems have been available for many years, but market adoption has been extremely low because of the high cost of fiber-optic cables, low light transfer efficiency, and installation difficulty (Vu et al. 2016). In addition, the market for these systems within integrated connectivity features is nonexistent. This technology would typically be purchased by the end user and utilities may offer rebates or incentives. Overall, lack of market adoption and growth because of prohibitive costs is a significant challenge.

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[22] For more information on Heliobus, see: https://heliobus.com/en/products/daylight-engineering#1550745595527-eba18083-25f5.

<table>
<tr><th colspan="2">SSL Displays</th></tr>
<tr><td>Overview</td><td>SSL displays are a system of connected lighting displays leveraging either LED or OLED technology to eliminate the need for windows and skylights as sources of daylighting. This technology consists of energy-efficient SSL displays in a networked system that mimic the daylighting and sun exposure that occupants would experience through a building's window or skylight. The SSL displays provide necessary lighting while eliminating heat loss associated with traditional windows and skylights. Currently, SSL displays are used to provide lighting in basements or other building spaces without windows, but they could potentially provide efficiency benefits from reduced heating and cooling loads if used to replace traditional windows and skylights. Heat loss and gain through windows are responsible for 25%–30% of residential heating and cooling energy use.[23] This technology could also provide limited demand response capabilities, reducing load during peak periods by modulate lighting levels or other power-consuming features (e.g., spectrum, reduced sensor, or network interface power).
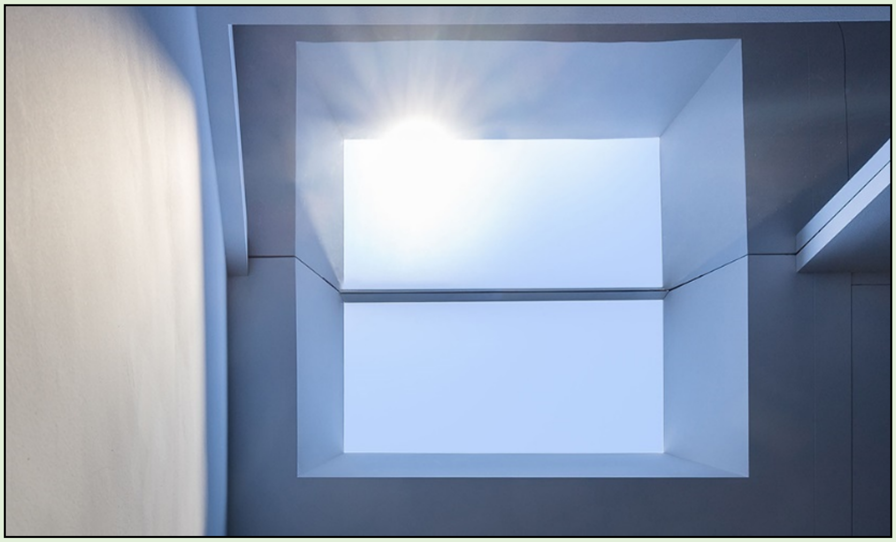
Figure 10. CoeLux 45 SQUARE artificial window
Source: CoeLux (2019)</td></tr>
<tr><td>Applicable Market</td><td>The primary market is commercial new construction; however, this technology may also have applications in both new construction and retrofits for commercial and residential buildings. Installation costs may be prohibitively high for many commercial retrofit applications as well as new construction or retrofits for residential buildings.</td></tr>
<tr><td>Growth Potential</td><td>The market for SSL displays for windows and skylight simulation is in its infancy, and they are currently used for lighting basements or other spaces without windows. In addition, the growth potential for this technology is limited to high cost and customer preferences for windows. Overall, lack of market adoption due to negative customer perceptions is a significant challenge.</td></tr>
</table>

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[23] For more information, see the U.S. Department of Energy web page, "Update or Replace Windows": https://www.energy.gov/energysaver/design/windows-doors-and-skylights/update-or-replace-windows.

2.3 Evaluation of Technologies

2.3.1 Technology Evaluation Criteria

In this section, the identified technologies are evaluated based on their ability to provide grid services (energy, capacity, contingency reserves, frequency regulation, ramping services, and non-wires alternatives).[24] In general, building technologies can provide these grid services through demand-side management strategies:

1. **Efficiency:** the ongoing reduction in energy use while providing the same or improved level of building function.[25]
2. **Load Shed:** the ability to reduce electricity use for a short time period and typically on short notice. Shedding is typically dispatched during peak demand periods and during emergencies.
3. **Load Shift:** the ability to change the timing of electricity use. In some situations, a shift may lead to changing the amount of electricity that is consumed. Load shift in the *GEB Technical Report Series* focuses on intentional, planned shifting for reasons such as minimizing demand during peak periods, taking advantage of the cheapest electricity prices, or reducing the need for renewable curtailment. For some technologies, there are times when a load shed can lead to some level of load shifting.
4. **Modulate:** the ability to balance power supply/demand or reactive power draw/supply autonomously (within seconds to subseconds) in response to a signal from the grid operator during the dispatch period.

The focus of the GEB technical reports is primarily load shed, load shift, and modulating load (referred to throughout the series as demand flexibility), which are typically enabled by the controls and analytics found in a GEB.

Energy efficiency and demand response are the most mature and established demand-side management resources in buildings. In addition to overall energy savings, efficiency plays an important role in supporting grid reliability by decreasing peak demand and easing strain on the transmission and distribution (T&D) system. Demand response is the main form of demand flexibility used today, though it is fairly limited in scope. The majority of demand response programs are generally focused on reducing peak demand through shedding or shifting through direct load control (by utilities/demand aggregators) or behavioral load control programs in which utility customers make a decision to reduce or shift their energy load in response to price signals. In large commercial buildings, load shedding and shifting may also be used for building peak demand reduction to avoid demand charges.

In addition to peak demand reductions, a GEB may also be able help regulate power quality, provide contingency reserves, provide ramping services, or help avoid renewable energy curtailment. Table 3 outlines requirements needed to provide each of these grid services, including the response time, load change, duration of event, event frequency, and other relevant requirements. These requirements inform the evaluation of the technologies in the following section.

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[24] Voltage support is not included here because lighting/electronics are unlikely to provide this service.

[25] This would have the greatest impact for the grid during high-cost periods and minimize utilization of costly generation resources.

Table 3. Mapping Demand-Side Management in Buildings and Grid Services

Response time is defined as the amount of time between receiving a grid signal and the technology (lighting system) responding to change the load. Duration is defined as the length of time that the load change occurs. Voltage support is not included here because lighting/electronics are unlikely to provide this service.

Demand-Side Management Strategies	Grid Services	Definition	Key Characteristics	
Efficiency	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Persistent reduction in load. Interval data are needed for measurement and verification purposes, but this is not a dispatchable service.	Typical duration	Continuous
			Load change	Long-term decrease
			Response time	N/A
			Event frequency	Lifetime of equipment
Load Shed	Contingency Reserves	Load reduction for a short time to make up for a shortfall in generation.	Typical duration	Up to 1 hr
			Load change	Short-term decrease
			Response time	<15 min
			Event frequency	20 times per year
	Generation: Energy Generation: Capacity T&D: Non-Wires Solutions	Load reduction during peak periods in response to grid constraints or based on time-of-use pricing structures.	Typical duration	30 mins to 4 hrs
			Load change	Short-term decrease
			Response time	30 min to 2 hrs
			Event frequency	<100 hrs per year/seasonal
Load Shift	Generation: Capacity T&D: Non-Wires Solutions	Load shifting from peak to off-peak periods in response to grid constraints or based on time-of-use pricing structures.[26]	Typical duration	30 mins to 4 hrs
			Load change	Short-term shift
			Response time	<1 hour
			Event frequency	<100 hrs per year/seasonal
	Avoid Renewable Curtailment	Load shifting to increase energy consumption at times of excess renewable generation output. This type of load shifting is not a dispatchable service but can be indicated through time-of-use pricing structures.	Typical duration	2 to 4 hrs
			Load change	Short-term shift
			Response time	N/A
			Event frequency	Daily
Modulate	Frequency Regulation	Load modulation in real time to closely follow grid signals. Advanced telemetry is required for output signal transmission to grid operator; must also be able to receive automatic control signal.	Typical duration	Seconds to minutes
			Load change	Rapid increase/decrease
			Response time	<1 min
			Event frequency	Continuous
	Ramping	Load modulation to offset short term variable renewable generation output changes.[27]	Typical duration	Seconds to minutes
			Load change	Rapid increase/decrease
			Response time	Seconds to minutes
			Event frequency	Continuous

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[26] Time-of-use pricing that specifically incentivizes energy use at times when renewable generation output is high and electricity prices are low.

[27] This is not currently offered as a grid service by any RTOs/ISOs.

2.3.2 Evaluation of Technology Characteristics

In this section, each technology is given a qualitative rating based on its capability to provide grid services through the energy efficiency and demand flexibility strategies outlined in Table 3. It should be noted that these ratings are *qualitative* and are based on estimated theoretical technological potentials, available research studies, and expert guidance. No lab testing or experimental pilot tests have been performed as part of this evaluation. The ratings are summarized as follows:

○ **Not Applicable:** Unable to provide the demand-side management strategy because it has no potential to meet the response time, data, and technology requirements for the corresponding grid services.

◑ **Low Capability:** May be able to provide the demand-side management strategy, but it is not well suited. It meets some or none of the response time, data, or technology requirements to provide the corresponding grid services and has low potential to meet all of them. Other technologies exist that are better fitted to perform the demand-side management strategy.

◐ **Medium Capability:** Able to provide the demand-side management strategy, but in a limited capacity. Meets all the response time, data, and technology requirements to provide the corresponding grid services or has the potential to meet all of them, but other barriers exist that limit the capacity.

● **High Capability:** Well suited to provide the demand-side management strategy and the corresponding grid services or possesses high potential through continued R&D. Current technologies meet all the response time, data, and technology requirements to provide the corresponding grid services and have been proven capable of providing the grid services through experimentation or field testing. Prospective technologies will possess characteristics that indicate a high likelihood to meet all grid service requirements following advances in R&D.

In addition, each grid service is weighted based on the opportunity space in the building sector. Building technologies provide the greatest value to the grid through energy efficiency and peak demand reductions based on addressable market sizes for these grid services.[28] Therefore, the ability to perform efficiency, shedding, and shifting is weighted higher than modulating loads. Based on the capability to provide each demand-side management strategy, the number of strategies provided, and the weighting of each (efficiency/shedding/shifting weighted higher than modulating), each technology is determined to have low, medium, or high potential to provide grid services in a GEB. Table 4 provides a summary of this evaluation, including the capabilities to perform demand-side management strategies and the overall potential rating.

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[28] Further discussion on this is available in the *Overview of Research Challenges and Gaps* report.

