Digitization, Standards and Interoperability: Lighting as a Team Player

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ABSTRACT

The rapid significant energy savings from light-emitting diode (LED) technology has led many within the buildings community to believe that lighting offers no additional opportunity beyond the conversion to LED technology. Savings from lighting controls has lagged, partially because advanced lighting controls have typically been proprietary and/or analog. Recent advances in digital lighting technology and open protocols/standards offer an opportunity to break through longstanding technology silos and realize the value of lighting beyond efficiency and reduced load. This paper closes the lighting knowledge gap in relationship to multiple climate change goals by addressing specifics about technology, standards, use cases, market drivers, and value propositions. Standards such as DALI-2®, D4i®, DALI+® and Zhaga® books 18 and 20 enable digitally addressable two-way communication and interoperable components. These benefit building owners and managers by mitigating the risk of vendor-locked controls and improving maintenance, choice, cost, reliability, circularity, and forward compatibility. Standardized data includes real-time light output and energy monitoring, fault detection, diagnostics, digital color control, and remote testing for emergency lighting. This information provides the foundation for digital integrations with HVAC systems, building automation and space management platforms, granular energy monitoring and control, hybrid workplaces, and more. When used with occupant location and space type data, artificial intelligence and software platforms can deploy peak load management to support interactive grid strategies. Financial considerations are discussed along with electrification, low-voltage and DC-DC (direct current) lighting, distributed energy resources, and grid-interactive energy efficient buildings. This paper will dispel common myths to put lighting back into the suite of options to further climate change goals.

Introduction

Within the energy efficiency and environmental industries/community, the interest in lighting since 2005 has been the market adoption of solid-state lighting, primarily in the form of LED (light-emitting diode) light sources. By 2020, LED penetration increased to 16 times the levels in 2010 in commercial buildings (DOE 2012, 2024a). Many of the technology, production, and design challenges have been addressed and the prevalence of LEDs in the marketplace has resulted in dramatic cost reductions. Market penetration of LED retrofits into existing buildings is thought to be 40 to 50%. Since 2019, LEDs are the primary light source in new construction. Table 1 presents lighting energy usage in the U.S. and compares it to total energy use in the U.S from the Department of Energy (DOE) *Lighting Market Characterization* reports for the years 2001, 2010, 2015, and 2020. Table 1 also presents the same data in the form of electricity (TWh) and the portion of lighting as U.S. electricity use. While the US total energy use decreased by 5 percent (93 / 98.3 quads), lighting energy decreased by 72 percent. As shown in Table 1, lighting electricity use significantly reduced post-2015 when LED penetration significantly increased.

Table 1. Lighting Energy Use

Feature	Lighting Energy (Quads)[*]	Total U.S. Energy[†] (Quads)	Lighting as portion of U.S. Energy	Lighting Energy (TWh)	Lighting as portion of U.S. Electricity
2001	8.2	98.3	8.3%	765	22%
2010	7.5	97.8	7.7%	700	18%
2015	6.8	97.0	7.0%	641	17%
2020	2.3	93.0	2.5%	244	9%
[*]Quad = quadrillion British thermal unit. [†]Total U.S. energy includes energy in all forms, including transportation.					

By contrast, lighting controls have remained largely similar over the last 20 years. Energy codes post-2010 increased requirements for lighting controls, which have resulted in measurable lighting energy savings. Requirements are mostly prescriptive, requiring an auto shutoff function either via timeclock or occupancy, and dimming and daylight harvesting within the spaces when occupied. Energy code requirements focused on control function have not included requirements for either digital or interoperable lighting systems.

Market Drivers

Many of the topics covered within this paper have been under consideration and discussion for quite some time. North American adoption of digital lighting protocols has been stunted. There are multiple barriers, including but not limited to technology limitations, lack of collaboration between disciplines, limited availability of experienced installers and integrators, and costs for equipment and labor. Some early adopters within the lighting and buildings community have implemented advanced networked controls, but their results were disappointing. Given this, it’s tempting to draw conclusions about the viability for market adoption of digital lighting. However, the same can be said of other technologies and practices within the buildings industry. Although lighting might be slow to fully digitize compared to some other building systems, new market drivers may be a sufficient catalyst to push the industry to change long-standing perspectives about technology and business models. From a technology perspective, evolution of standards, interoperability, and digital lighting product offerings demonstrate unprecedented readiness to contribute to climate change goals with other building systems.

Decarbonization

Recently, concerns about climate change have created new decarbonization drivers in the marketplace, including electrification and grid-interactive efficient buildings (GEB). This will require contributions from many technology systems, including lighting. Digital communication lays the groundwork for system integrations, enabling higher-level software platforms to optimize performance toward these challenging goals.

