LED SCALE-UP

Accelerating corporate adoption of connected LED lighting

Smarter offices of tomorrow

LED: Scale-up

This is part of a series of briefing notes designed to support The Climate Group's global LED lighting scale-up work

TheClimateGroup.org

The historic national commitments made at COP21 in Paris in 2015 were followed by urgent action to reduce carbon emissions. In support of these ambitions, The Climate Group, in partnership with Signify (the new name for Philips Lighting), is continuing its work to increase awareness of the energy saving benefits of light emitting diodes (LEDs) – and the huge impact that will be realized through scale-up of LEDs across all sectors around the world.

Buildings offer one of the biggest opportunities for emission reduction activities[1] as they can consume up to 1/3 of global energy demand, and account for about 1/4 of greenhouse gas (GHG) emissions globally. Lighting alone can represent up to 40% of a building's energy footprint[2] and, with the advent of highly efficient and affordable LEDs, can offer direct energy savings of 50-70%. This percentage is even greater when LEDs are used in conjunction with smart controls.

As part of our work in 2018, The Climate Group will therefore highlight the immediate and accessible savings, benefits and wider opportunities that connected LED lighting solutions can provide for indoor work-office environments.

LEDs are a solid-state lighting solution that have demonstrated unprecedented energy savings in a direct replacement technology. But the benefits of LEDs go far beyond energy savings. The available options for smart controls, light level adjustment, color tuning and digital connectivity now offer corporations and property building managers new opportunities to implement modern, adaptive and interactive lighting solutions. The inclusion of 'connected' lighting provides an opportunity for every office user to adjust their local and personal lighting environment to suit their working hours. This 'human centric' lighting capability for users to 'take control' and adapt to their preferred environment, can aid in employee well-being and help optimize potential performance and productivity. For corporations where flexible working and hot-desking is common, this allows employees to work in a range of locations and still individually configure their local working environment to their personal preferences.

Signify

PRINCE ALBERT II OF MONACO FOUNDATION

To maximize energy savings in the built environment, linking LED lighting with smart building sensors can provide office and property asset managers with compelling opportunities to gather data on asset occupancy, office area usage patterns and environmental status.

The data can provide the capability to automatically turn off lighting when employees are no longer present, turn down heating or air conditioning in areas not scheduled for imminent use, schedule cleaning activities to only used areas, and coordinate with other building services such as access, safety and security systems.

THERE IS AN URGENT NEED FOR DEPLOYMENT OF ENERGY EFFICIENT TECHNOLOGIES WHICH ARE SCALABLE, RAPID AND EASY TO DEPLOY – AND WHICH CAN INTEGRATE AND ENHANCE CURRENT AND FUTURE BUILDINGS SYSTEMS AND SERVICES.

Keeping energy efficiency top of the agenda

Energy efficiency is STILL ranked the highest policy priority by energy professionals.[3]

Buildings have very long economic lifespans when compared to other energy consuming infrastructure.

Building efficiency is one of the most affordable ways to curb climate change.[4]

With high levels of carbon emissions linked to buildings[5], there is a justified sense of urgency to focus attention on increasing energy efficiency in existing buildings, and rapidly accelerate the rate of existing building renovations and upgrades. Connected LED lighting combined with building environmental sensors can help unlock a far wider range of additional energy savings possibilities through enhanced smart building asset management. It also creates a platform of connected infrastructure that can support future roll-out of new building systems, sensors and data 'Internet of Things' (IoT) services[6].

As part of this urgent action on accelerating building renovations and emissions reduction, LEDs and connected lighting infrastructure represents a priority action, in terms of level of impact, speed of impact and ease of deployment.

This document covers key themes that LED adopters may consider when reviewing their future lighting needs and exploring options for indoor lighting upgrades. We discuss various levels of options for core energy savings, lighting system connectivity and future-proofing systems, so users can maintain flexibility and interoperability as new IoT technologies become available for trials and roll-out.

A TRANSITION TO CONNECTED ENERGY EFFICIENT LED LIGHTING CAN DELIVER IMMEDIATE AND SIGNIFICANT SAVINGS, AND CATALYZE AND SUPPORT ROLL-OUT OF NEW SMART TECHNOLOGIES AND LINKS TO THE INTERNET OF THINGS.

LEDS REPRESENT A PRIORITY #1 ACTION ON CLIMATE CHANGE.

Owned and leased office buildings

"Owners don't want to spend their capital budgets, especially where tenants pay the utility bills. Tenants don't feel empowered to invest in capital projects, especially when their leases are short term.

Hence the opportunity for third-party service providers[7] ...and the potential for new business models such as 'lighting as a service' which in turn can drive new 'service' options to optimize other building services.

FOREWORD

Over the past 7 years, The Climate Group's city lighting work, in partnership with Signify, culminated in a call to action that all public lighting should be LED (or as efficient) by 2025[8]. We are now seeking to drive a more urgent goal for indoor – and specifically corporate – lighting. This document is designed to support our ongoing consultation activities with corporates, as they explore LED options and develop their supporting business case. We showcase key topics and themes that have arisen during our consultations and seek to highlight options and solutions for the different lighting stakeholders.

LED lighting is an established and mature technology with proven energy savings, extended lifetimes and reduced maintenance costs. First and foremost we seek to highlight LED scale-up as a priority action on energy efficiency for corporations. Based on energy savings alone, the case for LEDs is compelling. But benefits are extended much further with options to add connected controls, smart controls, dimming and color selection.

When LEDs are matched with connected controls and data gathering sensors to facilitate optimization of all key building services, the potential energy savings opportunities in the built environment are taken to another level. With the evolution of 'smarter' offices and flexible work environments, the gathering of accurate office usage data and wider use of linked systems and controls could not be more pertinent today. Smart lighting, sensors and controls will play a compelling and catalyzing role in the transitioning office work environment – and optimizing the energy-driven services that support them.

There has never been a better time to switch your business to smart, connected LED lighting.

CALL TO ACTION: ACCELERATING CORPORATE LED ADOPTION

We are making clear 'calls to action' on connected LED lighting for corporates, landlords, property developers and all stakeholders with responsibility for office building assets.

The Climate Group calls on:

- **All property developers to install connected energy efficient lighting solutions, LEDs (*or as efficient)* in all new/future buildings as a key facilitating infrastructure to help accelerate existing building retrofits**.

And:

- **All corporate owned built environment lighting assets to be rapidly assessed for upgrading to LED-based connected solutions and scheduled for trials/installation by the end of 2020.**

- **For all leased building assets, landlords to offer LED options to existing tenants – and for tenants to request that landlords offer connected, energy efficient LED lighting options for all work/office environments by the end of 2020.**

WHY SHOULD WE PRIORITIZE LED LIGHTING?

THE RELATIVE IMPACT OF LEDS

There is a broad range of actions that can be taken to reduce energy demand and ultimately emissions. The U4E/en.lighten[9] campaign by United Nations Environment has undertaken a series of studies on the energy efficiency benefits of different technologies and their potential relative energy usage and savings that could be realised in 2030.