Table 4. Evaluation of Connected Lighting Technologies and Demand-Side Management Strategies

Technologies		Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
Connected Lighting Systems	**Advanced Sensors and Controls**	●	◐	○	◑	High
	• Provides both efficiency gains and demand responsive capabilities to shed lighting loads • Additional energy savings are possible through the collection of real-time data on building environment and activity through lighting sensor networks as well as adjusting lighting and HVAC usage accordingly • Has the capability to provide fast response grid services through shedding and modulating, though in limited capacities that are not disruptive to occupant productivity/comfort/safety					
	Hybrid Daylight SSL Systems	●	◑	○	◑	Medium
	• Greatly reduces lighting loads during peak and off-peak periods when daylight is available • Load shedding is also possible, though in limited capacity because electric lighting energy use is typically low (or zero) when daylight is available • These systems could potentially be used to provide frequency regulation/ramping services by modulating lighting loads between daylight and LED lighting as needed					
	SSL Displays	●	◑	○	○	Low
	• Provides grid benefits via reduction of heating and cooling loads • Eliminating natural daylighting increases the electricity consumption from electric lighting sources • Eliminating windows could also increase ventilation energy usage in some buildings • When combined with controls that modulate lighting levels or other power-related lighting features, it could provide only limited demand response capabilities (load shed) because the magnitude would be minimal without the presence of daylighting					

○ **Not Applicable** ◑ **Low Capability** ◐ **Medium Capability** ● **High Capability**

2.3.3 Evaluation Results

The potential levels shown in Table 5 correspond to each technology's capability to provide the grid services through the demand-side management strategies (as outlined in Table 3). These potential levels are relative to other connected lighting technologies and are not meant to be compared to other building technologies (e.g., HVAC, appliances, etc.), which may have lesser or greater overall potential to provide energy savings, building/grid peak demand savings, and other grid services.

Table 5. Technology Priority Levels

High Potential	Medium Potential	Low Potential
• Advanced Sensors and Controls	• Hybrid Daylight SSL Systems	• SSL Displays

High Potential. Lighting systems with advanced sensors and controls have the advantage of providing shedding for demand response/building peak demand-side management and total energy savings over traditional SSL lighting technologies. For example, systems with occupancy sensors, daylighting sensors, and automated dimming can optimize lighting use across control zones based on occupant patterns, available daylighting, and learned lighting level preferences/needs, while also reducing energy use (shedding) during peak periods or emergency events. However, the shedding/modulation strategies are restricted to dimming and limited modulation of lighting levels or other power-consuming lighting features because of the necessity of lighting in occupied spaces. The greatest benefit from systems with advanced sensors and controls is energy efficiency, achieved using adaptive algorithms for optimized LED and control performance (including artificial intelligence and machine learning). However, without the addition of batteries, they have no capability to shift loads.

Lighting systems with advanced sensors and controls also offer the opportunity for additional building-level energy savings by sharing their data with other building systems. Sensors integrated in lighting devices are inherently distributed throughout the building, and thereby allow for the collection of a vast array of data on the building environment (temperature, daylight, etc.) or building activity (occupancy, movement, and asset location). These data can help building owners understand how the space is being utilized and apply adaptive strategies to optimize energy use and occupant comfort in real time. The embedded sensor network can allow building automation systems to measure real-time energy usage, temperature, and daylighting levels. Energy savings can be achieved by adjusting lighting and HVAC energy usage based on current occupancy or with better targeted scheduling practices and demand response programs. If connected lighting products have the capability to self-measure and report energy use, utilities could offer incentives to customers based on actual savings instead of estimated savings.

Medium Potential. Hybrid daylight SSL systems provide primarily passive energy savings and peak reduction potential. In general, these systems have some potential for demand response through shedding, but they can reduce overall lighting electricity consumption substantially on an annual basis, though estimations vary widely (Ullah and Whang 2015; Volotinen and Lingfors 2013a). Also, although grid peak demand periods vary by regional transmission organization/independent system operator (RTO/ISO) or utility, they typically fall within daylighting hours, meaning that hybrid daylight SSL systems could contribute to reducing peak demand from electric lighting as well. Consequently, this technology could also increase grid peak demand in certain regions of the United States in the future if more distributed solar generation is added to the grid. In other words, without integrating the system with PV cells and batteries (Tsuei et al. 2010), the system would increase consumption as the sun sets and at nighttime, exasperating the so-called solar duck curve,[29] in which the system peaks occur when distributed solar generation is unavailable.

In addition to passive energy savings, these systems may provide load shedding and modulation. Load shedding is enabled through dimming of electric lighting components (in response to grid/pricing signals) when daylighting is available. However, the energy reduction capacity is limited because electric lighting use is already minimized by daylighting. Finally, grid-interactive hybrid daylight SSL systems may have the potential to provide frequency regulation and ramping services by modulating loads between daylight and LEDs during times when adequate daylight is available. However, there is no known research available on this topic to prove this capability.

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[29] More information on the solar duck curve can be found at: https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy.

Low Potential. Lastly, SSL displays have been identified as offering the lowest potential for grid services of the three evaluated technologies. Their primary grid service contribution is load reduction through heating and cooling energy savings. Replacing windows with SSL displays reduces infiltration losses by windows and skylights, which has been estimated to account for 25%–30% of residential heating and cooling energy use.[30] A recent building simulation study showed that increasing the window-to-wall ratio on the west side of a building from 10% to 30% led to about a 65% increase in the average heat gain rate (W/h) and a 124% increase in the average heat loss rate (W/h) (Feng et al. 2017). However, eliminating daylighting sources through windows and skylights also has a consequence of increasing the electricity consumption from lighting. In addition, they could also contribute to increased ventilation energy consumption in some buildings that may use windows to ventilate spaces. Although these SSL displays could also potentially provide demand response services if integrated with controls, the peak reduction potential is significantly restricted (similar to advanced sensors and controls) because of the necessity of lighting in occupied spaces. Further, if daylighting is reduced through the loss of windows and skylights, there would be even greater necessity to maintain lighting output levels in the SSL displays.

2.4 Technology Attributes

Beyond the capability to provide grid services, connected lighting technologies offer additional benefits to manufacturers, consumers, and society that match or exceed their value to the grid. Further, some of these technologies face major market/consumer challenges that prevent them from realizing their grid service potential. Understanding these additional benefits and market/consumer barriers supports the assessment of each technology in a holistic and realistic way. In this section, the key technology attributes of each medium- and high-potential connected lighting system technology are discussed. The attributes considered for each technology—resilience, usability, cost, human health, and energy performance—are defined in Table 6. Because not all system attributes are relevant to each technology, only relevant attributes are discussed for each technology. In addition, although these state-of-the-art lighting technologies could be deployed in the residential sector in the future, all connected lighting systems today are only deployed in the commercial buildings; for this reason, all examples and discussions hereafter omit residential buildings and customers.

Table 6. Technology Attribute Descriptions and Criteria

These definitions are for the purposes of the *GEB Technical Report Series*. They may be defined differently in other reports or contexts.

System Attribute	Definition
Resilience	The ability of the technology to predict and prepare for, withstand, recover rapidly from, and adapt to major disruptions including natural disasters and energy supply losses (electricity, natural gas, etc.) by providing energy, services, occupant comfort, protection, and/or damage resistance.
Usability	The ease of use of the technology to the customer, including ease of installation, ease of implementation, ease of operation, and ease of maintenance.
Cost	The manufacturing and capital costs of the technology and components.
Human Health	The extent to which the technology contributes to a healthy and safe living environment for the building occupants.
Energy Performance	The estimated impact on energy use from implementing the technology relative to baseline technologies.

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[30] For more information, see the U.S. Department of Energy web page, "Update or Replace Windows": https://www.energy.gov/energysaver/design/windows-doors-and-skylights/update-or-replace-windows.

2.4.1 All Connected Lighting Systems

As mentioned in the previous section, the lighting technologies evaluated in this report are all dependent on the development of connected lighting. Connected lighting systems enable LED-based lamps and luminaires as well as control devices to exchange digital data, positioning these systems as the foundational technology that will enable grid services beyond efficiency. As such, Section 2.4.1 discusses the technology attributes of connected lighting systems that are applicable to each of the two high-/medium-potential lighting technologies—advanced sensors and controls and hybrid daylight SSL systems. Sections 2.4.2 and 2.4.3 then discuss the benefits and barriers unique to each. It is also important to note that R&D advancements to sensor and control technologies, though essential to the realization of grid benefits from lighting, are discussed at greater length in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

2.4.1.1 Usability

As connected lighting systems expand their applications and capabilities, they often also become increasingly complex and more difficult to install, operate, and maintain. In addition, lighting needs may vary by application, users, location, and building demographics. When developing advanced systems, it is important to find the right balance between capability and complexity that can meet the needs of building occupants without requiring expertise beyond typical user capabilities to install, commission, and operate them.[31] This is especially important for lighting systems, because those that are overly complicated and time-consuming to configure have historically delivered less than ideal performance (Taylor 2018).

Commissioning is one of the biggest challenges for any connected lighting system because of the complexity of the technologies as well as the variety of communication protocols used (Slupik and Rzadkosz 2018). The commissioning process generally consists of network formation, device identification/mapping, and logic configuration, each of which requires specific software tools and expertise (Slupik and Rzadkosz 2018). The Next Generation Lighting Systems program has conducted evaluations of a dozen connected lighting systems that incorporate advanced sensors and controls. This program has found that luminaires with greater integration (e.g., embedded sensor and control systems) that leverage wireless communication connections were the least complicated to commission, while systems that incorporate remote-mounted control devices, require syncing to external systems, and utilize wired communication connections were among the most complex (Taylor 2018).

Communication, documentation, and configuration tools are also a significant challenge and contribute to the issues associated with commissioning. The configuration tools provided by manufactures vary and can ultimately impact the system installation and usability.

Despite the usability challenges associated with connected lighting systems, there are some commercially available products that allow for streamlined/automated installation and configuration. Products that employ greater integration of components and control devices, wireless communication, software-based tools for configuration, and predictive maintenance capabilities help to ensure consistent and persistent energy savings and grid services. In addition, these connected lighting systems can result in greater occupant comfort and satisfaction.[32]

2.4.1.2 Cost

One of the primary barriers to adoption for any SSL product, and particularly connecting lighting systems, has been high upfront cost. Although prices have dropped rapidly over the past few years, analysis of LED pricing in recent studies conducted by California investor owned utilities (CA IOUs) and National Grid shows that on a first-cost basis, connected lighting systems are typically priced 40%–90% higher than noncontrollable LED

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[31] For more information, see the U.S. Department of Energy web page, "NGLS Indoor Evaluations: Operational Complexity," https://www.energy.gov/eere/ssl/ngls-indoor-evaluations-operational-complexity.

[32] For more information, see the Pacific Northwest National Laboratory report, "DLC Advanced Lighting Technology Demonstration: Digital Lumens." https://www.designlights.org/default/assets/File/Lighting%20Controls/DLC_Advanced-Lighting-Fact-Sheet_Digital-Lumens.pdf.

products (Yamada et al. 2018). Figure 11 compares the price findings of the National Grid potential study to that of the LED DesignLights Consortium[33] LED pricing results for the California LED Pricing Study.