Building Performance Standards (BPS)

Building performance standards (BPS) are "outcome-based policies and laws aimed at reducing the carbon impact of the built environment by requiring existing buildings to meet energy and/or greenhouse gas emissions-based performance targets" (DOE 2024b). BPS are growing across the country and represent a grass roots type of deployment that drives the market at a local level.

To meet BPS, buildings will need systems and tools to help them determine energy usage at a system level or by floor level. Digital lighting systems allow for two-way communication, and some digital lighting systems include on-board energy monitoring and reporting systems. Building operators can use this precise and real-time energy data to determine how lighting can contribute to meeting the requirements of the BPS and assist with compliance.

Artificial Intelligence

Artificial Intelligence (AI) has become a powerful tool throughout the world for many applications and is a logical choice for inclusion in the operation of buildings. AI has a technical definition, but here is used as an umbrella term that encompasses technologies including machine learning; smart buildings, digital twins, and actual AI. In simple terms, the functionality of AI in buildings is to capture data from as many sources as possible, clean the data so it can be interpreted, which then enables the AI computing platform to identify patterns and opportunities far beyond what we have been able to see before.

Sensors are an essential element of data collection for AI. While sensors are useful for existing buildings control systems, without advanced analytical capabilities they are limited in what they can do. AI can evaluate all the data sets together to make decisions across multiple building systems. Multiple real estate technology companies have started selling various types of stand-alone sensors that are not part of the building systems to support use cases driven by AI such as optimized space utilization, room requests, workstation usage for hybrid workplaces, and improved building and energy operations. The net result can optimize operations overall, including occupant experience, ultimately contributing to multiple environmental goals.

Sensor Technologies and Lighting

Recent advances in miniaturization of digital sensor technology have spurred new advances in many disciplines and lighting is no exception. There are a wide range of sensor options in buildings capable of capturing many types of data, such as: occupancy, temperature, contaminants, pathogens, sound, light, and more. The potential is tremendous, yet all face similar challenges including proper placement in the space, a source of power, and of course a method of capturing and storing the data.

Sensor data for buildings can only be transformed into value propositions if sensors are installed in their proper positions and assigned to specific locations within building spaces. Location is central to digital integration with other building systems and the various use cases that deliver tangible value to owners, managers and occupants (e.g., the use of presence or location data for hybrid workplaces). To that end, installation of sensors typically requires on-site services to geolocate mounting positions onto a digital floor plan.

Finally, sensors without a constant supply of power must be battery powered. Battery life is affected by the type of sensor, data frequency, type of data, and other factors. Batteries last 2 – 10 years and create a long-term burden to facility management to keep them functioning.

Clearly, the choice to install sensor systems brings additional costs along with value. Lighting has a role to play primarily because the ubiquitous nature of lighting throughout the built environment provides access to power and mounting locations for sensors. Lighting occupancy sensors are already a common practice way to comply with the auto shut off requirement in energy codes and are typically mounted in ceilings. By comparison, sensors mounted within lighting fixtures increase density and granularity of data to enable building integrations, analytics, and AI. In addition to occupancy data, some lighting sensors can also measure, temperature, humidity, and more. The elimination of what otherwise would have been a parallel sensor system saves the initial costs of procurement, installation, and provisioning, as well as the ongoing costs of batteries and associated maintenance services.

Fixtures with integral sensors are called luminaire-level lighting controls (LLLC). In addition to the value described above, dimming per fixture saves energy when compared to larger zones that only dim when the entire area is unoccupied. (Sathe et al. 2023) In many cases this also can reduce the complexity of sensor placement resulting in logistical, cost, and power source benefits. Lighting fixture types vary significantly depending on the type of space, design intent, and project type. Certain types of fixtures are more suitable for LLLC such as recessed fixtures with parabolic cubes or lenses (e.g., 2-foot by 2-foot).

It is critical to note that sensors integral to lighting fixtures are by no means the only way to capture high value data in buildings. Speaking generally, projects in existing buildings have strict economic constraints, so the LLLC approach could be a better financial option than adding separate sensor systems. Retrofit kits with LLLC have become common and affordable, providing a scalable way to integrate sensors throughout many commercial properties in existing buildings. Note that analog LLLC products are capable of dimming per fixture, but digital and addressable systems are necessary to provide the numerous high value features discussed below.

Analog vs. Digital

Analog controls were the first controls in North America and remain the current default technology. The most common form of analog lighting controls is 0-10V. There are three common 0-10V standards in North America: ANSI/ESTA 1.3-2001 (R2021); IEC 60929; ANSI C137.1-2019. Each standard has nuances. Analog signals are one-way with a simple voltage that carries no information. Digital signals are two-way and contain information in the signal.