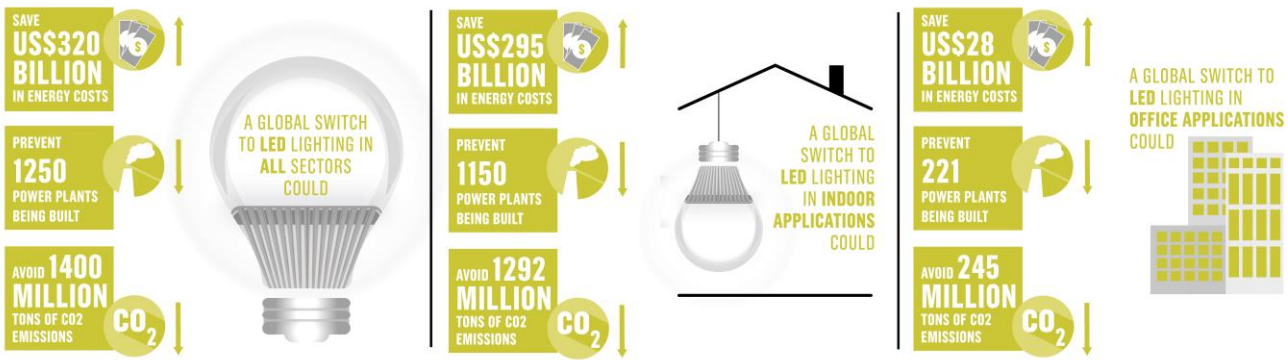
The study compares lighting, residential refrigerators, room air conditioners, distribution transformers and industrial electric motors. It revealed that significant savings could be realized across all technologies, and in many regions potential savings from lighting were compelling.

Country examples: highlighting[10] relative impact of energy efficient technologies. Percentage of each product's estimated contributions to savings in 2030.

Country	Lighting	Residential refrigerators	Air Conditioning	Transformers	Industrial motors
Argentina	43 %	23 %	5 %	7 %	22 %
Brazil	11 %	36 %	32 %	16 %	5 %
China	41 %	10 %	4 %	45 %	0 %
India	27 %	11 %	33 %	5 %	24 %
Israel	31 %	15 %	17 %	20 %	17 %
Kuwait	51 %	10 %	3 %	22 %	14 %
Namibia	49 %	9 %	16 %	18 %	8 %
Oman	42 %	8 %	12 %	16 %	22 %
Russia	36 %	10 %	5 %	17 %	32 %
South Africa	43 %	7 %	1 %	21 %	28 %
Uruguay	35 %	22 %	7 %	21 %	15 %
Zimbabwe	51 %	16 %	7 %	23 %	3 %

"With (up to) 20% of the world's electricity[11] used for lighting, it's been calculated that optimal use of LED lighting could reduce this to 4%.

LED LIGHTING GLOBAL SAVINGS POTENTIAL[12]



CONNECTED LED LIGHTING GENERATES BENEFITS FAR BEYOND SIMPLY THE DELIVERY OF LIGHT

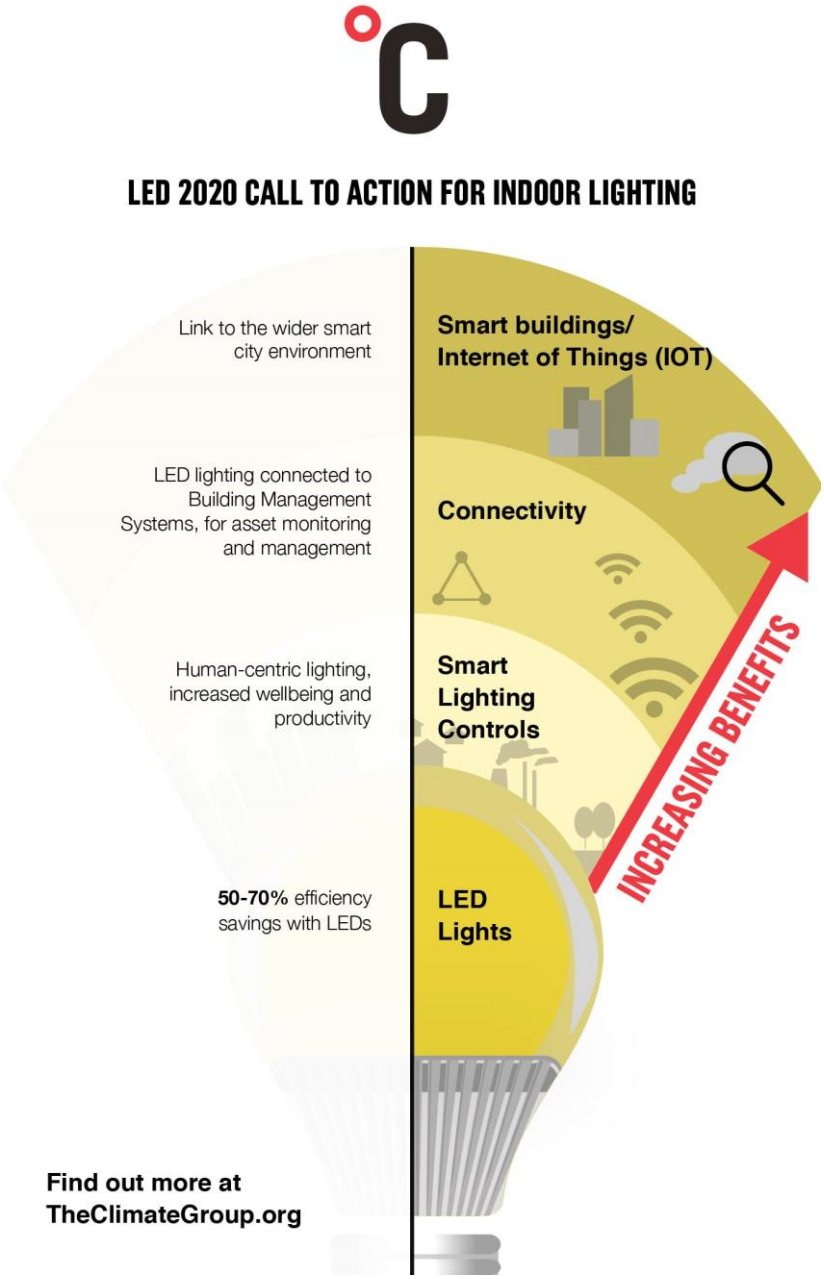
Beyond lighting

LEDs can provide energy savings of up to 50-70%, **even before** the addition of smart controls.

Connected LED lighting with in-built environment and occupancy sensors can provide real-time asset status monitoring.

The area-use scheduling of lighting, heating-cooling systems and cleaning services can all be accurately assessed and optimized for the building 'as a whole'.

The availability of such operational data in buildings can be truly empowering.



'Smart lights to become largest IoT devices in next 5-10 years'[13]

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INTRODUCTION

The Paris Agreement, which commits nearly 200 countries to make efforts to limit global temperature increase to under 2 degrees Celsius above pre-industrial times, presents the challenge of identifying urgent 'next step' practical actions to drive down global emissions.

The role that energy efficient lighting technologies can play in reducing global energy demand is commonly underestimated. The unprecedented scale of the savings -- 50-70% -- and the immediacy and relative impact that this can have when implemented at scale, means LEDs should not be underestimated or overlooked.