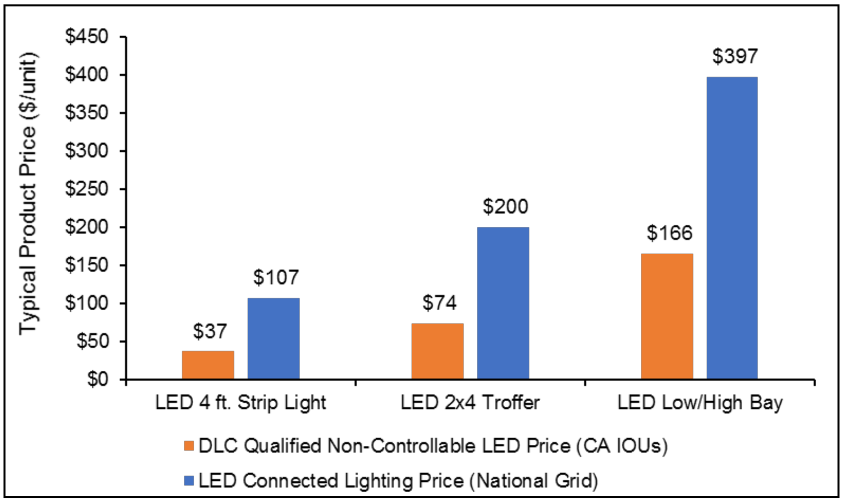

Figure 11. 2016 Q4 price comparison of DesignLights Consortium (DLC) noncontrollable and connected LED products

Source: Yamada et al. (2018)

2.4.1.3 Other Technological and Market Constraints

One of the major opportunities for all connected lighting to provide grid services is through automated demand response. However, lighting is generally considered necessary in occupied spaces, meaning it must always be provided to ensure occupant safety and productivity. Though lighting is technically capable of providing shedding and modulation services, the reality of providing these grid services while maintaining occupant needs is more challenging. When buildings are occupied, lighting systems cannot be turned off during a demand response event. Although controls enable lighting systems to reduce load through lighting level reduction, or even spectral changes or auxiliary load reduction (i.e., reduced sensor or control load), the depth is limited to levels that are not disruptive to occupants. In addition to automated demand response services, load shedding in connected lighting systems may also be used in large commercial facilities for peak demand-side management to avoid demand charges.

Case studies have evaluated a variety of dimming strategies for lighting. The example shown in Figure 12 illustrates an automated demand response strategy tested within a Southern California Edison office building. In this study, demand response signals controlled the lights to 90%, 75%, and then 50% of full power (California Energy Commission 2011). Although the case study comments that the building occupants did not notice the events, it did not examine how various dimming levels may have impacted occupant comfort, productivity, or well-being. Another study found that lighting in commercial buildings may be dimmed as much as 20% in areas with no daylighting and as much 40% in areas with daylighting (Newsham and Piette 2014). In general, more research is needed to better determine appropriate dimming levels in different contexts (building type and design, occupational use and patterns, geographic location and season, etc.).

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[33] The DesignLights Consortium is a nonprofit organization that establishes SSL product quality specifications. More information can be found on their website: https://www.designlights.org/.

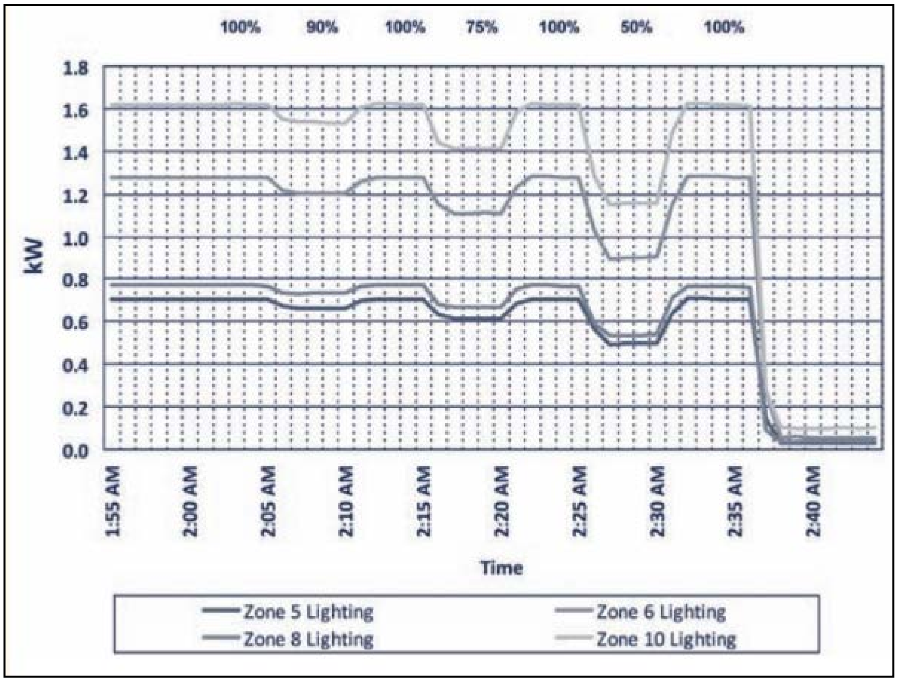

Figure 12. Southern California Edison office building demand response power reduction testing

Source: California Energy Commission (2011)

2.4.2 Advanced Sensors and Controls

2.4.2.1 Energy Performance

Advanced sensors and controls for lighting systems deliver improved lighting quality and energy performance because they leverage multiple sensing strategies, such as occupancy sensing, daylight harvesting, high-output trim, scheduling, and personal area controls. The combination of these approaches has been shown to provide substantial additional energy savings beyond a static LED lighting system, increasing savings from 20% to 80%, depending on the application and use case (DesignLights Consortium 2017). If these advanced sensors and controls are part of a connected lighting system, they can also improve the energy performance and management of other building systems such as HVAC equipment, track assets such as wheelchairs in a hospital, space utilization, and potentially occupant health and productivity (discussed in Section 2.4.2.2). It is likely that these additional capabilities will offer benefits that match or exceed the value of the energy savings they deliver (Pattison et al. 2017). For example, the Enlighted system by Siemens uses Bluetooth low-energy tags, a network of sensors installed in each lighting fixture, and cloud-based data analytics to optimize lighting and HVAC usage for comfort, security, and energy savings. The sensors collect data on temperature, light levels, heat, motion, and occupancy. The sensors and controls network have a reported lighting energy savings of 38% and HVAC energy savings of 35% (Enlightened, Inc. 2018).

Even though advanced lighting controls currently comprise approximately 0.1% of all luminaires in the United States and only 2% of the total realized savings, this technology is pivotal to maximizing future potential energy savings. As shown in Figure 13, DOE estimates that connected lighting systems leveraging these advanced controls represent up to 32% of total remaining lighting energy savings potential.

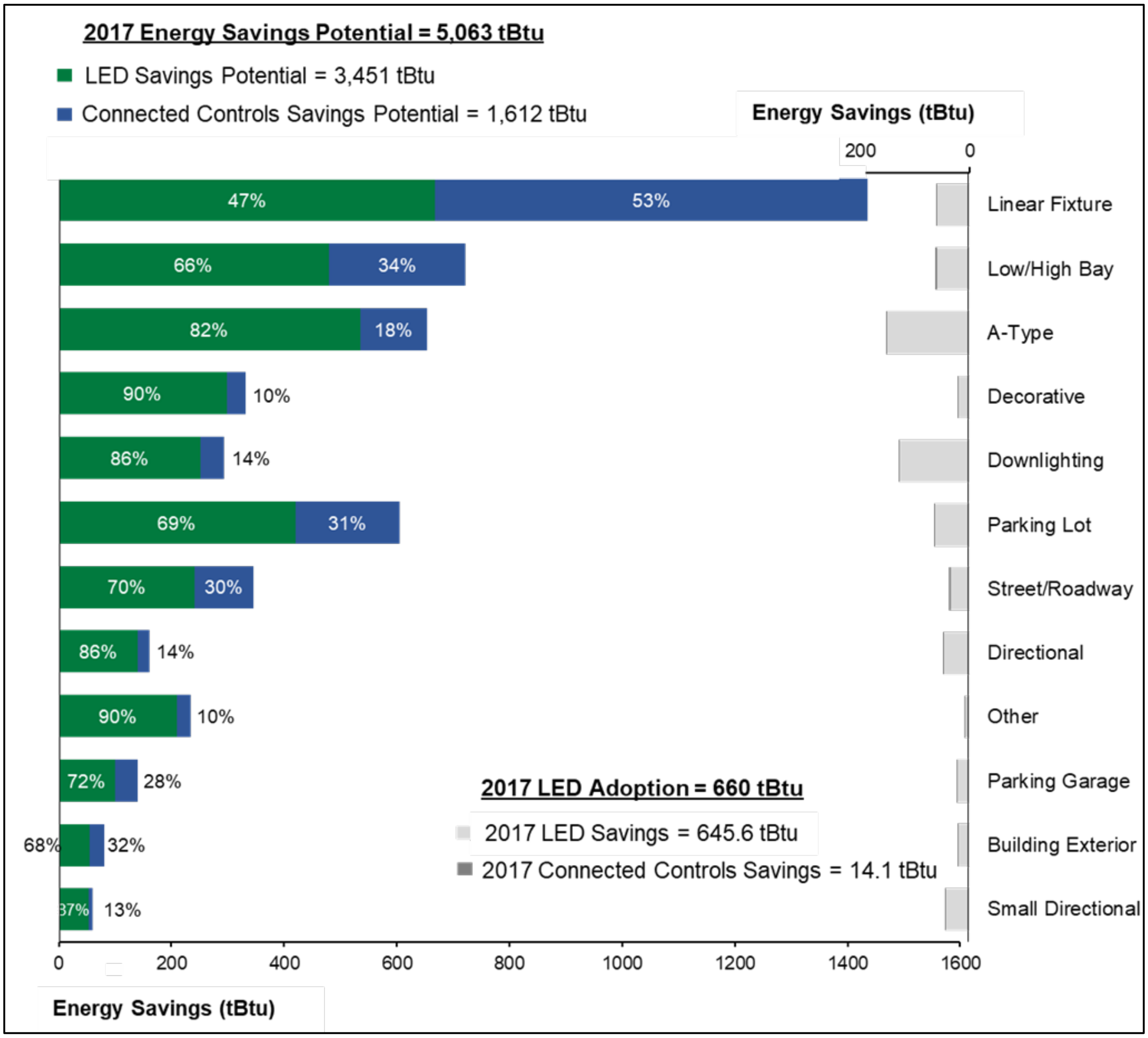

Figure 13. U.S. energy savings potential of LED and connected lighting systems by application

Source: Adapted from Penning et al. (2017) with updated data from the DOE Lighting Market Model.

Potential savings for connected lighting controls (shown in blue) represent savings beyond those that could be achieved through LED lighting efficacy improvement alone (shown in green). Advanced lighting controls will have especially strong impacts on the savings achieved by commercial and industrial LED applications, such as linear fixture and low/high bay.

2.4.2.2 *Human Health*

Advanced sensors and controls and spectral tunable SSL technologies can be designed to engage human physiological responses, including alertness, productivity, and human circadian rhythms that aid in sleep and wake cycles. Traditional lighting systems provide only low-intensity lighting during the daytime hours at warm color temperatures, which is inconsistent with natural daylighting conditions (Pattison et al. 2019). Further, exposure to cooler (blue) temperature lighting during night hours may confuse human diurnal rhythms (Pattison et al. 2019). The ability to dynamically control the emitted spectrum and light intensity of an LED or OLED lighting source is a distinguishing feature of the technology and can add value to SSL beyond energy savings. For example, a recent study showed that spectral tunable lighting systems could be used to mimic daylight patterns in buildings with limited natural light by varying the light intensity and spectrum (Wilkerson and Davis 2017). These lighting patterns were used to aid in sleep/wake cycles for occupants with little exposure to daylight to help energize them in the morning and calm them at night (Wilkerson and Davis 2017). Overall, researchers have shown that spectral tuning can:

- Improve classroom alertness for students;
- Promote daytime activity, alertness, and better sleep at night for the elderly;
- Assist chronic pain therapy through structuring the day and stabilizing sleep/wake cycles;
- Increase evening and nocturnal relaxation and morning activation for aircraft passengers; and
- Reduce the duration of time of therapy to relieve unipolar depression (Wojtysiak 2015).

It is too early to quantify the impact these features may have, but even slight improvements in workforce productivity could justify the added expense of integrating advanced sensors and controls. In addition, though the impact of lighting on human health is the subject of ongoing research, it is important to acknowledge that much of the current research for these effects is at an early stage and additional research is necessary to fully understand these biological responses.