There are two primary digital lighting protocols in North America: digital multiplex (DMX) and digital addressable lighting interface (DALI®). Both are suitable for interior and exterior lighting, but they have different strengths. In general, DMX is most often used for color control, dynamic "shows," creative eye-catching solutions, and other niche commercial applications in the North American region. DALI is more widely used for general lighting and includes digital features that make it suitable for integrations in buildings at scale.

The original DALI protocol was launched in in the early 90's, but was superseded by the current version, DALI-2, in 2017. DALI-2 protocol requires testing for certification and labeling, to ensure interoperability of components. Given its global footprint and potential for expanding adoption into the North American market, as well as its interoperability, DALI-2 will represent open standard digital lighting protocol for the purposes of this paper, unless specified otherwise.

Comparison between 0-10V and DALI-2

Analog systems are capable of dimming, but not much else because the analog drivers lack memory banks, the analog signal is one-way, and the analog signal does not contain information. Table 2 provides a comparison between analog and DALI-2.

Table 2. Feature Comparison of Analog (0-10V) vs. Digital (DALI-2) Lighting Control

Feature	Analog System	Digital System
Standards	ANSI/ESTA 1.3-2001; IEC 60929; ANSI C137.1-2019	DALI-2
Dimming Capabilities	Voltage, light output and dimming curves are variable depending on standard, manufacturer, and product.	Dimming is digitally controlled, dims consistently across different products and fixture types.
Precise Control	Difficult to make precise adjustments to light levels due to variable dimming curves. Not individually addressable.	Digital addressability supports maximum control and flexibility per driver and/or sensor.
Interoperability	No interoperability between device manufacturers, limits ability to change devices or components as needed.	DALI-2 requires testing and certification to ensuring interoperability of devices.
Flexibility and Scalability	Changes may require significant time/expense to modify (rewiring) after installation.	Wired and wireless architectures work together seamlessly for scalability. Remote reconfiguration. Specific digital features can be specified per fixture type.
Integration	Analog systems have limited integration possibilities, resulting in isolated lighting control systems.	Standardized data formats and schema simplify integrations with other building systems.
Diagnostic Capabilities	Analog systems provide minimal diagnostic information.	Device-level diagnostic capability identifies location and nature of the fault, streamlines maintenance, reduces cost.
Remote Control	Changes to control settings typically require on-site adjustments.	Centralized, remote control allows updates to zones and settings. Digital addressability supports churn, reconfiguration, and space re-use goals.
Energy Monitoring	Energy monitoring not available. Energy savings reporting is predictive/ calculated, can be highly inaccurate.	Precise real-time energy monitoring. Accuracy enables informed granular adjustments to support savings goals.

Inaccurate Energy Reporting

The inaccuracy of reported energy consumption when using analog drivers is a limitation. Conversion devices can be applied to analog drivers to translate to a digital controller and lighting control systems user interface, but useful information is difficult to extract. As we continue to work to bring consumption and carbon emissions to lower levels, inaccurate savings data are more of a concern than in the past. The root causes for this problem include:

- Analog systems do not have an onboard chip to enable two-way communication, so savings must be estimated. A maximum power for the light fixture must be manually provided to the control system, which carries the inherent risk of human error. The digital controller captures run time, then the system calculates and predicts energy savings.
- Within the analog standards, although the range is labeled as 0–10V, actual maximum voltage may vary. Therefore, if an estimate is based on a maximum wattage of 10V, but the actual maximum voltage of the driver is 8V, 9V, or 10V, it is a source of imprecision.
- Dimming curves are not standardized within analog systems. For example, one curve may be linear while another is logarithmic. As a result, two systems could be dimmed to the same percent (e.g., have same control signal voltage), but have different power draw from the lighting fixture (Waghale et al. 2023).

Analog controls will meet the bare minimum for code compliance but have substantial deficiencies. Collectively, the use of 0-10V analog technology represents a missed opportunity for net zero energy, reduced load, building system integration opportunities, and interactive grid.

Proprietary Digital Systems

The barrier to integration with other building systems is not simply the shift from analog (0 – 10V) to digital technology. Multiple digital products exist within the lighting industry, but they are proprietary systems that lack interoperability.

Unlike the HVAC industry where BACnet allows for the transfer of data in a consistent manner, the lighting industry in North America has not embraced a standardized method of lighting protocol and digital specification. The business strategy overall has been differentiation between manufacturers, rather than taking the leap to interoperable components. As digitization is being widely implemented throughout the rest of the buildings industry, the lighting industry would benefit from embracing standardization to tap into a larger and more progressive market.