Total energy use from the lighting sector accounts for around 16% of global electricity consumption[14], with its use concentrated in cities – where over half of the world's population live. The built environment is a priority target for emission reduction as it can contribute up to 40% of the world's CO_2 emissions. Governments around the world are encouraged to schedule supporting policies to help accelerate renovation of aging and inefficient building stock, and drive down city and building related emissions. And this opportunity is set to grow. The International Energy Outlook 2016 report anticipates total world energy consumption in buildings to increase by an average of 1.5% a year from 2012 to 2040.[15]

LED LIGHTING IS PROVEN AND MATURE, ACHIEVING 50-70%+ ENERGY SAVINGS – AND IS NOW CATYLZING WIDER ADOPTION OF SMART, CONNECTED AND DATA-ENABLED LOW CARBON SOLUTIONS.

By applying experience from the past 7 years of work by The Climate Group in highlighting the benefits of LEDs in cities, we are now expanding LED consultation work to help accelerate the adoption of indoor lighting, particularly focusing on corporate office solutions.

AIMS AND OUTCOMES

CONSULTATIONS: STAKEHOLDER ENGAGEMENT

The Climate Group's consultations and events are designed to support corporates in exploring and ultimately adopting energy efficient LED lighting – and meeting our 2020 LED adoption target. We do not intend to duplicate the efforts of national, regional, lighting standards and trade organizations that support the adoption of LED lighting. Many sources of information on LEDs exist and are a valuable resource for covering general and specific regional examples, with examples referenced in this document. Our goal is to support corporates in achieving our 2020 LED lighting target.

For leaders and policymakers: the role of leaders and policymakers is crucial in helping create the policies and incentives that can facilitate adoption of energy efficiency technologies such as LEDs.

For office tenants and occupier groups: we invite you to participate in our series of events, roundtables, webinars and workshops to explore the opportunities that LEDs can provide.

For corporates considering the switch to LEDs: we invite you to participate in our consultation activities, which are designed to provide effective forums for reviewing key topics of interest, addressing specific queries, facilitating expert advice and offering guidance on adoption routes and solutions.

For corporates that have already switched to LEDs: we would like to highlight your example, achievements and savings, as well as exploring how your installation is, or could be further enhanced through addition of new sensors and IoT innovations.

For building management/property leasing managers: focusing on asset management and the capability and proven savings that connected LEDs could provide your sites and clients, we would seek your involvement as a key stakeholder in helping to drive scale-up of such technologies in the leased office sector.

For integrators/installers/lighting solution providers: alongside corporate representatives, we invite technology service providers and consulting organizations to participate and contribute to the conversations, discuss local and regional topics and highlight perceived challenges.

Telecom companies on the themes of connectivity and the IoT: with a range of current and future wireless/mobile/ethernet connection solutions, the involvement of communication platform providers will be essential to guide participants on options and ensure systems are flexible, scalable, adaptable, interoperable and secure.

Big data/building data/analysis consultancies: the advent of sensor-enabled smart buildings inevitably brings vast opportunities for data gathering and optimization of all aspects of building operations including office services, space usage, overall asset efficiency and employee/visitor preferences.

Application developers: there are a vast array of existing and future opportunities for application development in support of control systems and the wider development of IoT related technologies that will inevitably feature in smart buildings and office environments.

Academic/governmental institutions covering themes: the wealth of data that could be collected and made available is extensive. In particular, focusing on light levels, color, time of day, temperature and how these can affect employee health, comfort and well-being and potentially productivity.

For finance providers: the opportunities for financing corporate and leased building lighting upgrades is growing, and the energy savings potential of LED based projects and rapid payback are attracting strong interest. We seek your participation in the review of financing mechanisms tailored for LED

Accelerating rates of building renovation[16]

There are estimates that in the UK alone, up to 75-85% of current buildings will still be in use by 2050.

Governments have a key role to play in accelerating the adoption of energy-efficient lighting.[17]

projects (e.g. 'pay as you go', and 'lighting as a service'), and to explore new investment models that can help drive LED adoption based on future savings.

CONSULTATIONS: TOPICS AND THEMES

The following sections discuss a range of key topics and themes that have arisen during our early LED dialogues with corporations and aim to highlight common examples and recurring questions

The sections are ordered to initially discuss the supporting business case validation, through proven energy savings, and review some of the underlying decisions that corporates and property managers may face when reviewing infrastructure upgrades. The underlying technology benefits are presented, followed by a discussion of the upgrade options – in particular options around connectivity and coupled sensors and smart technologies.

"A cutting-edge lighting solution will help the customer make significant energy, cost and CO_2 savings while improving the overall working environment."
Mark Wray, E.ON [18]

WHAT INFORMATION AND GUIDANCE WOULD YOU LIKE TO SEE COVERED IN LED AND CONNECTED LIGHTING CONSULTATIONS?

UPGRADING TO LED LIGHTING

PROVEN ENERGY SAVINGS

LED retrofit will cut Chase Bank's lighting bill in half

"Doing this LED retrofit made sense because the payback on lighting is pretty swift compared to other interventions you could make,"

"Makes enormous environmental and economic sense for us."[19]

The underlying energy savings and efficiency business case for LED adoption is proven. There is now a growing number of successful corporate installations showing dramatic energy savings and connected solutions, as well as the wider socio-economic benefits for employees and asset managers.

But given the growing weight of 'real-world' evidence of LED benefits and savings, we would have expected to see a much faster drive towards adoption around the globe. A contributing factor to the delay may be poor experiences during the very early roll-out of LEDs, where minimum quality thresholds, LED luminaire design criteria, and agreement of LED standards may have been evolving.

Our consultations will therefore focus on highlighting examples of best practices, successful corporate roll-out of LEDs, business cases and payback, lessons learned, and in supporting office and property managers as they assess the level of savings and wider benefits they can expect for their unique circumstances, and particularly as they seek to build their internal business case.

DECISIONS FOR CORPORATES TO UPGRADE

Most buildings have grown organically over many years, with investment in infrastructure being undertaken in various stages as the assets develop, modernize, and in some cases change ownership.

As a result, asset managers of existing buildings are not usually provided with an opportunity to design and install new lighting infrastructure from scratch. LEDs can offer managers an opportunity to reassess lighting requirements, with a wide range of retro-fittable and flexible lighting options and colors, long operational life, high energy efficiency, smart controls and opportunities to dramatically reduce running and maintenance costs – all of which represent compelling additions to the overall business case.

Royal Mail Group UK[20]

The Royal Mail Group has achieved savings of 11GWh per annum following LED upgrades.

This provided modern efficient lighting solutions and significant energy savings and reduced maintenance costs.

The luminaires included light level and motion sensors, to turn off lights when they were no longer required.

Energy savings of up to 70% have been achieved.[21]

"The highly energy-efficient LED technology delivers huge energy savings, reduces CO_2 consumption and minimizes maintenance costs without any compromise on light quality."
Mark Cavill, Energy & Building Engineering Services Manager at Royal Mail;

LED ADOPTION: NOW OR LATER?

The potential for significant energy savings with LEDs and wider benefits clearly make the technology a very attractive infrastructure investment. However, a key challenge commonly faced by stakeholders is to assess the optimum time to make the transition to LEDs based on existing assets and running costs, the availability of finance options, and the practicalities of scheduling the hardware upgrade. Some asset managers may therefore elect to postpone upgrading to LEDs, and this is where the 'cost of doing nothing' and 'opportunity costs' must be balanced.