Furthermore, lighting controls that are used to promote human health and well-being often conflict with the grid service objectives. For example, a color tunable and/or dimmable LED system that aims to improve classroom alertness for students or improve sleep/wake cycles could not easily be used for demand response or building peak demand-side management. In addition, more research is needed to understand how connected lighting systems can provide positive physiological effects to occupants without compromising energy efficiency (Pattison et al. 2019).

2.4.3 Hybrid Daylight SSL Systems

2.4.3.1 Energy Performance

Hybrid daylight SSL systems offer the combined energy savings benefits of both daylighting and high-efficiency LED lighting sources. Studies have shown that daylight harvesting and controls in buildings reduce lighting energy use by 28% on average (Williams et al. 2011). In addition, technologies that concentrate and transport daylight, such as fiber-optic light systems, have demonstrated lighting load reductions of 50% in comparison to traditional LED systems (Ullah and Whang 2015). Other systems, such as the Canadian SunCentral system that uses an array of mirrors and highly reflective films, have reported lighting energy savings of up to 75% (Mayhoub 2014). The South Korean Sunportal system, which uses a heliostat[34] with an ultra-daylight concentrator and optical relay lenses, has shown lighting energy savings up to 60% (Mayhoub 2014). However, energy savings in these systems can be highly variable depending on factors such as weather patterns and geographic location, seasons, building design, lighting system design, and occupancy patterns. For example, buildings located in regions that experience high cloud coverage or limited daylight hours in winter months are not well suited to implement this technology and may experience much lower energy savings.

2.4.3.2 Usability

Maintenance and installation difficulties are major challenges facing many hybrid daylight SSL systems. For daylight concentrating systems in particular, the optical materials used in the daylight transport componentry must be cleaned regularly to avoid precipitation of particulates (dust, smoke, and so on) and condensation of water vapor on the materials, which greatly reduces the light transmission efficiency. In addition, mechanical parts of the systems, such as daylight trackers on solar concentrators, may require repair and part replacement. Depending on the type of system, installation of these can be very difficult in existing buildings. Hybrid daylight SSL systems using flexible fiber-optic cables are easier, whereas systems using light ducts are much more difficult to install (Mayhoub 2014). In general, hybrid daylight SSL systems, including traditional

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[34] Heliostats collect daylight by using a set of mirrors and/or lenses, which send it into the building core via vertical voids (Mayhoub 2014).

daylighting (windows, skylights, etc.) are better suited for new construction so they can be incorporated in the building design process.

In addition, hybrid daylight SSL systems with daylight concentrators are limited in use to certain building types and certain geographic regions. For example, though some of these systems are technically capable of transporting daylight over 200 meters,[35] a typical light delivery distance is less than 20 meters for most systems because of light transfer efficiency losses and cost constraints (Mayhoub 2014). As shown in Figure 14, buildings designed with hybrid daylighting systems must install multiple solar collection points throughout the outer building facade in order to ensure adequate lighting levels are received within the building's interior spaces.

Figure 14. Example of a hybrid daylight system schematic

Source: Mayhoub (2011)

2.4.3.3 Resilience

Windows and skylights provide lighting to buildings during power outages during daylight hours. In addition, hybrid daylight SSL systems that concentrate and transport daylight to places not reached by windows offer increased resilience in buildings. Technologies such as fiber-optic daylighting, tubular skylights, and sun pipes provide lighting to interior spaces in buildings (without windows or skylights) during daylight hours when electricity is not available, such as a power outage. This can provide increased safety and productivity to building occupants during daylight hours. Because the hybrid daylight system combines both daylighting and electric lighting via integrated LED sources, it has the potential to offer greater flexibility in how light is distributed and provided to interior spaces. In addition, if combined with PV solar and energy storage,[36] the hybrid daylight system could also reduce electric load to the grid, providing increased resilience to the building during electric power outages and/or natural disasters (including earthquakes, hurricanes, tornadoes, and floods).

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[35] According to claims from Sunportal: http://www.thesunportal.com/sunportal_brochure.pdf.

[36] Such as the system in Tsuei et al. (2010).

2.4.3.4 Cost

Although windows and skylights are standard building components, integration with daylighting sensors and controls is a substantial expense added on to already expensive building components. Further, although hybrid daylight SSL systems that concentrate and transport daylight in buildings have been developed, few have been manufactured and commercialized. The high cost of these light guiding systems is the primary barrier that has prevented widespread commercialization and adoption of these technologies. The cost of tubular daylighting systems or sun pipes has been estimated to be 76% more expensive than an equivalent electrical system (Mayhoub 2014; Mayhoub and Carter 2011). Systems that utilize fiber-optic cables and solar concentrator lenses, such as the Swedish Parans systems, are about six times more costly than a traditional electric lighting system (Mayhoub 2014; Mayhoub and Carter 2011). The main costs of the system come from optical materials (e.g., fiber-optic cables, lenses, piping, etc.) and the complexity of the technologies used (e.g., solar trackers, integrated PV solar, etc.). In addition, the cost of the system is also dependent on the lighting level needs of the building and the light transport distance. The current high manufacturing and capital costs of the light guiding systems result in long payback periods, despite the high energy savings of 50%–75% over electric lighting systems. In 2011, one study estimated that light guiding systems have a payback period of around 20 years or more, making them uneconomical for most manufacturers and consumers (Mayhoub and Carter 2011).

2.4.3.5 Human Health

Daylighting in buildings has been shown to have numerous positive effects on human health and well-being. Daylight provides an optimal spectrum of light to the human eyes. It is composed of a balanced color spectrum peaking in the blue-green area and contains the highest levels of light needed for biological functions (Lieberman 1991; Hathaway et al. 1992). Studies examining the health benefits of daylighting have shown correlations with improved mood, enhanced morale, lower fatigue, and reduced eyestrain (Edwards and Torcellini 2002). In addition, daylighting in buildings is also associated with decreased occurrence of headaches, seasonal affective disorder, and reduced eyestrain (Franta and Anstead 1994). Most traditional electric light sources cannot match the spectral distribution of daylight (Hathaway et al. 1992); however, newer LED lighting products can be designed to emit almost any spectrum of visible light. Commercial LED products such as the Philips Hue and specialty products such as the Telelumen Light Replicator can provide active control of the emitted spectrum with varying degrees of spectral resolution and intensity control, though these products have significantly higher capital costs (Pattison et al. 2017). Therefore, combining the natural daylight access and LED integration enabled through hybrid daylight SSL systems has the potential to improve human health within the built environment.

Additional studies have also shown evidence that exposure to daylighting has positive effects on productivity and sleep cycles. A study of 90 Swedish elementary school students found that classrooms without daylighting disrupted hormones levels, which can influence children's ability to concentrate or cooperate (Kuller and Lindsten 1992). Another study of 21,000 U.S. students in three school districts found that students in California with the most daylighting in classrooms progressed 20% faster on math tests and 26% faster on reading tests in comparison to students with the least daylighting, and students in Washington and Colorado with greater exposure to daylight had 7% to 18% higher test scores than those with the least (Heschong Mahone Group 1999). One study of office workers found that workers near windows experienced increased physical activity, better sleep quality, and longer sleep durations (Boubekri et al. 2014).

2.5 Challenges and R&D Opportunities

Connected lighting systems are an emerging and rapidly developing technology area. As discussed in Section 2.2.1, the technologies proposed in this report are all variations of connected lighting systems that enable grid interactions and services and operate through SSL technology as the electric light source. These technologies face technological challenges that inhibit their performance and/or market adoption. Further, technology gaps exist in which novel research is needed to bring new technology capabilities to the market. This section identifies and discusses these key attributes and technical characteristics that need to be improved for each technology to better provide grid services. Based on the identified challenges, R&D pathways are proposed that can potentially enable each technology to better serve the grid and/or increase the market adoption. This section focuses on the two medium- and high-potential lighting technologies identified in Section 2.3.3—advanced sensors and controls and hybrid daylight SSL systems. The purpose of this section is to identify R&D opportunities that relate to each technology's ability to provide grid services beyond energy efficiency alone and/or to address market barriers. For more information on energy efficiency R&D pathways in SSL and connected lighting technologies, refer to the 2018 Solid-State Lighting R&D Opportunities report (Pattison et al. 2019).

2.5.1 All Connected Technologies

All internet-connected technologies in buildings with data communication and control capabilities face common challenges, including interoperability, cybersecurity, and cost barriers. Many of the challenges identified here apply to connected lighting and consumer electronics/IT equipment technologies, as well as other connected building technologies including HVAC equipment, appliances, water heaters, electronics, and connected controllers. For more information on interoperability and cybersecurity challenges facing all connected technologies, refer to the *Whole-Building Controls, Sensors, Modeling, and Analytics* report.

Interoperability. Interoperability is the ability of devices or software systems to reliably and consistently exchange data. This is a key technical and market barrier to connected technologies providing grid services (U.S. Department of Energy 2015). Interoperability relies heavily on communication within the building as well as between buildings and the grid (Hale et al. 2018). GEBs involve numerous previously separate industries—HVAC, lighting, envelope, electronics, water heating, major appliances, DERs, IT and network security, controls vendors, and utilities—that have developed their own communication approaches and protocols. Accordingly, there is little incentive for competing device/system manufacturers to develop interoperable devices and systems because developing proprietary hardware/software forces consumers to purchase all products from a single vendor. Developing common interoperable platforms and communication protocols is critical to maximizing grid service provision and ensuring that vendor lock-in does not curtail consumer interest in connected technologies.

Electronic telecommunication is typically thought of as a hierarchy of protocols operating at different layers. Interoperability requires compatible protocols within a given layer and all of the layers below. At the bottom of the hierarchy are physical data layers, which define the physical medium and the properties of signals that are exchanged on it (e.g., ethernet, Wi-Fi, Bluetooth). Several industry organizations are working to support increased interoperability at this layer through common communication protocols and established standards, including the Open Connectivity Foundation, the TALQ Consortium, oneM2M, Bluetooth special interest group, the Industrial Internet Consortium, and the Zigbee Alliance. In the middle are network layers, which define the form, routing, and delivery of messages (e.g., Transmission Control Protocol/Internet Protocol, Secure Sockets Layer/Transport Layer Security). On top are application layers, which define the internal structure and semantics of the messages being sent (e.g., BACnet and Project Haystack, respectively).

GEB technology telecommunication protocols do not map cleanly to these layers, but most activity takes place at and above the application layers, leveraging common data and networking protocols like Wi-Fi, Transmission Control Protocol, and Transport Layer Security. Common data models are also critical to ensuring interoperability between devices; however, at the level of an individual device or technology, because it only needs to model itself, the common data model is less critical and therefore not discussed at length. Research is needed to support the development and adoption of standardized semantic and syntactic specifications for connected devices and software systems. Standardized semantic and syntactic specifications have the potential to reduce deployment costs and increase adoption of connected technologies.

Cybersecurity. Cybersecurity is the process of enabling appropriate confidentiality of information, integrity of that information and the devices on which it resides, and availability of devices and information when needed. For an interaction between a building and grid, a cybersecure service would be delivered such that only the building and the service aggregator or utility would know (1) what service is being provided and when, (2) that the measurement and verification information is accurate, and (3) that devices that support service delivery and measurement and verification are available when needed. Cybersecurity is necessary for data privacy and critical for communication network reliability.