Understanding Interoperability

The topic of interoperability is fraught with confusion for many reasons. The words interoperable, interchangeable, and compatible have distinct definitions, but they are often used incorrectly. Additionally, the differences between software, hardware and firmware, make it more complicated. Understanding these distinctions helps to assess how lighting can interact within the parts of its own system, and beyond to the building and the grid. Definitions and examples follow in Table 3, below.

Table 3. Interoperability Definitions and Examples

Name	Definitions	Examples
Compatible	Compatibility is when two systems can operate (or simply reside) in the same environment without adversely affecting the behavior of the other system. Compatibility is the first step for better system operations. If the components are not compatible, behavior of one or more of the components will be negatively affected.	Lighting integrating with the mechanical system is an example of compatible systems. The lighting control system operates the lighting, and the building automation system (BAS) operates the mechanical system. These two systems co-exist in the building and operate different systems. However, the lighting system can communicate occupancy of rooms to the HVAC system. The HVAC system can then setback the temperature and fans resulting in 20%+ mechanical energy savings. (Myer et al. 2023, 9)
Interoperable	Communication protocol is a standardized method of data transmission and does not by itself ensure interoperability. Semantic operability is when data is structured and encoded across the systems. Semantic interoperability allows the components to interpret and share data.	DALI-2, D4i and DALI+ certified components (e.g., drivers, sensors, application controllers) are interoperable because they use a common communication protocol *as well as* semantics to understand and interpret the information, thus facilitating consistent lighting control. Interoperability enables component replacement in the future, mitigating the risk to the owner of replacing the lighting system altogether when parts start to fail.
Interchangeable	Interchangeable systems have components that are identical for practical purposes. Each component has specifications that ensure that more than one manufacturer can produce a unit so nearly identical that the new unit will fit into any assembly of the same type.	The electrical industry and specifically lighting systems have historically had interchangeability of physical components such as standardized lamp sockets, mounting enclosures, and wiring elements. The introduction of LEDs has been a paradigm shift, making interchangeability of the lighting source far less common.

With these definitions and examples in hand, we can start to understand the opportunities and challenges in how lighting can interact within the parts of its own system, and beyond to the building and the grid.

Types of interoperability

When evaluating interoperability, one should ask, “interoperable with what?” In the DALI-2 example above, the standardized protocol and data format enables products such as drivers and sensors to communicate and function consistently. Interoperable components can reduce the risk and cost of having to replace entire light fixtures, but lighting controls software and UI's will almost certainly be differentiated. For example, many lighting controls companies extract data for energy reporting or diagnostics and maintenance, but the way they analyze or visualize that data will vary. Similar to other digital technologies, priorities, content and interfaces will vary, but standardized communication protocol, semantics, and data formats are necessary for scale and reliability.

Importantly, with DALI-2, building systems (e.g., BMS/BAS, IWMS and their platforms) do not have to reinvent the wheel for individual manufacturers' proprietary technologies. The ability to obtain relevant data due to consistent data structure and communication protocol eliminates a significant pain point for owners and managers. Various value propositions from one project or property to the next become more achievable with less burden on the high cost of human capital and budgets. This type of interoperability can be the difference between a series of one-off digital projects versus scalable adoption.

Digital open standards and protocols

Interoperability of lighting controls has long been elusive. A 1997 article titled "Interoperable Systems: The Future of Lighting Control" illustrates both the need for interoperability and that it has long been sought (Wolsey 1997). The focus of the article was integrating lighting with BAS. The article states that BAS is made possible because of direct digital control (DDC) and that DDC signals can be transmitted via anything from radio signals to the internet.

Part of the challenge in reaching this goal is that multiple layers of standards are needed to create functional interoperability within lighting systems and for integration with other building systems. Recent years have seen multiple standards developed and improved, which have collectively made progress on the path to lighting interoperability using digital technologies.

DALI® (Digital Addressable Lighting Interface)

The DALI Alliance (formerly the Digital Illumination Interface Alliance, DiiA) is a non-profit standards organization that creates specifications (called "Parts") which are then incorporated into the IEC 62386 Standard. The protocol started with a 2-wire digital bus and has expanded to include additional control devices as well as multiple features ranging from diagnostics to color control and calibration.

In 2017, a testing and certification program for DALI-2 was launched which verifies that products meet the IEC 62386 standard, to ensure proper performance, reliability, and interoperability between certified devices. The certification program proved to be pivotal in continued global adoption of DALI-2, making DALI the recognized internationally standardized protocol for digital communication between lighting control devices.

DALI-2 has a wired infrastructure which is suitable for new construction and major renovation. In 2020 the DALI Alliance continued to expand DALI-2 with a release of D4i, to standardize digital functionality *within* lighting fixtures. D4i is especially significant for existing buildings in the North American market as it enables digital control and data collection within individual fixtures that are communicating wirelessly. This opens the market of existing buildings to the many benefits of digital systems, as detailed elsewhere in this paper. DALI+ is the most recent extension of DALI-2, designed to integrate DALI systems with IP-based networks, e.g., WiFi and POE.