ARE YOU DELAYING LED PROCUREMENT? WHAT IS YOUR SPECIFIC CRITERIA FOR ADOPTION?

A common question in our LED consultations concerns the potential for future improvements in LED efficiency. Over the next five years, incremental improvements in LED efficiency are to be expected, but a balance must be made between benefitting from up to 50-70% savings today and waiting to benefit from additional, albeit small, improvements in the future.

With the growing interest in LEDs, there may be an opportunity for luminaire price reductions in the future[22]. While increased volume production of assembled luminaires means prices may continue to incrementally reduce over time, the LED element itself forms a relatively small part of the overall assembled luminaire costs (i.e. which also includes housing, driver electronics, lenses, diffusers, connectors etc.) Therefore, for fixed color lighting, further manufacturing cost savings linked to the LED component are likely to have a limited impact on the final assembled luminaire pricing.

Employee enabled 'Human Centric' lighting[23],[24]

"Warmer (yellow rich) lighting... is known to help establish a comforting or relaxing environment, which many people welcome early in the morning or in an evening setting.

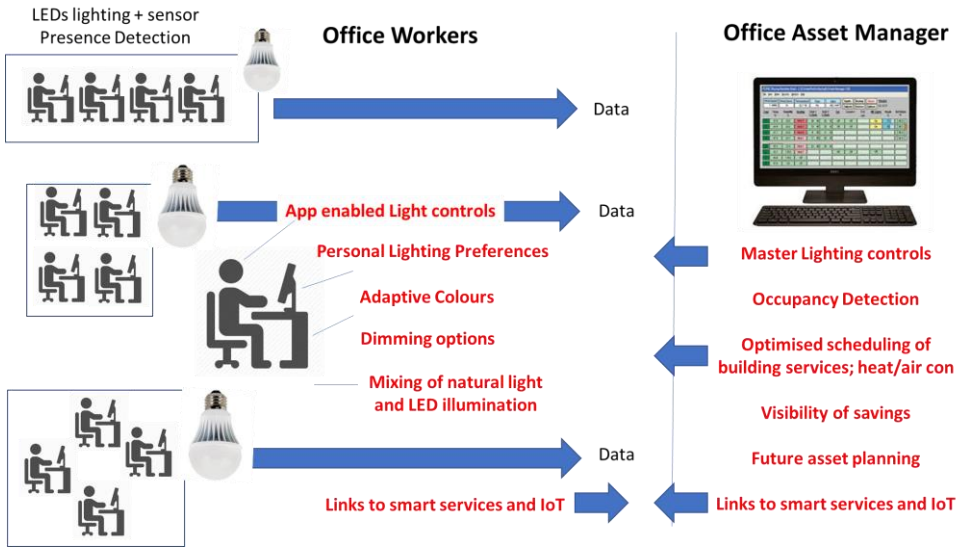
Cool (blue rich) lighting […] on the other hand, can have an invigorating effect during the day, and therefore is often preferred in contexts such as industrial workplaces, offices.. to help enhance concentration and maximize human productivity".

BEYOND SIMPLE ILLUMINATION: OWNER AND OCCUPIER BENEFITS

LED lighting options provide asset managers with a wide range of choices to upgrade lighting infrastructure. This not only realizes significant energy and cost savings, but the potential benefits can go beyond this. Upgrading provides an opportunity to reassess lighting needs and future requirements and trial different lighting designs, colors, area coverage, system connectivity and smart adaptive operation.

With the flexibility that can be achieved with LED lighting, comes additional opportunities to use new 'human centric' lighting solutions to provide employees control over their environment and help maximize employee well-being health and productivity. For example, studies report that blue enriched light in the morning can help increase attention and awareness, but warmer, yellow-rich light can be beneficial in the lead up to sleep[25].

The breadth of building data that can also be gathered provides not only opportunities to fully optimize and align building services, but also reveals asset utilization against predictions, and facilitates forward planning of employee and office/meeting space needs.



Schematic showing how sensors and controls can provide individuals the opportunity to control/enhance their work environment, health and well-being. In parallel, a wealth of operational data on lighting usage and area occupancy can be gathered by asset managers to help optimise all buildings services; providing full visibility of costs and assist in scheduling future office service needs.

MONITORING SENSORS PROVIDE LIVE STATUS AS WELL AS HISTORIC DATA, ENABLING GREATER BUILDING ASSET CO-ORDINATION.

EXAMPLES: Should businesses see the light with LEDs? [26,27,28]

LEDs can provide savings up to 50-70%, with this increasing up to >80% with smart controls. In a commercial building filled with halogen lamps, swapping out these bright but inefficient lights could see businesses reduce their lighting bills by a massive 90%.[6] Furthermore, 69% of businesses agreed improving the design of their office environment boosted productivity.[29]

The Edge:[30,31]

One of the world's most sustainable office buildings is Deloitte's The Edge which opened in 2015, and is fitted with LED lighting that can allow employees to personalize their office environment. Fixtures fitted with sensors monitor lighting levels and air temperature, and employees are able to optimize their desired lighting levels, and local temperature using app-based controls. For Deloitte this individual and local control can greatly facilitate flexible working and hot-desking. Data is gathered from when employees arrive to when they go home; if they arrive by car/bicycle they can be directed to free parking locations; general employee movements, meetings, events, and selected preferences can be logged through the day and across the seasonal year. All data is coordinated through a building Centralised Management System allowing managers to view real-time data, and provide opportunities to optimise operations over time. The Edge building has been rated by BREEAM as one of the world's most sustainable buildings. There was also an additional benefit; Deloitte experienced a 4- fold increase in the number of applicants for job roles based at The Edge.

The Leadenhall Building:[32]

The application of smart sensors and controls for LED lighting also feature in the offices of the Architect Practice Rogers Stirk Harbour & Partners, where they have installed a tuneable LED system. This allows the color temperature (K) of the luminaires to be adjusted through the day, using an approximation to our natural circadian cycles. At the start of the day the LEDs emissions are 'warm white' yellow, through the day they can be adjusted to 'cool white' to help raise levels of alertness, and then warmer white is then selected as evening approaches. The lighting sensors and controls are also able to take into consideration the outside light levels, and adjust the LEDs accordingly, to maintain the required lighting levels and maximize the use of natural light and increasing potential for further energy savings.

Cisco Canada, RBC WaterPark Place[33]

The RBC WaterPark Place are Cisco's headquarters and incorporate a range of smart buildings technology, including smart, connected infrastructure which enables employees to use mobile phones to control personalised comfort settings, including lighting and heating.

Much of the discourse around the clever science of smart buildings misses the point about the rich opportunities it affords to address the very human challenges of productivity, innovation and wellbeing."

Al Bahr Towers, Abu Dhabi[34]

Architectural firm AHR designed the Al Bahr Towers for the Abu Dhabi Investment Council and is a high-profile example of how buildings can take advantage of the latest sensor technologies. The tower facade/shutters exploit sun-tracking sensors and can open and close depending on the sun's position in the sky and lighting requirements inside. Sensors also capture wind speed and solar radiation data to adjust the building façade controls in cases of extreme winds or prolonged overcast conditions.