As more and more devices and software systems interconnect and interact, a vulnerability in one component can provide backdoor access or compromise other systems on the same network. Such vulnerabilities can even lead to impacts on corporate enterprise IT systems, slow digital business processes, or even cause them to cease operating altogether. In addition, connected, major end-use loads could provide access points to the greater electric grid. Previous cyberattacks have demonstrated the ability to damage or compromise targeted hardware equipment, though this requires significantly greater skills, time, and system knowledge (Langner 2011; Lika et al. 2018).

Cybersecurity must be implemented at multiple logical levels, from individual devices to systems, whole buildings, service aggregators, and the grid. As such, some system architectures are more compatible with cybersecurity than others. Further development is needed to integrate end-to-end data security. Research is needed to support the adoption of secure system architectures and cybersecurity best practices. Promoting cybersecurity reduces a major risk associated with digital automation and has the potential to increase adoption of connected technologies.

Currently, DOE and Pacific Northwest National Laboratory are collaborating with Underwriters Laboratory and other Industrial Internet Consortium members of a Security Claims Evaluation Testbed to help develop test methods for cybersecurity vulnerabilities in connected lighting (Pattison et al. 2019). DOE also plans to conduct studies to evaluate the cybersecurity vulnerabilities in connected lighting, and perhaps the effectiveness of strategies and technologies for addressing them (Pattison et al. 2019).

High Cost. Current high product and installation costs for many connected technologies represent a significant barrier to widespread adoption. Payback periods for additional sensors, controls, software, and commissioning may be too long to justify the added cost (without incentives). Further, additional communication components and software are needed to enable grid interactivity. Currently, grid-interactive systems are considered premium products with prohibitively high costs for many residential consumers and commercial building owners, though this is often a result of the inclusion of many high-cost features that are not required for grid interactivity.

Research is needed to develop manufacturing processes that have low capital costs or can use existing manufacturing equipment with minimal investment in tooling or reconfiguration. Further, there is a need to develop materials and technologies compatible with scalable manufacturing methods that enable increasing production volumes without incurring linearly increasing capital costs.

2.5.2 Advanced Sensors and Controls

Demand Response Protocols and Control Algorithms. Demand response and building peak demand-side management for lighting is still emerging and is not widely adopted. The 2012 Commercial Buildings Energy Consumption Survey estimated that demand responsive lighting is only implemented in about 4% of commercial buildings (EIA 2012), while these technologies are essentially nonexistent in the residential sector. A 2018 survey of 155 U.S. utilities found that only 8 utilities reported that commercial and industrial customers enrolled in automated demand response utilize lighting, in comparison to 23 utilities utilizing HVAC (Chew et al. 2018).[37]

Load shedding in connected lighting systems can be used for automated demand response and/or building peak demand-side management, though providing grid services through automated demand response requires grid-responsive communication. When using connected lighting controls to provide grid services, an important

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[37] Not all utilities that have automated demand response programs responded to this survey question.

consideration is the input demand response signal that is received and the resulting output and load curtailment at the lighting luminaire or lamp level. Regulators have yet to specify the single, uniform, standards-based demand response signals that provide a consistent sequence of operations that building owners and operators should follow for their lighting systems (Jackson 2017). In addition, there is no standard testing procedure that has been established for lighting demand response. As such, lighting systems are rarely optimized for demand response capabilities. Because of the lack of both utility incentives and regulatory drivers, lighting manufacturers have not prioritized automated demand response solutions for use with their lighting control systems. This lack of industry focus and incentives has left many unanswered questions.

First, minimal research has been done to optimize the implementation of automated demand response or building peak demand-side management control algorithms for lighting systems. Connected lighting systems have the potential to provide shedding and modulation because of the quick response capability of lighting. However, because lighting systems are critical loads in occupied spaces, lighting systems cannot be turned or rapidly modulated to provide grid services or building peak demand-side management. Connected lighting controls may be used to shed or modulate lighting loads, but the power reduction is limited to levels that are not disruptive to occupants. For load shedding, results from case studies and demonstration projects vary, and there is a lack of consensus on the appropriateness of dimming “depth” and power reduction levels. For load modulation, some researchers have proposed that lighting could act as a frequency regulation or ramping resource because of the quick response capabilities of SSL technology, but the overall potential and benefits are still unclear.

The opportunity for lighting to provide grid services or building peak demand-side management in buildings will also vary the building type, building activity, and building design. More research is needed to understand how the types and quantity of lighting manipulations (dimming, spectrum, power features, etc.) can be curtailed or modulated by advanced lighting controls without causing occupant harm or declines in productivity. This research should answer not only the appropriateness of various lighting curtailment protocols, but also the signaling and sequence of operations that regulators use to communicate how advanced lighting controls within a building will respond. Comprehensive research is needed to both quantify the potential of modulating power-consuming features (e.g., spectrum, reduced sensor, and network interface power) and determine the optimal control algorithms (e.g., the magnitude and speed of controls) for maximizing grid services/building peak demand-side management while minimizing occupant impact. Research is needed to develop novel control algorithms that leverage data analytics to automatically customize strategies according to the needs and preferences of the occupants and building owners. In addition, more research is needed to understand the impact to occupants from lighting systems providing load shedding and modulating.

Sensors Integration. Although many products for controlling lighting have been commercially available for quite some time, their deployment and resulting energy savings have been limited because of their complex configuration, high cost, limited interoperability among devices from competing manufacturers, and a narrow range of people who know how to efficiently design, install, commission, and operate them. However, SSL products are poised to unlock the potential of advanced sensors and controls because of their unprecedented controllability and increasing degrees of automated configuration. Sensors integrated directly into the LED lamp or luminaire is an emerging technology area enabled by the miniaturization and cost reduction of sensors. The integration of sensors into lighting devices allows for better data communication and demand response capabilities necessary to provide many grid services, and it has been shown to increase the likelihood that building owners/operators will continue to utilize (and not disable) advanced control features, such as daylight harvesting, occupancy detection, demand response peak savings, and time-of-day dimming scheduling (Pattison et al. 2017). Additionally, integrated sensors allow for more granular control and reduce the complexity of the lighting system, making installation easier.

The integration of existing and new sensor functionality into smaller and lighter form factors at the luminaire level is an emerging area in connected lighting. As such, research is needed to optimize techniques, design, and methods for embedding sensors directly in lamp/luminaires to enable multiple methods of control. In addition, more research is needed to improve signal-processing techniques to reduce the error margin within the sensing range and increase the task-specific ability of the sensors. Such improvements enable greater accuracy and density of sensor networks in the building, which in turn will enable increased granularity and flexibly when controlling lighting or other connected building technologies within the system (through data sharing with building automation systems).

2.5.3 Hybrid Daylight SSL Systems

Efficiency of Lighting-Guiding Materials. Though lighting systems that concentrate and transport daylight have existed for decades, adoption has been stagnant. One reason for this is the inefficiency of light-guiding materials and systems. Many of these systems have limited light transport distances (typically about 20 meters or 5 levels) and excessive light losses. For example, plastic optical fibers have been shown to have output efficiencies of only 19% and 17% for 10- and 20-meter fiber-optic cable distances, respectively (Lingfors and Volotinen 2013b). Though silica optical fibers have shown lower losses and high heat resistance, they are prohibitively expensive (up to five times greater than plastic optic fibers) and less flexible, making them difficult to install and weaker than plastic optical fibers (Vu and Shin 2016; Ullah and Whang 2015). Other light-guiding materials such as sun pipes can transport daylight up to 40 meters, but they are limited by installation difficulty because the pipes are inflexible and a bigger pipe diameter is needed (Mayhoub 2014). While some manufacturers offer solutions with high transmission rates, claiming maximum daylight transport distances as great as 200 meters, the cost is prohibitively high and these products lack third-party verification and performance testing.[38] In addition, light transmission efficiency can be significantly impacted by precipitation of particulates (dust, smoke, etc.) and the condensation of water vapor on the light guide and optical materials (Mayhoub 2014). The design of hybrid daylight SSL systems needs to consider all facets of material efficiency losses to ensure that this technology offers consistent and persistent grid services.

High Cost. The current high manufacturing and capital costs of hybrid daylight SSL systems result in long payback periods, despite the high energy savings of 50%–75% over traditional lighting systems.[39] In 2011, one study estimated that daylight guiding systems have a payback period of around 20 years or more (Mayhoub and Carter 2011), making them uneconomical for most manufacturers and consumers. The cost of tubular daylighting systems or sun pipes has been estimated to be 76% more expensive than an equivalent electrical system, while systems including fiber-optic cables and solar concentrator lenses, such as the Swedish Parans systems, are about six times more costly than traditional electric lighting systems (Mayhoub 2014; Mayhoub and Carter 2011). The main costs of the system come from optical materials (e.g., fiber-optic cables, lenses, piping, etc.) and the complexity of the technologies used (e.g., solar trackers, integrated PV solar, etc.). In addition, the installation of hybrid daylight SSL systems can be very difficult in existing buildings, causing total capital costs to increase substantially. Systems using flexible fiber-optic cables offer increased installation flexibility, while systems using light ducts are more rigid and space intensive, which can make retrofit installations challenging and costly (Mayhoub 2014). In general, hybrid daylight SSL systems are better suited for new construction so they can be incorporated in the building design process. More research is needed to develop higher-efficiency light-transmitting systems at lower costs and technology payback periods.

Integration with LED Systems. Though lighting systems that concentrate and transport daylight exist in a variety of forms, few have been able to commercially integrate them in LED lighting systems to provide seamless and consistent high-quality lighting for building occupants. The hybrid daylight system requires more complex technology integration, including photosensors and automated dimming controls that can adjust electric lighting output in response to changing daylight availability to maintain consistent lighting output and spectrum so that changes between electric lighting and daylighting are not noticeable to occupants. Currently,

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[38] For more information, see SunPortal's brochure: http://www.thesunportal.com/sunportal_brochure.pdf.

[39] See Section 2.4.3.1 for more details on this estimate of energy savings.

very few commercially available systems offer this integrated strategy.[40] Research and demonstration is needed to further optimize the design of hybrid daylight SSL systems.

Load Modulation Benefit Quantification. Integrating daylight-concentrating technology with LED lighting systems and the appropriate controls enables the potential for quick response grid services, such as frequency regulation and ramping services. Lighting loads can be rapidly shifted from daylight to LED light in response to grid signals, potentially without impacting the lighting output, when adequate daylight is available. However, this technology has not been developed, proven in practice, or proposed for grid service purposes. Thus, the overall feasibility, potential, and benefits are unclear.

As such, research is needed to develop prototype hybrid daylight system products that are designed to autonomously respond to grid signals within seconds/subseconds. In addition, studies that identify the use cases as well as measure and verify these potential frequency regulation and ramping benefits are essential to determining the viability of this grid service.

Demand Response Protocols. Hybrid daylight SSL systems have never been developed specifically to respond to grid/pricing service signals for load shedding or modulation. As such, research is needed to develop protocols for these events, integrated controllers, as well as drivers and power supplies that enable the LED lighting system to seamlessly switch between daylight and LEDs (only when adequate daylight is available) or dim electric lighting in response to grid/pricing signals without impacting occupancy comfort, productivity, or overall well-being. In addition, research could explore uses for the concentrated daylight when LED lights are in use or when lighting is not needed (unoccupied spaces); for example, systems could be paired with solar PV cells and batteries to generate and store electricity for later use.

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[40] For more information, see the SunCentral System web page: http://suncentralinc.com/.