Two of the most recent DALI-2 specifications (Parts 341 and 342) expand market relevance and value by providing a gateway (interface) to two of the most common and well-known wireless communication protocols, Bluetooth® Mesh and Zigbee®.

Bluetooth®

There are several versions of Bluetooth wireless protocol with different capabilities. It is important to understand these differences in advance of choosing a Bluetooth enabled lighting control system. Table 3 provides a summary of the differences between Bluetooth wireless protocols. Bluetooth Mesh is one of the most common options for wireless lighting control.

Multiple manufacturers have developed lighting control systems using Bluetooth Mesh, and they are typically cost effective, with friendly user interfaces, and well-suited for existing buildings. However, Bluetooth Mesh lighting is not interoperable. Although the control systems are built on the same underlying protocol, device profiles are proprietary, so products must be sourced from the same vendor.

The exception is Bluetooth® NLC (Networked Lighting Controls), which was developed by the Bluetooth SIG (Special Interest Group) in a consensus process. Bluetooth NLC launched in 2023, and for the first time requires a testing and qualification process to ensure full functionality and interoperability. For example, sensor replacement from different vendors becomes possible. DALI-2 systems with their Part 341 gateway (interface) to wireless Bluetooth NLC are an optimal approach to wireless standardized interoperable lighting.

Table 3. Comparison of Bluetooth Protocols and Specifications

Name	Description	Common Application Examples	Substantive Distinctions
Bluetooth Classic	Original Bluetooth technology, continuous high data-rate transmissions	Streaming audio to wireless earbuds and speakers; computer peripherals such as mice and keyboards	Base radio layer protocol upon which BLE, Bluetooth Mesh and Bluetooth NLC are built. *Not used for lighting*.
Bluetooth Low Energy (BLE)	Wireless communication for short-range, optimized for low power intermittent transmissions	Wearables such as fitness trackers and smart watches, thermostats, indoor navigation, residential lighting control	Primarily consumer and residential. Lighting devices and control systems are *NOT interoperable.*
Bluetooth Mesh	Networking protocol built on top of BLE, mesh topology (many to many), large-scale and reliable	Commercial/industrial lighting control with optional features, potential for one-off project integrations, e.g., HVAC with thermostats, asset tracking via beacons, security systems.	Topology offers high resiliency, efficient communication, and scalability. *Does NOT support interoperability*, as systems have proprietary device layers and optional features.
Bluetooth NLC	Bluetooth Mesh with enhancements, full-stack standard for lighting control, mandatory features for qualification	Commercial/industrial lighting control, integrations similar to Bluetooth Mesh, but with multi-vendor products (e.g. sensors, drivers, wall switches).	Standardized, developed by Bluetooth Special Interest Group (SIG), *offers qualification for interoperability*. Multi-vendor compatibility and replacement.

Zigbee®

Zigbee is a low power wireless mesh network that is similar to Bluetooth Mesh (before the release of Bluetooth NLC) in that devices are built on the same protocol but are not likely to work with each other. There have been improvements to create certified routers to connect one device to another, but with mixed results. Perhaps the most relevant distinction is that Zigbee is more commonly used for smart home systems than commercial environments.

Zhaga® with D4i

Many of the integrations that contribute to digital integration are enabled with the use of sensors integral to the lighting fixtures. As integration of lighting sensors and wireless radios are becoming more prevalent, standardized compatibility with luminaires becomes a greater necessity. To meet that need, the Zhaga Consortium developed Book 18 (exterior) and Book 20 (interior), which are open standard specifications for mechanical form factors and electrical compatibility for LLLC. The electrical and data components of these books support D4i certified drivers as well as defining standardized mechanical form factors to enable room facing replacement. Zhaga-D4i is a joint certification program from the DALI Alliance and Zhaga Consortium organized to get both certifications to ensure plug-and-play interoperability of sensors, communication nodes and luminaires.

Like DALI, Zhaga has more market penetration in Europe than North America. In 2021, the US-based National Electrical Manufacturers Association introduced NEMA LS 20000-2021, which focused only on the physical form factors and did not include electrical specifications or certification requirements. NEMA LS 20000-2021 includes additional form factors for interior, but specifications that overlap with Zhaga are harmonized.

Digital Integration Methods

In the simplest terms, building system integrations are digital relationships between the horizontal layers shown in Figure 1. At the bottom in the blue boxes are end-use devices, apps, and data. The digital content goes to one of the standardized protocols show in green boxes (e.g., Bluetooth, Zigbee, Thread, etc.). They transport information (often in packets) which then feeds into a data topology. As stated above, control systems may be using the same protocol, but it does not guarantee the same functionality or interoperability.