A key driver in the design was a more natural views form the building and minimizing the use of artificial light.

LED LIGHTING: THE TECHNOLOGY

CHARACTERISTICS AND BENEFITS OF LEDs

This section is designed to provide a technology overview of LEDs, highlighting the underlying properties and capabilities that make them an attractive opportunity for building managers. The key features worth emphasizing in the context of office lighting are outlined below.

Solid-State Lighting (SSL): [35] LEDs are based on solid semiconductor structures that can be manufactured in high volume and mounted directly onto printed circuit boards. This means:

- LEDs are 'solid-state' in structure and therefore more robust compared to conventional glass enclosed, vacuum/filament, fluorescent and discharge lamps.
- LEDs can be manufactured in volume, at low cost covering a broad range of output powers and color options.
- White light LEDs can be manufactured at low cost using a blue LED coated by a phosphor material (see side Box: How does an LED generate white light?)
- LEDs have long operational lifetimes, requiring less frequent replacement and maintenance.
- LEDs can be connected and controlled individually using a unique digital ID / IP address.
- LEDs can be turned on/off very rapidly with no warm-up time required, making them suitable for smart controls e.g. light activated when a person/vehicle is detected by a motion sensor.
- LEDs can be operated over a wide range of intensities, making them suitable for adaptive lighting (e.g. scheduled dimming) applications.
- The long operational life of LEDs means they will need to be replaced typically much less frequently, with a corresponding dramatic reduction in the number of luminaires required to be recycled[36].
- LEDs do not radiate high levels of 'direct' heat – e.g. as with a filament.
- Discharge lamps may generate visible light by converting UV light in phosphor inside the glass envelope, and may not always eliminate residual UV emission, whereas white-light lighting LEDs typically use blue LEDS covered by phosphors which emit negligible/zero UV levels.
- LEDs generate heat at their base, which is typically efficiently dissipated using metal plates.

High efficiency: compared to conventional lighting, LEDs have demonstrated savings of up to 50-70% and beyond when combined with smart sensors and controls. LEDs can produce more light output 'per Watt of power' than conventional lamps. The light output is typically measured in lumens (See box on Lumens and Watts).

Long lifetimes: [37]LEDs have a very long operating life and can maintain a minimum light level (in lumens) over an extended time (e.g. up to 50,000 hours[38]), as defined by LM-79, LM-80[39] standards, which specify 'lumen maintenance'. The long operational lifetime of LEDs requires fewer replacements and failed luminaires, providing significant maintenance cost savings opportunities and similarly reduced need for recycling of luminaires[40].

Efficient and flexible use of light: LEDs are typically small almost single 'point-like' sources of light, rather than a conventional glowing hot filament or a glowing gas discharge lamp. The fact that LED light comes from a small area allows lighting engineers to employ very efficient optical designs that can deliver light to the required place at the required 'lumen' light level. LED luminaire designs can be optimized for a breadth of lighting needs, and specified to reduce over-lighting and light pollution.

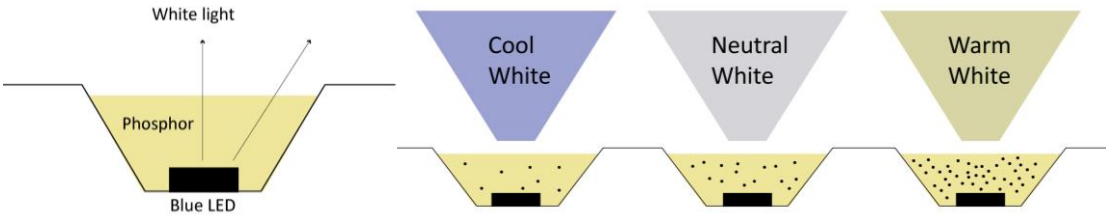
SAVINGS FROM LED LIGHTING CAN COME FROM REDUCED ENERGY USE AND FROM REDUCED MAINTENANCE/REPLACEMENT COSTS.

Broad range of LED color options: LEDs can be manufactured to emit specific light colors as well as different white light options (e.g. warm 'yellow', neutral and cool 'white'). Very early LED products suffered from color instability, particularly with low quality lamps and the color would change as the LED aged. This issue has greatly improved and LED manufacturers are now able to specify and warranty long-term LED color operation.

HOW LEDS GENERATE WHITE LIGHT AND 'COLORS'

LEDs were first developed in the 1960s, and since then multiple variations of color ranging from red, yellow, green and blue have been developed. A major breakthrough that allowed LEDs to be used in general lighting applications came in the 1990s with the development of high power blue LEDs based on new semiconductor materials. By using a single high power blue LED, coated with a phosphor material, a low cost white light could be developed. The blue light is absorbed by the phosphor which then emits light across a range of spectrum colors which combine to create white light (see figure).

By selecting the composition of the phosphor material it is now possible to create white lights with different appearances. They can range from blue 'cool' white, 'neutral' white, or yellow 'warm' white, with each characterized by a specific numerical 'color temperature'[41] – expressed in units Kelvin(K). There are 8 nominal white LED 'color temperatures' defined: 2700K, 3000K, 3500K, 4000K, 5000K, 5700K and 6500K. The overall efficiency and lighting benefits can vary depending on the selected white option, with the 'cool white' (high Kelvin values) being slightly more efficient compared to 'warm white' LEDs (low Kelvin values).



For general lighting applications, where low cost options are important, white light LEDs based on the structures shown above are the main products of interest. The combined use of different cool, neutral and warm white LED solutions is being explored as an option to provide office lighting with options to activate cool-blue white LEDs in the mornings, to help employees increase their alertness, and to switch to warm-yellow/white LEDs in the mid/late evenings to help reduce blue-light exposure in the immediate lead up to bed-time.

TUNABLE WHITE AND DYNAMIC COLORS[42]:

There are product options available that can offer adaptive 'white' office lighting; using a mix of cool, neutral and warm white LEDs in office as indicated above. This capability to tune the 'white' color mix from blue-rich to yellow rich colors can be termed 'dynamic' lighting.

In many circumstances most office lighting needs can be satisfied with such solutions. However, in some bespoke situations, full color spectrum tunability (Red/Green/Blue LED mixed) may be required which can provide both mixed white as well as individual specific color lighting capabilities – but may require more complex controls and are primarily selected for artistic lighting, external lighting, entrance foyers etc.

LED CONSULTATIONS: RECURRING TECHNOLOGY QUESTIONS

Recurring technical questions are raised in consultation events, and examples include:

LED color: There are a range of LEDs with fixed and tuneable color options, however for most office and building applications connected and adaptive white light LEDs are usually sufficient. These can come in a range of cool, neutral and warm white appearance and can be installed with dimming capabilities. There is ongoing debate on which option could be best suited as a general lighting solution, or whether for different circumstances and times of day, one may be more optimum. Therefore trials of one fixed white option, and also mixed (cool/neutral/warm) arrays of white LEDs can provide options for optimising the lighting through the day, and identifying user preferences.

Each lighting situation is unique

The advent of LEDs can provide an opportunity to completely reassess office lighting needs; color, adaptive controls, the use of sensors, and the wider role connected lighting could play in building operations.