3 Electronics

This section of the report focuses on the grid service potential from consumer electronics and IT equipment technologies, which are a subset of miscellaneous electrical loads (MELs) in buildings. MELs represent electricity consumed by end uses that fall outside core building functions of HVAC, water heating, refrigeration, and lighting (Sofos 2016). MELs outside of electronics and computing are covered in the *HVAC; Water Heating; Appliances; and Refrigeration* report. Historically, DOE has focused energy efficiency initiatives on core building functions because they have traditionally constituted the majority of building energy consumption. However, as the energy efficiency of core loads has improved, the proliferation and energy consumption of MELs have increased.

The EIA 2019 Annual Energy Outlook forecasts MELs to increase both their share and magnitude of total building energy consumption through 2050. Figure 15 compares EIA's 2019–2050 forecast of delivered electricity (quads) between core loads and MELs in residential and commercial buildings.[41] Together, MELs account for nearly 50% (161 quads) of forecasted delivered electricity consumption in residential and commercial buildings for this period. In 2018, consumer electronics/IT equipment alone consumed approximately 10% and 23% of residential and commercial site electricity.[42]

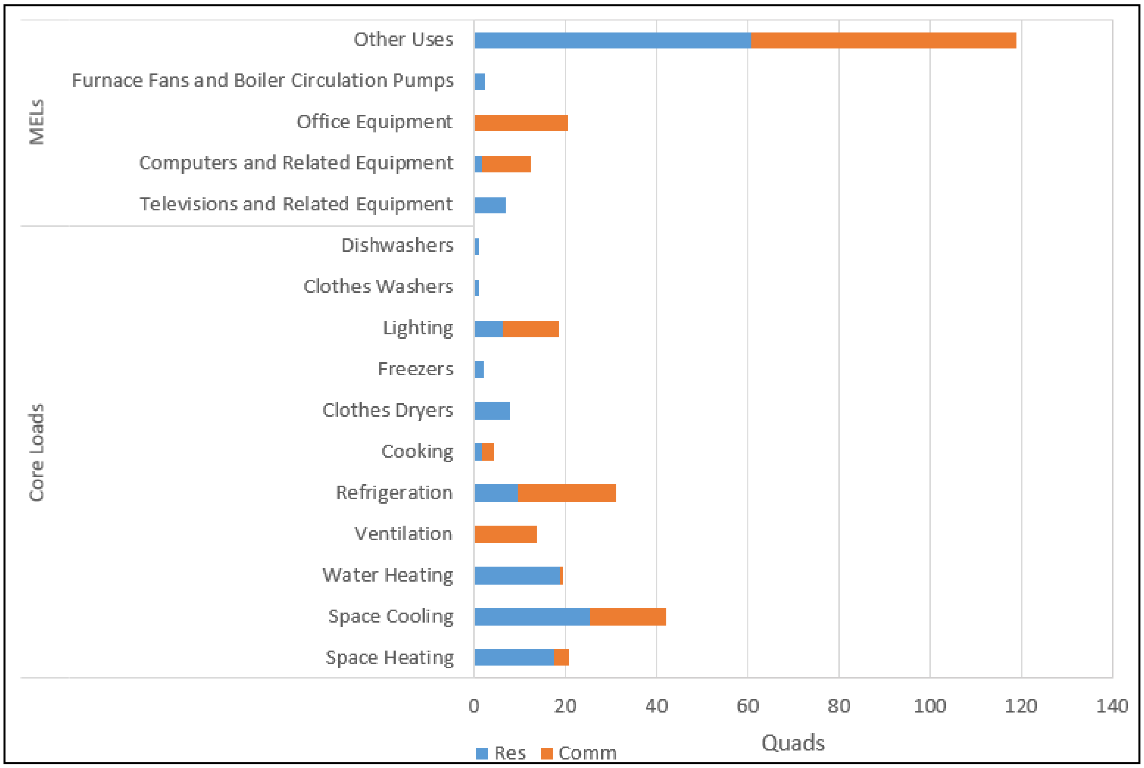

Figure 15. Forecasted residential and commercial building delivered electricity consumption (quads) by end-use category (2019–2050)

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[41] The following EIA end-use categories were assigned as MELs: televisions and related equipment, computers and related equipment, office equipment, furnace fans and boiler circulation pumps, and other uses.

[42] See Section 1.4 for more information.

3.1 Current Electronics State-of-the-Art

The rapid growth of consumer electronics, data centers, and related IT equipment makes electronics an increasingly viable candidate to provide grid services such as energy efficiency and demand response. Energy efficiency regulations and ENERGY STAR® requirements have led to energy savings and efficiency improvements in consumer electronics and IT equipment. Demand response programs today tend to focus on large industrial equipment and HVAC systems, whereas consumer electronics and IT equipment are typically not used to provide demand response or any other grid services outside of energy efficiency. In addition, these technologies are not currently manufactured to provide automated demand response, though direct load control can be enabled through smart plugs, connected smart strips, load control switches, and home hubs. For instance, TP-LINK Smart Plugs paired with any plug device can work with OhmConnect, a voluntary demand response incentive program available in California, Texas, and Ontario.[43] These smart plugs allow the consumer electronics/IT equipment to shed or shift energy use. In addition, staging of electronics equipment in commercial and industrial facilities may be used for building peak demand-side management to reduce billing demand charges.

The primary market for grid-interactive consumer electronics and IT equipment is large commercial office buildings and data centers, in which significant portions of the building loads come from computing, electronics, network equipment, and data storage. In this section, consumer electronics/IT equipment technologies are evaluated based on their technological potential to provide grid services through efficiency, shedding, shifting, and modulation of loads. For the purposes of this evaluation, consumer electronics/IT equipment technologies are bucketed into three categories:

- **Continuous-Operation Electronics**: Stationary computing devices and IT equipment used for computing, data storage, network supply, and related purposes, and that require constant power supply and often network connection to operate.
- **Battery-Powered Electronics**: Computing devices and IT equipment that are powered by an integrated rechargeable battery and that require a charger connected to a power supply.
- **Electronic Displays**: Electronic equipment with integrated lighting (OLEDs or LEDs) used for display purposes that requires a constant power supply to operate.

Table 7 provides additional details on the three technologies categories, including a breakdown of individual types of equipment included, example types, and their energy use patterns. Unlike many other building loads, consumer electronics/IT equipment have significant variance in their energy use patterns and user profiles, which affects their capability to provide demand-side management strategies, as discussed in Section 3.2. Because some technologies do not fit neatly into one category, simplifying assumptions were made. In addition, technologies listed serve as key examples in each category and are not meant to be comprehensive of all possible consumer electronics and IT equipment technologies.

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[43] For more information, see OhmConnect's web page: https://www.ohmconnect.com/.

Table 7. Current Consumer Electronics/IT Equipment Technologies

Adapted from ENERGY STAR data and specifications for office equipment and electronics.[44]

Continuous-Operation Electronics			
Technology	**Definition**	**Example Types**	**Typical Energy Use Patterns**
Network Equipment	IT equipment that allows users to connect to the internet or connect to other devices on a network	Cable and digital subscriber line (DSL) modems, optical network devices, cable and DSL access devices, routers, and switches	Tends to be on all the time and uses about the same amount of energy, regardless of activity
Set-Top Boxes	A cable, satellite, internet protocol, or other device that receives audio/video signals and delivers them to a display or recording device	Cable digital television adapter, and cable, satellite, or thin client/remote	Most tend to be on all the time and consume nearly the full level of power even when not in use; some have auto-power-down features that turn off after a period of inactivity
Stationary Computers	Electronic equipment for computing purposes without integrated batteries; require constant power supply when in use (nonportable)	Desktop personal computers, integrated desktops, workstations, and gaming consoles	Most computers can operate in multiple modes of operation (off, sleep, idle) and many also have power management features
Servers	A computer/computing system that provides services and managed networked resources for devices (computers, wireless devices, network devices, etc.); often used in data centers and offices	Computer server, blade system, multinode, and server appliance	Always on/consuming power, but most can operate in low power modes (idle)
Audio and Video (AV) Equipment	Electronic equipment offering audio amplification and/or disc player functions without integrated batteries	Speakers/soundbars, smart speakers/assistants, amplifiers, AV receivers, digital media players (e.g., Roku, Amazon Fire stick), Blu-ray disc players, and DVD players	Typically always on/consuming power and many can operate in low power modes (sleep, idle) or standby modes

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[44] For more information, see ENERGY STAR energy efficient products: https://www.energystar.gov/products?s=mega.

Battery-Powered Electronics			
Technology	**Definition**	**Example Types**	**Typical Energy Use Patterns**
Portable computers	Electronic equipment for computing purposes with integrated rechargeable batteries, allowing it to operate without constant power supply (portable)	Laptop personal computers, tablets, smart phones, e-readers, and handheld game consoles	Most laptop computers can operate in multiple modes of operation (off, sleep, idle) and many also have power management features. These technologies are generally designed to run efficiently so they can run on a battery for many hours. Charging cycles or batteries could potentially be used for grid services.
Uninterruptible Power Supplies (UPS) Battery Backups	UPS battery backups provide power to protect vital connected equipment (computer, servers, telecommunications equipment) from power outages	Voltage and frequency dependent, voltage independent, and voltage and frequency independent	Typically always on/consuming power and discharged as needed; some have low power mode
Miscellaneous	Wireless electronic equipment with integrated rechargeable batteries used for purposes other than computing	Speakers, smart watches, wireless headphones, etc.	Charged as needed or directed by users

Electronic Displays			
Technology	**Definition**	**Example Types**	**Typical Energy Use Patterns**
Signage Displays	Electronic displays used to show information, menus, advertising, or videos	Electronic billboards, video walls, menu boards, and flight information monitors	Generally always on/consuming power and able to automatically dim brightness to reduce power; some may operate in idle/standby mode when not in use (e.g., menu boards)
Computer monitors	Electronic monitor used with a computer but without integrated computing capabilities	Liquid crystal display, LED, and OLED	Typically on as needed and can switch to low-power modes or auto power down; able to automatically dim brightness to reduce power
TVs	Display used to transmit dynamic video and sound	Liquid crystal display, plasma, and OLED	Typically on as needed and can switch to low-power modes or auto power down; able to automatically dim brightness to reduce power

3.2 Evaluation of Technologies

3.2.1 Evaluation of Technology Characteristics

In this section, the three identified types of electronics technologies are evaluated based on their ability to provide grid services (see Table 3). In general, building technologies can provide these grid services through demand-side management strategies: efficiency, shedding, shifting, or modulating loads. In Table 8, each technology is given a rating based on its capability to provide grid services through demand-side management strategies. These ratings are *qualitative* and are based on estimated theoretical technological potentials, available research studies, and expert guidance. No lab testing or experimental pilot tests have been performed as part of this evaluation. For more information on the technology evaluation criteria and capability ratings, refer to Sections 2.3.1 and 2.3.2 in the lighting section of the report.