The topology provides an approach for classifying and managing data scenarios. The three options shown in the blue diamonds (BACnet, DALI-2, and TCP/IP) are all standardized data protocols which have been developed in a transparent process with diverse representation. BACnet is primarily used for HVAC systems, DALI is used for lighting control systems, and TCP/IP is used for computer information technology systems.

DALI-2 includes a protocol, but also includes a robust series of specifications that provide explicit detail about how to receive, use, organize, and store the digital content. Products must be tested to show that they meet the specifications in order to be certified. The consistency of the data schema from one product to the next allows the next layers above to query and use the data in the same way. The outcome is a plethora of value propositions in buildings.

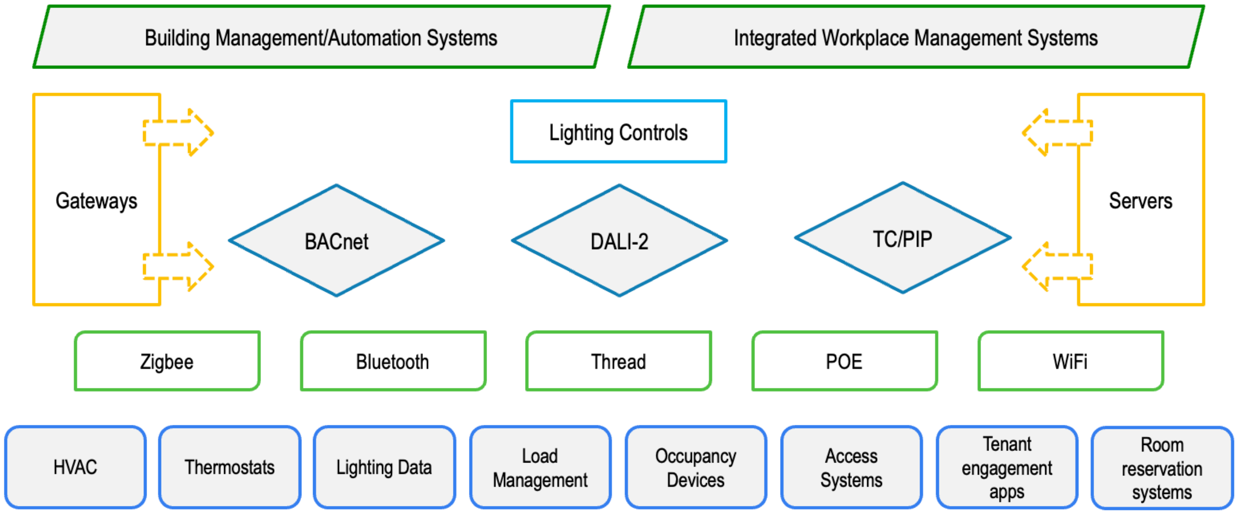

Figure 1. Conceptual representation of data layers from end use apps to platforms

The technical definitions and descriptions of digital networking are complex. Figure 1 lays out a basic conceptual view of some of the different digital layers within buildings. The bottom row of blue rectangles shows feature options which gather data and send it up to the green boxes, which will communicate with other compatible devices, and from there to another protocol that can interpret data for specific uses. The data ultimately should go to platform layers where analytics can be performed to optimize operations and performance of the building.

Digital Integration Possibilities

- Sensors can be linked to HVAC zones such that occupancy or vacancy triggers temperature setbacks to save energy. This integration is only suitable when the existing HVAC system supports the opportunity, for example, variable air volume (VAV). The integration can be done via BACnet with BAS/BMS, or wireless thermostats connected to wireless lighting sensors and setbacks.
- Daylighting/photocell sensors can be connected to shading systems, which can reduce cooling and heating needs.
- When digitally addressable lighting is used with space type data (e.g., workstations vs. hallways), analytics and AI can optimize demand response and load management to dim to the maximum viable level as appropriate per space type, which contributes to interactive grid strategies.
- When used with interior location data, occupancy sensor data can be integrated with room reservation software, tenant engagement apps, integrated workplace management systems (IMWS), and more.
- DALI-2 Part 253 is a specification for diagnostics and maintenance. It provides operating data for control gear (e.g., controllers, sensors, switches) including failure conditions, and runtime data, thereby enabling predictive maintenance.

Digital lighting contributes to GEB

GEB, which includes demand flexibility, is a departure from the previous "set and forget" methods of operating buildings. Flexible buildings can change the operation (e.g., pre-cool the building or shed lighting load) in response to either internal or external factors. A signal from the utility may be involved, but a system within the building would then inform the lighting system to dim to suitably address different conditions. For lighting to be a tool in demand-flexible buildings, it must be a networked lighting control system. In practical application, digital addressability is also necessary for lighting to contribute to GEB solutions.