LED glare: There have been examples where LED luminaires[43] exhibited glare (bright light emitted at specific or extreme angles), which may appear intense to drivers and pedestrians. A selected LED luminaire design[44] may be generally applicable across a wide range of indoor office lighting, but which may have undesired effects in certain specific locations. Such undesired effects can be minimized with luminaire design, using light diffusing elements, shades/baffles and options for lighting engineers to adjust the luminaire alignment at the time of installation.

Light flicker[45]: Flicker is the high frequency variation of light which can be present in all common electric mains powered lighting. Lighting standards define procurement guidance to ensure health and safety requirements are satisfied but LED adopters may also wish to include hardware compatibility testing and site specific functional acceptance tests at the time of installation to ensure flicker standards are satisfied.

Emission of blue light: The role of LEDs as a contributor to artificial light exposure (and in particular 'blue light' exposure), and the possible resulting disruption to sleep and subsequent health impact is a common question raised in our consultations. In terms of light intensity, individual luminaires are specified within national safety exposure standards, where light intensity levels are strictly tested and certified. The effects of all artificial light exposure on the level of human alertness can depend on a variety of factors including the source of light, the amount (intensity) of light, the duration of exposure, the light colors, the time of day the exposure occurs, the age of the observer, etc. Such cumulative exposure can come from wide variety of direct sources including existing (non-LED) office lighting, direct viewing of computer screens, mobile phones, tablets and e-readers.[46]

The European Union Scientific Committee on Health, Environment and Emerging Risks published research[47] stating that there is no health risk for healthy humans to be exposed to LEDs in the normal use of lighting and display products.[48]

ARE THERE SPECIFIC TOPICS OF INTEREST OR REMAINING LED MISCONCEPTIONS THAT YOU WOULD LIKE US TO ADDRESS?

FRAMING LED INDOOR LIGHTING OPTIONS

LIGHTING OPTIONS

Building asset managers seeking to upgrade their lighting infrastructure will likely base their decisions on the status of the current infrastructure, available funding and what potential savings and wider benefits could be realized. The range of available lighting options and the relative ease of implementation of LEDs compared to other energy saving building renovation solutions means managers can completely revisit their lighting requirements and add previously unavailable controls and sensor capabilities. For the purposes of our consultations, we can discuss the adoption of LED lighting on four simplified levels.

1. Direct replacement of conventional luminaires with equivalent on/off LED luminaires.
2. LED luminaires controlled with manual and app enabled on/off controls, optional fixed dimming, and photo-sensors. These may also include motion/proximity sensors to trigger lights.
3. Connected LED luminaires accessible by users and linked to a centralized building management system, allowing optimisation of building services beyond the lighting systems. E.g. live occupancy sensor data and scheduled space usage could allow optimisation of heating/cooling systems, update security status, and schedule cleaning/servicing etc.
4. A fully integrated building management system and additional links to external inputs, and the wider city and IoT.

The relative and cumulative benefits of the four options can be summarized in the figure below:

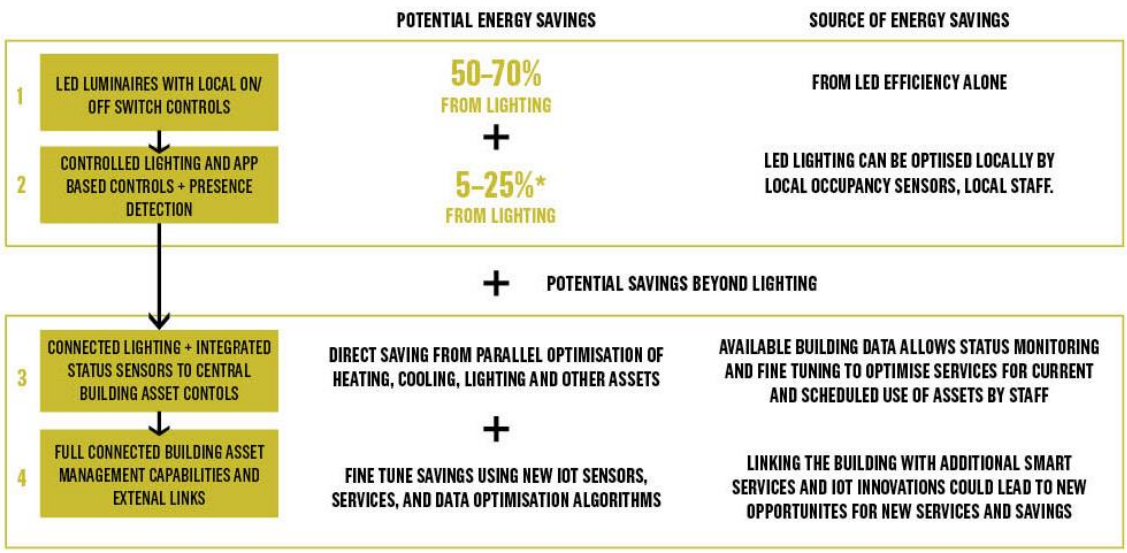


Figure: Option 1 represents the core savings that a basic switch to LEDs can provide. Option 2 could be considered a minimum recommendation for adoption in office environments. The addition of connectivity and sensors provides routes to maximise benefits and functionality, as outlined in Options 3 through 4, where data gathering allows enhanced co-ordination and optimization of wider building systems.

Single or multiple budget holders may exist

Most lighting[49] is not installed and directly paid for by the end-user, and as a result different budget holders and incentives may exist.

Private organizations may historically manage their infrastructure and operations budget separately and this may create competing incentives to reduce equipment costs at the likely consequence of higher running costs.

Options 1, 2 each offer immediate energy savings from LEDs compared to traditional lighting. Options 3 and 4 also offer lighting managers opportunities for connected, building-wide monitoring, control and asset management capabilities via tools such as a central management systems (CMS) and dashboards. Where budgets may be constrained, and for circumstances where basic lighting solutions are sufficient (e.g. simple on/off control) then Option 2 could be considered a minimum specification, but modular options to upgrade to add 'connectivity' capabilities should be explored.

ARE YOU CONSIDERING A SIMPLE LED RETROFIT, OR A FULL CONNECTED BUILDING INFRASTRUCTURE UPGRADE?

INTELLIGENT AND SMART CONTROLS

For the purposes of the consultations we can use the term intelligent luminaires as meaning a pre-set luminaire programmed to turn on in response to activation of a local intelligent presence detection sensor. Such features can provide additional energy savings, particularly if lights can be turned off, dimmed and activated automatically when needed.

Currently many new and exciting smart control and IoT concepts are in development and will likely require periods of trialling and testing to assess their benefits and business case. Therefore, system flexibility, interoperability and security are key themes to keep in mind when linking core building assets (e.g. lighting, heating, water etc.) to the breadth of new smart/IoT technologies in development – all of which may have different:

- speeds of innovation and product development;
- ranges of key adopters and managing stakeholders;
- technical specifications and applicable standards;
- physical connection interfaces, power requirements, and data protocols;
- safety and security requirements;
- new and 'unproven' operating business models;
- legal operating requirements;
- data gathering rights e.g. of public and citizen information; and
- data ownership and rights of commercial use.