Table 8. Evaluation of Consumer Electronics/IT Equipment Technologies and Demand-Side Management Strategies

<table>
<tr><th>Technologies</th><th>Efficiency</th><th>Load Shed</th><th>Load Shift</th><th>Modulate</th><th>Overall Potential</th></tr>
<tr><td>Continuous-Operation Electronics</td><td>●</td><td>◑</td><td>○</td><td>◑</td><td>High</td></tr>
<tr><td colspan="6">• Power management controls can automatically transition computers and electronics into low-power modes as well as automatically power-down devices after periods of inactivity
• Power scaling by computing task can decrease power draw for specific operations so full computing power is not utilized for less sophisticated computing tasks (e.g., game console streaming video)
• Sleep/idle/off power modes allow devices to draw a fraction of energy use while powered down to idle/off when not in use
• Deep sleep, minimal-latency mode for networked computers and electronics can allow devices to stay connected for activation (e.g., wake-on-LAN) while using a fraction of typical power
• Computers and electronics in continuous connectivity (e.g., servers) can potentially modulate or shed loads
• Staging of large electronics loads can be used to avoid spikes in building demand</td></tr>
<tr><td>Battery-Powered Electronics</td><td>◑</td><td>○</td><td>◐</td><td>◑</td><td>Medium</td></tr>
<tr><td colspan="6">• Portable electronics powered by batteries and external power supplies can shift charging cycles to off-peak periods or rapidly modulate charging while plugged in
• Portable computers can be used for staging loads to avoid peak demand charges
• Sleep/idle/off power modes allow devices to draw a fraction of energy use while powered down to idle/off to potentially provide efficiency/shedding
• UPS battery backups in continuous connectivity could potentially shift/modulate loads
• Battery-powered equipment is generally already designed for efficiency to increase battery life</td></tr>
<tr><td>Electronic Displays</td><td>●</td><td>◑</td><td>○</td><td>○</td><td>Low</td></tr>
<tr><td colspan="6">• Power management opportunities for dimming, automatic brightness control, auto power-down, and occupancy sensing to transition into low-power states
• Emerging technologies to improve energy efficiency include OLEDs, quantum dots, and reflective polarizer
• Dimming could be used for shedding in limited capacities that do not impact viewing abilities</td></tr>
</table>

○ **Not Applicable** ◑ **Low Capability** ◐ **Medium Capability** ● **High Capability**

3.2.2 Evaluation Results

The high-, medium-, and low-potential consumer electronics/IT equipment technologies are listed in Table 9. These potential levels correspond to each technology's capability to provide the grid services through the demand-side management strategies. These potential rankings are relative to other consumer electronics/IT equipment technologies and are not meant to be compared to other building technologies (e.g., lighting, HVAC, appliances, etc.), which may have lesser or greater overall potential to provide energy savings, building/grid peak demand savings, and other grid services.

Table 9. Consumer Electronics/IT Equipment Evaluation Results

High Potential	Medium Potential	Low Potential
• Continuous-Operation Electronics	• Battery-Powered Electronics	• Electronic Displays

High Potential. Continuous-operation electronics have the highest relative potential to provide grid services because equipment in this category (e.g., desktop computers, servers, network equipment) tend to be consistently connected to a power supply and on most/all hours of the day. The greatest opportunity for demand-side management is through energy efficiency by utilizing low-power/standby modes, deep sleep, or power scaling. In addition, grid-responsive servers in data centers and offices also have the potential to provide load shedding and/or fast modulation. For building peak demand-side management, staging of these consumer electronics/IT equipment loads can be employed when they are being turned on to avoid spikes in building demand.

Medium Potential. Battery-powered electronics have moderate relative potential to provide grid services. Because much of the equipment in this category is designed to be portable (laptop computers, smart phones, e-readers, tablets, etc.), energy use patterns are highly variable. In addition, these technologies are typically already designed efficiently to maximize battery life. Grid-responsive technologies that are connected to a power source could potentially shift their charging cycles to align with off-peak periods or to allow for load staging to avoid building peak demand charges. The batteries could also potentially quickly modulate charging to provide fast response services. However, as these loads are generally smaller and portable (often disconnected from the grid), they are not ideal candidates for load shifting and modulating. UPS battery backups, however, have greater potential for load shifting and modulating because they are generally always on and account for substantial loads in office buildings.

Low Potential. Electronic displays have the lowest relative potential to provide grid services. Computer monitors and TVs have little potential for providing demand response because they are generally only used when needed. However, electronic displays provide efficiency through dimming, automated brightness controls, occupancy detection, and emerging backlighting technologies (OLEDs, quantum dots, etc.). Signage displays could potentially shed loads through dimming, though they are restricted to levels that do not compromise viewing capabilities.

3.3 Challenges and R&D Opportunities

The potential for consumer electronics/IT equipment technologies to provide grid services faces several key technological challenges that are outlined in the following subsections. These challenges and R&D opportunities were developed based on input from researchers and electronics technology experts. Additional R&D needs related to control capabilities will be discussed in the *Whole-Building Controls, Sensors, Modeling, and Analytics* report. An overview of the challenges facing all connected technologies, including consumer electronics/IT equipment—cybersecurity, interoperability, and cost—is available in Section 2.5.1.

3.3.1 Communication

Electronics need to communicate seamlessly in a multivendor environment, adapting to changes in communications technologies, exchanging messages reliably, and functioning in an interoperable plug-and-play manner (Butzbaugh et al. 2017). Further, communication protocols and architecture are needed to allow electronics to receive and respond to grid/pricing signals. Communication hubs can enable this grid communication and aggregated control of all connected devices on the network at once (assuming standardized communication protocols are in place). Whether core decision-making is dependent upon data originating from the utility or aggregator, electronics will also have to accommodate the needs, expectations, and feedback of their users (e.g., via smartphones, voice assistants, or building management systems) and complementary equipment to optimize demand-side management potential. The development of the control intelligence, particularly with the long-term vision of autonomous control, will call for extensive R&D. In addition, for these technologies to achieve widespread deployment, users will need to trust the communications and control algorithms to behave justifiably and equitably, which may call for third-party validation and reoccurring verification.

3.3.2 Consumer Impact

The loss of consumer utility during a curtailment event must be managed to acceptable levels. For example, dimming a screen or powering off a device should not significantly impact the consumer experience. The effects on product efficacy is another concern. As grid-responsive controls become prevalent, users will have the ability to determine the extent to which they are willing to forego efficacy to provide grid services, and whether this calls for an incentive or benefit in return. Opportunities for R&D include research on the relationship of consumer preferences to product functionality limitations and integrating control logic into existing algorithms to enable users to set energy rate and efficacy preferences.

4 Summary of Findings

Table 10 summarizes the primary challenges and R&D opportunities identified in Sections 2 and 3 for connected lighting systems and electronics/computing technologies. These R&D opportunities were developed based on the benefits and challenges of each technology and with input from researchers and technology experts. Based on the technology evaluation results, the R&D for advanced sensors and controls for lighting systems and continuous-operation electronics should be considered highest priority. These R&D opportunities for connected lighting systems and consumer electronics/IT equipment comprise a small portion of the GEB opportunities identified through the *GEB Technical Report Series*.

Both connected lighting systems and consumer electronics/IT equipment technologies are largely untapped resources in grid service markets today, as penetration of grid-responsive capabilities is very low. For lighting systems, significant barriers exist that limit the potential to provide grid services, including limited dimming levels for lighting load shedding, lack of OpenADR lighting products, traditional focus on HVAC and industrial loads in automated demand response industry, focus on commercial and industrial sectors for lighting demand response, and market adoption barriers for connected technologies (cybersecurity, interoperability, and high cost). For consumer electronics/IT equipment technologies, challenges and barriers limiting the potential include lack of commercially available grid-responsive technologies, highly variable energy use patterns, primary market of commercial office buildings and data centers, impacts to consumers, and market adoption barriers facing all connected technologies (cybersecurity, interoperability, and high cost).

However, as technological advances are made in connected lighting systems and consumer electronics/IT equipment, the potential to provide grid services may increase. In most circumstances today, efficiency is the greatest grid benefit that either lighting systems or consumer electronics/IT equipment can provide. Generally, more research is needed to better understand and quantify the potential for connected lighting systems and consumer electronics/IT equipment to provide grid services beyond efficiency.

Table 10. Lighting and Electronics Challenges and Opportunities

Technology	Challenges	R&D Opportunities
All Connected Technologies	Interoperability	• Support the development and adoption of standardized semantic and syntactic specifications for connected devices and software systems
	Cybersecurity	• Support the adoption of secure system architectures and cybersecurity best practices
	High Cost	• Develop manufacturing processes that have low capital costs or can use existing manufacturing equipment with minimal investment • Develop materials and technologies compatible with scalable manufacturing methods that enable increasing production volumes
Advanced Lighting Sensors and Controls	Demand Response Protocols and Control Algorithms	• Quantify the demand flexibility potential of lighting manipulations in various building types, designs, activities, and conditions • Determine the optimal communication protocols and control algorithms for maximizing grid services provided (shedding and modulating) and minimizing occupant impact • Develop novel control algorithms that leverage data and machine learning capabilities to customize strategies • Determine the impact to occupants from lighting systems providing grid services through demand flexibility (productivity, comfort, etc.)
	Sensors Integration	• Optimize techniques, design, and methods for embedding sensors directly in lamp/luminaires to enable multiple methods of control • Improve signal-processing techniques to reduce the error margin within the sensing range and increase the task-specific ability of the sensors
Hybrid Daylight SSL Systems	Efficiency of Light-Guiding Materials	• Improve design of hybrid daylight SSL systems and materials to minimize daylight transmitting losses
	High Cost	• Develop higher-efficiency daylight-transmitting systems at lower costs to decrease technology payback periods
	Integration with SSL Systems	• Optimize the design of hybrid daylight SSL systems to ensure lighting levels/spectrum are consistent and transitions from daylight to electric light are seamless • Conduct field validation studies that inform design and foundational science • Develop models to improve insights into efficiency and other value propositions for established and emerging applications
	Load Modulation Benefit Quantification	• Develop hybrid daylight system prototypes that are designed to autonomously respond to grid signals within seconds • Identify the use cases and measure/verify the potential load modulation benefits
	Demand Response Protocols	• Develop demand response protocols and integrated controllers that enable the lighting system to switch between daylight and electrical lighting seamlessly in response to grid signals
Consumer Electronics/IT Equipment	Communication	• Develop control intelligence for electronics with the long-term vision of autonomous control
	Consumer Impact	• Integrate control logic into existing algorithms to enable users to set energy rate and efficacy preferences • Research the relationship of consumer preferences to product functionality limitations

References

Bonneville Power Administration. N.D. "Emerging Technologies: Luminaire Level Lighting Controls." https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Pages/Easily-commissioned-Lighting-Controls-.aspx.

Boubekri, Mohamed, Ivy Cheung, Kathryn Reid, Chia-Hui Wang, and Phyllis Zee. 2014. "Impact of Windows and Daylight Exposure on Overall Health and Sleep Quality of Office Workers: A Case-Control Pilot Study." *Journal of Clinical Sleep Medicine*, vol. 10, no. 6, pp. 603–611. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4031400/.

Buccitelli, Nicole, Clay Elliott, Seth Schober, and Mary Yamada. 2017. "2015 U.S. Lighting Market Characterization." U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/EE-1719. https://www.energy.gov/sites/prod/files/2017/12/f46/lmc2015_nov17.pdf.

Butzbaugh, JB, ET Mayhorn, GP Sullivan, and SA Whalen. 2017. *Connected Equipment Maturity Model, Version 1.0.* Pacific Northwest National Laboratory: Richland, WA. PNNL-26413. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26413.pdf.

California Energy Commission. 2011. "Lighting the Way to Demand Response." Public Interest Energy Research Program. CEC-500-2011-FS-001. https://www.esource.com/system/files/files/2011-04/CEC-TB-47_Lighting_web_7.pdf.

Chew, B., B. Feldman, D. Ghosh, and M. Surampudy. 2018. "2018 Utility Demand Response Market Snapshot." *Smart Electric Power Alliance*. https://sepapower.org/resource/2018-demand-response-market-snapshot/.

CoeLux. 2019. "CoeLux 45 SQUARE." https://www.coelux.com/en/p/coelux-45-square-en-11.