Digital addressability allows lighting control systems to send commands and receive data from drivers and sensors belonging to individual light fixtures. When these fixtures are then geolocated to a map, it becomes possible to reduce light levels in a precise manner, based on the needs of the space type. Some spaces will need to be more sensitive to reducing light levels and durations to avoid unintended consequences, whereas other areas may dim more deeply. Overall, the addressability of individual lighting devices maximizes potential for demand and load management.

Load Management

Load management (also known as continuous demand management) is the strategy of "smoothing" the electrical load of the building to prevent the building establishing a new monthly billing peak. Load management requires active monitoring of the electrical load in the building coupled with compiled data about electrical usage. As the building gets close to establishing a new monthly demand charge, the building could instantly shed electrical lighting load to help prevent the new demand charge.

Load shedding of lighting can also be used at the grid level via the traditional demand response. In the event the electrical load on the grid is reaching a point where relief is needed, a demand response signal can be sent to reduce electrical load. Automated demand response (ADR) signals can be sent from the utility to the building and related equipment to shed load. ADR signals involve a price component. Pricing data/signals may not correspond to the greenhouse gas (GHG) associated with electrical generation. Utilities are exploring a GHG signal. A building could receive data both about the price of electricity as well as the GHG-content of the electricity. The building could then operate the loads in response to those signals.

Distributed Energy Resources (DERs)

Many demand-flexible buildings incorporate on-site distributed energy resources (DERs). These on-site DERs (or site adjacent in the local community) may be in the form of renewable energy (e.g., photovoltaics) and/or energy storage systems. Beyond energy generation and storage, these communities may also include a microgrid. A microgrid coupled with storage contributes to both storage and renewable energy by generating native DC (direct current) power. Lighting can contribute to DER with low voltage and DC technologies.

Low Voltage and DC-DC

Traditional LED lighting is DC downstream of the LED driver. If DC circuits were employed in the building it would eliminate the electrical inefficiencies of AC (alternating current) to DC conversion. DC-powered LED systems, such as Power-over-Ethernet (POE), have the potential to directly integrate with DERs and contribute to the larger goals of electrification and decarbonization.

Like many emerging technologies, it is important to consider system architecture and application requirements when using lighting powered by POE or other low voltage DC systems. In some cases, lighting fixtures could be centrally powered without drivers, but most architectural lighting projects require POE nodes to be factory configured by the fixture manufacturer, and POE is still not widely integrated into lighting fixtures. Provisioning of POE lighting on-site must be managed carefully to meet specifier controls intent narratives, and POE lighting systems should meet "low risk" flicker requirements as defined in the IEEE 1789 Standard.

Value Propositions

Building owners have multiple motivations for decarbonizing buildings. From a financial standpoint, owners are anticipating policy and regulations that mandate lower emissions, along with increased energy costs. Investing in decarbonization proactively reduces these risks. The expected financial benefits include long-term cost savings, increased property value, and reduced operational costs. Compliance with environmental regulations avoids penalties and offers access to tax benefits and incentives.

Some benefits are not purely financial at first glance but are important, nonetheless. For example, financial investments in healthy buildings are realized primarily through positive outcomes for building occupants and employees. Better working environments and property technologies that maximize the functionality and employee experience for hybrid work are more significant post-pandemic.

The same can be said for digital and interoperable lighting systems. Some of the benefits derived from the features in digital lighting systems are direct contributors to the value propositions listed above. Other features are relevant because the resulting benefits stack up to a greater overall value, which contributes to adoption. The measures selected for a given project will vary depending on a myriad of factors and goals overall. Features and benefits can be readily defined, but the value will be project specific.

Ecosystem of Market Actors

For a market transformation to occur, most of the market actors within the ecosystem must support the technology. While the focus of this paper is digital systems that will contribute to larger environmental goals, the viability is inextricably linked to acceptance from buildings and lighting domain professionals, installers and integrators, and occupants. The paragraphs below provide a high-level summary of the desirable outcomes per market actor, along with their motivations.