Le Hive Building, Paris[50]

Schneider Electric's global headquarters in Paris is a 7-storey building with 1,850 employees that has reduced by 50% its heating, ventilation, air conditioning (HVAC) and lighting energy use from 150kW/m^2/year to 78kW/m^2/year in three years.

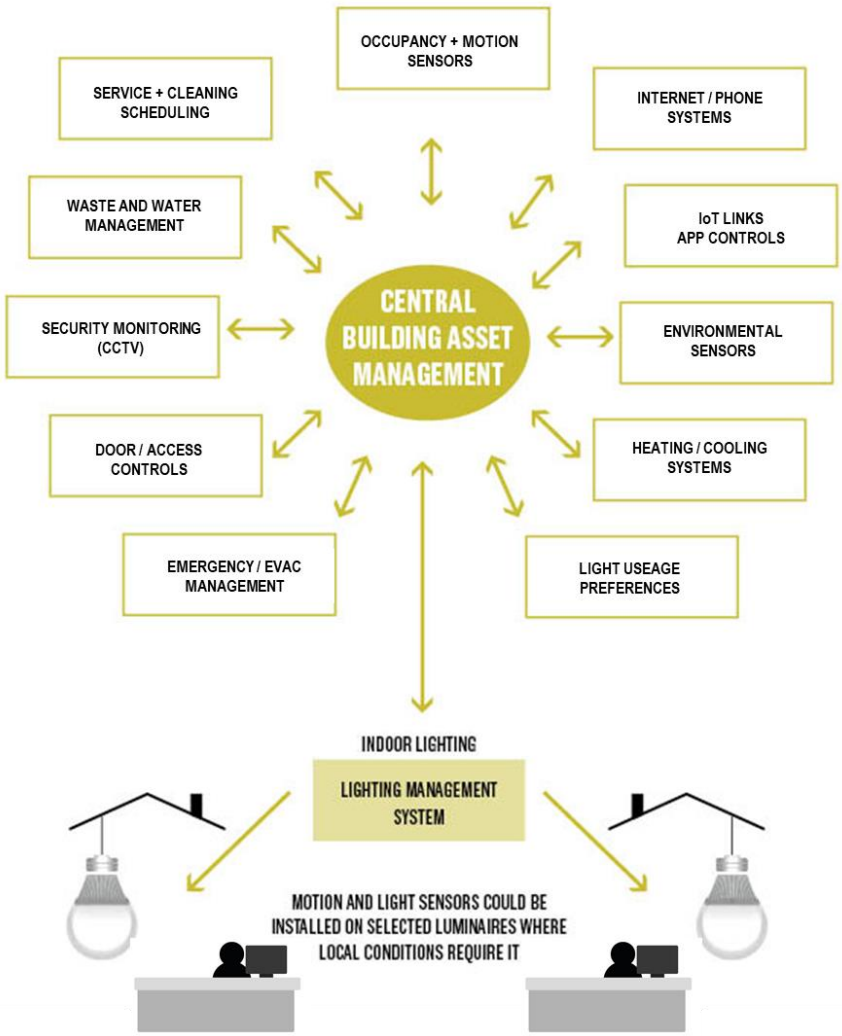
WHAT BUILDING SENSOR DATA WOULD YOU SEEK TO COLLECT?

CONNECTED LIGHTING

Connected lighting (or connection ready) should ideally be considered the minimum requirement for LED lighting upgrades, in both indoor and outdoor applications. Connectivity (e.g. wireless/mobile based) can provide the fundamental linkage between lighting assets, end users, building managers and the wider smart-building environment. The adoption of these links can allow software upgrades to be made, and allow luminaire-mounted sensors to be incorporated within existing light fittings, negating the need for separate sensor installations.

CONNECTED LED LIGHTING SOLUTIONS MUST INCORPORATE: FLEXIBILITY, INTEROPERABILITY, FUTURE SCALABILITY AND ROBUST SECURITY

One solution to connected building infrastructure could be to define fixed, secure, flexible and manageable interfaces for systems and services linked to the building communications (cloud) platform and to a central asset management system (see figure below). This approach could help reduce the dependence of specifying today all the different possible operating permutations, requirements and connection standards for what could be a multitude of new and evolving smart and IoT technologies from a range of manufacturers.



Concept of lighting, sensors and other building services linking to a central asset management system. Asset managers can control and update core building systems independently while also exploiting a connected and co-ordinated suite of systems.

EQUIPMENT INTEROPERABILITY

With the growing range of products and services and potential for increased public access (via IoT) to control critical building systems there is a need to ensure secure and protected installations, and defined levels of accessibility. Conversely, there is a desire for wider, more standardized 'plug and play' approaches for new smart and IoT hardware and wider demand for more interoperability of equipment across different manufacturers. It is inevitable a single supplier will not be able to provide all of a buildings operational products and services, which inevitably leads to the use of equipment from different manufacturers, and a growing recognition of the need for wider use of non-proprietary sockets and open (but data secure) protocols to allow future procurement flexibility for customers as well as to drive standardization in the industry.

SMART BUILDINGS INHERENTLY RELY ON AN IN-BUILT AND INTEROPERABLE ECO-SYSTEM. ARE YOU EXPLORING HOW TO BETTER INTEGRATE MULTIPLE BUILDING SYSTEMS?

DATA PRIVACY, DATA SERVICES, SECURITY AND OWNERSHIP

The growing interest in deployment of sensors and 'Big Data' gathering projects in cities and buildings data can encompass many activities; e.g. status of core building services, assessing energy use, occupancy and use of assets, identifying employee activities and preferences, security monitoring, access control to secured areas and emergency response planning.

As the number and variety of interactive services increases, and the corresponding number of potential users and access points increases, the potential for hacking, and 'denial of service' attacks becomes a concern. There is therefore a balance to be made between maintaining the operational security of fundamental infrastructure, and the level to which it is allowed to be accessed by employees, visitors, and wider cloud based systems. One approach mentioned above could be for the manager to maintain control of critical assets via an isolating 'interface' to the building 'cloud' – where the level of access from external links are managed, limited and when required overridden by asset management systems and managers.

Finally, it is apparent from our previous city focussed consultations that the laws governing public data collection, (e.g. including invasion of individual privacy), ownership, and rights of commercial use remain largely undefined in many countries. Therefore, legal advice should be sought regarding rights of data collection and ownership linked to monitoring and security activity in buildings, particularly where this may include monitoring of employee and visitor movements.

Standards and quality thresholds

It is critical to define the required lighting product quality thresholds and lighting standards that suppliers must meet.

This helps to ensure that all suppliers are assessed on a 'level playing field' rather than simply on cost for what may be very different levels of product quality, build, reliability and operating standards.

LED STANDARDS, QUALITY AND ENFORCEMENT

With the advent of LEDs, many new lighting solution providers are offering products and services, and there is a need to ensure that all lighting products meet defined quality thresholds – and that local, regional and established international lighting manufacturers are all held accountable to the same standards and quality control enforcement. This allows lighting managers to undertake fair comparisons and assess product quality and performance from a range of providers.