Cori Jackson. 2017. "Commercial Lighting's Role in Automated Demand Response Programs." *The Illuminating Engineering Society*. https://www.ies.org/lda/commercial-lightings-role-in-automated-demand-response-programs/.

DesignLights Consortium. 2017. "Energy Savings from Networked Lighting Control (NLC) Systems." https://www.designlights.org/lighting-controls/reports-tools-resources/nlc-energy-savings-report/.

Edwards, L., and P. Torcellini. 2002. "A Literature Review of the Effects of Natural Light on Building Occupants." National Renewable Energy Laboratory: Golden, CO. NREL/TP-550-30769. https://www.nrel.gov/docs/fy02osti/30769.pdf.

Enlighted, Inc. by Siemens. 2018. "Enlighted Transforms Office Buildings." http://info.enlightedinc.com/rs/000-IKN-871/images/10195B-EL-Brilliant-Brochure.pdf.

Feng, Guohui, Dandan Chi, Xiaolung Xu, Baoyue Dou, Yixin Sun, and Yao Fu. 2017. "Study on the Influence of Window-wall Ratio on the Energy Consumption of Nearly Zero Energy Buildings." *Procedia Engineering*, vol. 205, pp. 730–737. https://www.sciencedirect.com/science/article/pii/S1877705817345526.

Fernandez, N., S. Katipamula, W. Wang, Y. Xie, M. Zhao, and C. Corbin. 2017. *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction*. Pacific Northwest National Laboratory: Richland, WA. Vol. 25985. https://buildingretuning.pnnl.gov/publications/PNNL-25985.pdf.

Franta, G., and K. Anstead. 1994. "Daylighting Offers Great Opportunities." Window & Door Specifier-Design Lab, Spring; pp. 40-43.

Hale, Elaine, et al. 2018. *The Demand-Side Grid (dsgrid) Model Documentation*. National Renewable Energy Laboratory: Golden, CO. NREL/TP-6A20-71492. https://www.osti.gov/biblio/1465659http://www.osti.gov/servlets/purl/1465659/.

Hathaway, Warren, John Hargreaves, Gordon Thompson, and Dennis Novitsky. 1992. *A Study Into the Effects of Light on Children of Elementary School Age—A Case of Daylight Robbery*. Alberta: Policy and Planning Branch, Planning and Information Services Division, Alberta Education.

Heschong Mahone Group. 1999. "Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance." Pacific Gas and Electric Company. http://h-m-g.com/downloads/Daylighting/schoolc.pdf.

Hutchinson, Lois. 2018. "DC Lighting: Empowering Our Digital Future." *West Coast Lighting Insider*, Aug. 2018. https://www.lightshowwest.com/dc-lighting-empowering-our-digital-future.

Jackson, Cori. 2017. "Commercial Lighting's Role in Automated Demand Response Programs." *LD+A Magazine*, Aug. 2017. https://static1.squarespace.com/static/59596ef4be6594dbcf0626ad/t/5a5d34b2f9619a9a19355146/1516057781340/Commerical+Lightings+Role+in+Automated+Demand+Response+Programs.pdf.

Kiliccote, Sila, Daniel Olsen, Michael Sohn, and Mary Ann Piette. 2016. "Characterization of Demand Response in Commercial, Industrial, and Residential Sectors in the U.S." *WIREs Energy Environ.*, vol. 5, pp. 288–304. https://onlinelibrary.wiley.com/doi/full/10.1002/wene.176.

Küller, Rikard, and Carin Lindsten. 1992. "Health and behavior of children in classrooms with and without windows." *Journal of Environmental Psychology*, vol. 12, no. 4, pp. 305–317. https://www.sciencedirect.com/science/article/abs/pii/S0272494405800799.

Langner, Ralph. 2011. "Stuxnet: Dissecting a Cyberwarfare Weapon." IEEE Security Privacy 9.3, pp. 49–51. ISSN: 1540-7993. DOI: 10.1109/MSP.2011.67.

Liberman, J. 1991. *Light Medicine of the Future*. New Mexico: Bear & Company Publishing.

Lika, Reyner Aranta, Danushyaa Murugiah, Sarfraz Nawaz Brohi, and Daksha Ramasamy. 2018. "NotPetya: Cyber Attack Prevention through Awareness via Gamification." *IEEE*. https://ieeexplore.ieee.org/document/8538431.

Lingfors, David, and Tarja Volotinen. 2013b. "Illumination performance and energy saving of a solar fiber optic lighting system." *Opt. Soc. Am.*, vol. 21, no. S4. https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-s4-a642.

Maxwell, Krystal, Benjamin Freas, and Neil Strother. 2017. "IoT for Lighting: IoT Lighting Solutions: Hardware, Software, and Services in Commercial Buildings." Navigant Research. https://www.navigantresearch.com/reports/iot-for-lighting.

Mayhoub, M.S. 2011. "Hybrid Lighting Systems: Performance, Application and Evaluation." DOI: 10.1177/1477153511416324.

Mayhoub, M.S. 2014. "Innovative daylighting systems' challenges: A critical study." *Energy Build.*, vol. 80, pp. 394–405. https://doi.org/10.1016/j.enbuild.2014.04.019.

Mayhoub, M.S. and D.J. Carter. 2011. "The costs and benefits of using daylight guidance to light office buildings." *Building and Environment*, vol. 46, no. 3, pp. 698–710. https://www.sciencedirect.com/science/article/pii/S0360132310002921.

Newsham, Guy, and Mary Ann Piette. 2014. "Demand-Responsive Commercial Buildings." https://nrc-publications.canada.ca/eng/view/accepted/?id=c52b4228-e3e2-4b91-986d-dbba8ba72946.

Pacific Gas and Electric Company. 2016. "Title 24 Demand Response Requirements." http://pge-adr.com/title-24/.

Pattison, Morgan, et al. 2017. "Solid-State Lighting 2017 Suggested Research Topics Supplement: Technology and Market Context." U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/EE-1658. https://www.energy.gov/sites/prod/files/2017/09/f37/ssl_supplement_suggested-topics_sep2017_0.pdf.

Pattison, Morgan, et al. 2019. "2018 Solid-State Lighting R&D Opportunities," U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/EE-1907. https://www.energy.gov/sites/prod/files/2019/02/f59/edit.ssl_rd-opportunities_jan2019..pdf

Penning, Julie, Kelsey Stober, Victor Taylor, and Mary Yamada. 2016. "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications." U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/EE-1467. https://www.energy.gov/sites/prod/files/2016/10/f33/energysavingsforecast16_0.pdf.

Penning, Julie, Seth Schober, Kelsey Stober, and Mary Yamada. 2017. "Adoption of Light-Emitting Diodes in Common Lighting Applications" U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/EE-1637. https://energy.gov/sites/prod/files/2017/08/f35/led-adoption-jul2017_0.pdf

Piette, Mary Ann, David Watson, Naoya Motegi, and Sila Kiliccote. 2007. "Automated Critical Peak Pricing Field Tests: 2006 Pilot Program Description and Results." Lawrence Berkeley National Laboratory: Berkeley, CA. LBNL-59351. https://drrc.lbl.gov/publications/automated-critical-peak-pricing-field.

Satre-Meloy, Aven, and Jared Langevin. 2019. "Assessing the time-sensitive impacts of energy efficiency and flexibility in the U.S. building sector." Environmental Research Letters. https://doi.org/10.1088/1748-9326/ab512e.

Slupik, Simon, and Simon Rzadkosz. 2018. "Commissioning connected lighting networks: Theory and practice, challenges and opportunities." *LEDs Magazine*, July 30, 2018. https://www.ledsmagazine.com/articles/print/volume-15/issue-6/features/smart-lighting/commissioning-connected-lighting-networks-theory-and-practice-challenges-and-opportunities.html.

Sofos, Marina. 2016. "Miscellaneous Electric Loads: What Are They and Why Should You Care?" U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/buildings/articles/miscellaneous-electric-loads-what-are-they-and-why-should-you-care.

Stober, Kelsey, Kyung Lee, Mary Yamada, and Morgan Pattison. 2017. "Energy Savings Potential of SSL in Horticultural Applications." U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/EE-1723. https://www.energy.gov/sites/prod/files/2017/12/f46/ssl_horticulture_dec2017.pdf.

Taylor, Ruth. 2018. *DLC Stakeholder Meeting: Connected Lighting Installations – Learning from Watching.* Pacific Northwest National Laboratory: Richland, WA. July 11, 2018. https://www.designlights.org/default/assets/File/SHM%202018/DLC_SHM-2018_NLCs-In-Action-Good-Bad-and-Awesome.pdf.

Tsuei, CH, WS Sun, and CC Kuo. 2010. "Hybrid daylight/LED illumination and renewable solar energy saving concepts for indoor lighting." *Opt. Express*, vol. 18, no. 4. DOI: 10.1364/OE.18.00A640. https://www.ncbi.nlm.nih.gov/pubmed/21165097.

U.S. Department of Energy. 2015. "2015 Quadrennial Technology Review."

U.S. Energy Information Administration (EIA). 2012. "Commercial Buildings Energy Consumption Survey (CBECS)." https://www.eia.gov/consumption/commercial/data/2012/.

U.S. Energy Information Administration (EIA). 2018. *Annual Energy Outlook 2018*. Washington, D.C. https://www.eia.gov/outlooks/aeo/.

Ullah, Irfan, and Allen Jong-Woei Whang. 2015. "Development of Optical Fiber-Based Daylighting System and Its Comparison," *Energies*, vol. 8, pp. 7185–7201.

Volotinen, T.T. and D.H. Lingfors. 2013a. "Benefits of glass fibers in solar fiber optic lighting systems." *Appl. Opt.*, vol. 52, no. 27, pp. 6685–6695. https://www.ncbi.nlm.nih.gov/pubmed/24085167.

Vu, Ngoc Hai, and Seoyong Shin. 2016. "A Large-Scale Daylighting System Based on a Stepped Thickness Waveguide." *Energies*, vol. 9, no. 71. https://pdfs.semanticscholar.org/494b/08d43ec33b40c7369fa6006837f92145b81a.pdf.

Vu, Ngoc-Hai, Thanh-Tuan Pham, and Seoyong Shin. 2016. "Modified optical fiber daylighting system with daylight transportation in free space." *Opt. Express*, vol. 24, no. 26. https://www.osapublishing.org/oe/abstract.cfm?uri=oe-24-26-A1528.

Wilkerson, Andrea, and Robert Davis. 2017. *Flexible Lighting Evaluated in Mental Health Facility*. Pacific Northwest National Laboratory: Richland, WA. Research Highlights. https://energyenvironment.pnnl.gov/highlights/highlight.asp?id=2891.

Williams, Alison, Barbara Atkinson, Karina Garbesi, and Francis Rubinstein. 2011. "A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings." Lawrence Berkeley National Laboratory: Berkeley, CA. LBNL-5095E. http://efficiency.lbl.gov/sites/all/files/a_meta-analysis_of_energy_savings_from_lighting_controls_in_commercial_buildings_lbnl-5095e.pdf.

Wojtysiak, A. 2015. "The Physiological Impact of Lighting." Presented at the DOE SSL R&D Workshop, San Francisco, CA.

Yamada, Mary, Dan Mellinger, George Lawrence, and Bill Goetzler. 2018. "Lighting Isn't Finished: Pivoting beyond the LED Bulb." ACEEE Summer Study 2018. http://energyfuturesgroup.com/wp-content/uploads/2019/05/Lighting-Isnt-Finished-Pivoting-Mellinger.pdf.

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