- **Lighting Specifiers and Engineers** are motivated to have lighting and controls contribute to project success both aesthetically and functionally. For example, one DALI-2 feature is the digital dimming curve that ensures multiple fixture types will consistently dim at the same rate. Project goals include design quality and compliance with voluntary standards such as LEED and WELL. In simple terms, specifiers want to deliver a project that meets client needs, comply with code, and contribute to environmental benefits.
- **Owners and Operators** view interoperability as highly desirable. The risks associated with vendor lock and proprietary lighting systems will ultimately result in subsequent maintenance and service costs and hassle. Accurate energy monitoring is high value for projects driven by emissions reduction, DER, and GEB. Fault diagnostics results in faster maintenance, and response times increases occupant satisfaction.
- **Occupants and Tenants** enjoy color control. DALI-2 DT8 color control reliably provides consistent color across all fixture types. Fault diagnostics increases maintenance response time and increases occupant satisfaction.
- **Electrical Contractors** benefit from simpler wiring and less risk of installation errors, centralized configuration and remote access, more accurate deployment of sequences of operations (SOOs), fault diagnostics for troubleshooting and ongoing maintenance, digital lighting equipment information, and less copper (circularity).

Lighting Considerations

Like any discipline, there are specifics about lighting that should be understood when moving forward with digital lighting control systems. Decision parameters include lighting fixtures, design intent, aesthetics, light source color, energy code compliance, control system features, and more. The particulars of these distinctions are beyond the scope of this paper, but the reader should be aware that there are many variables that apply to lighting projects. Table 4 provides a review of the parameters.

Table 4. Digital Lighting Parameters

Variable	Notes
Building type	Lighting requirements vary depending on building type. For example, consider the differences between commercial buildings, box retail, manufacturing and industrial, warehouse and distribution, etc. Within building types, particular space types will also vary.
Wiring and Communication Protocol	Digital lighting control can be either wired or wireless. Wired systems are most suitable for new construction projects or renovations because wiring for power is needed, and digital control can be included. Wireless communication and controls are the most affordable option for existing buildings where the power infrastructure already exists.
Sensors	Sensor types vary depending on project goals, but occupancy sensors with auto shutoff is typical for energy code compliance. When LLLC fixtures with integrated sensors are used, it’s critical to deliver proper dimming profiles and aesthetic requirements, while also ensuring sufficient data.

Color	Tunable White (TW) is the ability to change the light from “warm” to “cool” based on preference. Color changing includes not only gradations of white, but also a range of highly saturated colors which are used for visual interest and design aesthetics. Color features are often referred to as “human-centric” or “circadian tuning.”

Financial Considerations

Metrics for ROI are typically developed for individual building systems; that has certainly been true for lighting. Projects driven by GEB, electrification, net zero energy, and decarbonization are inherently complex and involve multiple building systems. Simple payback as a method to evaluate the value of interoperable digital lighting misses the point. What are the benefits of the lighting system, beyond connected load? How does it contribute to the high-level goals of a given project? How can it interact with other digital systems and leverage outcomes?

- **Project type.** The economics of different types of projects are entirely different. New construction and major renovation projects have dedicated budgets for lighting and electrical, and the expertise of a design team. Retrofit projects have tighter budgets due to payback requirements, either per system or as part of bundled measures. Tenant fit-outs in existing buildings sometimes include space upgrades, which can result in the tenant bearing a portion of the costs and are amortized over the duration of the lease.
- **Project Size.** Larger projects and buildings are more suitable for centralized lighting controls because the cost of the lighting controls system is amortized across the square footage. Larger projects are also more likely to benefit from centralized control as compared to programming controls behaviors for each room.
- **HVAC**. Integration. Lighting integration with HVAC can be a meaningful savings opportunity, especially on the journey to electrification, but it largely depends on given conditions. The system needs to be capable of variable operations and receiving information from the lighting system.
- **Efficiency of installed equipment**. Buildings that have not yet transitioned to LEDs will yield higher savings and more of an opportunity to integrate digital controls. Buildings where first-generation LEDs were installed should be evaluated to consider whether the substantial increases in LED efficacy make it worthwhile to do another retrofit.
- **Locality and Legislation.** Localities with BPS are under more pressure to make aggressive changes to their buildings. Additionally, technology investments are rolled up to a higher-level using Life-Cycle Cost Analysis (LCCA) which changes financial decisions that were previously based on individual system payback.

Conclusion

Conversion to LEDs has indeed made a great contribution to energy savings and climate goals. However, advanced lighting controls remain an unrealized opportunity because barriers to adoption have persisted over time. In the meantime, open standards and interoperability efforts have made great strides, and today’s digital lighting is qualified to be part of the team.

The most immediate challenge is to insist upon products and systems that provide the desired characteristics. The market pull represented by the owners and managers who are making progress right now with other technologies has the potential to close the gap between simply reducing lighting connected load and digital, interoperable, and grid-interactive buildings.

Given the urgencies of climate change, every contribution to the steep challenges of GEB, DER, and decarbonization should be considered. The comprehensive information in this paper makes a strong case for including digitally addressable and standardized lighting as a contributor. Next steps include raising awareness with non-governmental organizations, Federal agencies. and voluntary programs, while also educating specifiers, installers and integrators.

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