While many governmental, corporate and trade agencies are working to bring consensus on lighting standards, it is clear from our consultations that regional variations remain. Building and lighting managers may face an ongoing challenge of satisfying applicable local lighting standards, applying wider international guidelines and industry best practices, undertaking appropriate trials and assessments and benefiting from lessons learned by their peers.[51]

The role of government and policymakers is therefore critical, not only in publicly committing support to large scale energy efficiency initiatives such as LED adoption, but also in parallel capacity building initiatives in their regions to ensure that national testing labs and published standards are put in place, and strictly enforced[52].

INTELLIGENT LIGHTING CONTROLS CAN SERVE AS A PLATFORM FOR FUTURE SMART BUILDING SERVICES. THE SMART CITY MARKET[53] IS LIKELY TO BE WORTH US $ 1.5 TRILLION BY 2020.

DO YOU NEED GUIDANCE ON OPTIONS TO BEST FUTURE-PROOF YOUR INSTALLATIONS AND MAINTAIN BOTH FLEXIBILITY, EQUIPMENT INTEROPERABILITY AND SECURITY?

VISIONS OF THE FUTURE[54]

Future office trends[55,56]

Some of the growing trends in office working include; flexible working and hot desking, configurable office design including biophilic environments, with energy savings optimized relative to the outside environment, virtual reality meeting(s), family friendly offices, AI-based office administration, and the use of wearable technologies to facilitate a smooth transition for employees from commute to comfortable and efficient environments through the day.

By allowing individuals and groups to control their surroundings, we allow the space to come alive and become activated by people.

World's first LiFi office to open in Paris[57]

The new Sogeprom office is located in the La Defense area of Paris and is the first major workplace to exploit broadband bi-directional LiFi communications. Instead of WiFi or physical cables, office workers will insert a 'dongle' into their computers and connect to the internet via LiFi with the office lighting. The user will receive data using visible light and communicate back to the light fixture using an infra-red transmitter. A French firm also is installing LiFi based systems in the Paris Metro, involving over 250,000 LED luminaires in 66 stations.

Grand View Research has predicted the market for light-based data communications, including LiFi and visible light communication would be worth US$100 billion by 2024.

Risk of 'Big Brother' perception[58]

The use of sensors to monitor building occupancy and asset status can provide managers with powerful information to optimize overall asset use. However, the use of wearable technology and sensors can go far beyond simply building management. The use of employee smart badges and tags provide the potential capability to track individual employee and visitor behaviour, so corporations exploring such systems must ensure individual privacy considerations are not compromised.

"For workplace managers, there's a new kid on the block – live monitoring of employee behaviour – but while this is aiding better office design, privacy implications are extensive."

LED ADOPTION: HOW CAN WE SUPPORT YOU?

THE DECISION TO UPGRADE TO LEDS

Assessing 'total cost' and 'total value' of LED ownership.

The benefits and value of LED ownership can extend far beyond simply a reduced $ cost per light unit (lumen), and reduced maintenance costs.

Longer LED lifetimes also means far less luminaire replacement and recycling.

The addition of smart controls, and lighting connectivity can provide additional value supporting future smart building services, facilitate asset management, and provide opportunities for wider data collection.

Connected LED lighting solutions provide an opportunity for lighting and building asset managers to reassess and optimize the lighting capabilities in their facilities/offices, and to explore how a connected lighting infrastructure can integrate with and support other key building services. As a result, the LED procurement process will inevitably extend beyond the procurement of 'lamps', which means that multiple and new stakeholders could be involved in the procurement review decision.

> *"The current goals of sustainability, reduction in energy consumption or "carbon emissions" can distract us from the far better long-term success of achieving a truly sustainable lighting design.*
>
> *It's not just about the technology, but why and how that technology is applied..."*[59]

In undertaking procurement of new lighting infrastructure there are fundamental processes that asset managers will undertake. At the most basic level, the first step towards upgrading is to review the buildings current lighting assets inventory and the new, projected future lighting needs and building layout. This allows managers to explore new opportunities for removing or repositioning light fixtures, to help address over-lighting and identifying desired light levels and colors, and the coverage and quality of light and services required in different areas. The breadth of opportunities available with LEDs and matched controls can provide building managers and tenants with new and flexible options to enhance office lighting and maximize potential savings.

An assessment of needs, drafting of requirements, definition of required standards, and setting of product quality thresholds ultimately forms the framework for the internal business case, and we would encourage different scenarios and options to be explored and associated costs can be estimated. During this phase of project assessment, a commonly misplaced comparative metric is discussed; the project 'payback period'. It should be remembered that every project and building is unique, and caution should be applied when comparing different projects based solely on quoted 'payback periods'.

One interesting, new and evolving route to light procurement is based on 'lighting as a service', or 'pay by Lux' where the installation, operation and maintenance of lighting is managed by a service provider, and the end user/tenant pays a fee. One such examples is RAU Architects[60] and a similar 'pay as you' go facility lighting is in operation at Schipol airport in Europe[61].

CONSULTATION FINDING: BEWARE COMPARING REPORTED 'PROJECT PAYBACK PERIODS'

A common question in our LED consultation workshops is 'what is the typical project payback period?'

"The payback period can vary depending on your unique upgrade and financing circumstances."

Every project scope and circumstances are unique in terms of lighting design and financial approach. Project payback periods may therefore depend on a multitude of variables. Some building managers may also elect to pursue a fast payback, whereas others may deliberately spread their loans over a longer period for their particular financial circumstances.

Finally, the role and value of LED lighting trials should not be underestimated. Trials can prove invaluable for testing new lighting solutions and controls, and new configurations in different office situations, and provide sources of feedback and preferences from the office end-users before finalising procurement requirements.

Trials can aid adoption for all stakeholders

More and more building managers are exploring early LED lighting and connectivity options as they assess upgrade options.

The use of early LED trials can allow opportunities for managers and employees to experience and test the benefits of alternative whiter light color options, as well as adaptive smart controls and linked sensors – alongside traditional lighting sources.

WHAT INFORMATION OR SUPPORT DO YOU NEED TO PREPARE YOUR BUSINESS CASE FOR LED UPGRADE?

Post COP21 and COP22 there is a renewed urgency towards low carbon energy generation, increased energy productivity, and technological innovation to drive down emissions at scale. LED lighting is one of the most mature, proven and energy efficient low carbon technologies available today.

LED indoor lighting projects are already delivering and, in many cases, exceeding original projected energy savings while providing new socio-economic benefits for employees and tenants and wholly new approaches to controls and sensors for critical asset data gathering.

The need for a sustained effort to drive LED scale up in buildings is clear and urgent. The catalyzing role of supportive energy efficiency policies and national and sub-national commitments cannot be underestimated in driving urgency and consensus among local stakeholder groups.

Our ongoing consultations will seek to involve all key local stakeholders to identify new options and solutions that can facilitate LED lighting upgrades, at scale, around the globe. We look forward to your participation in our expanding LED consultation process.

FINAL WORD: ACCELERATING LED CORPORATE ADOPTION

LED technologies can offer unprecedented energy savings opportunities, as well as a wide range of lighting options and connected system capabilities that were previously unavailable to end users. When compared to other energy efficiency actions that can be implemented in the built environment, LEDs represent a significant and compelling savings opportunity.

Our goal is to 'spotlight' the immediate opportunity that LEDs and connected lighting can provide in terms of monetary and energy savings, the immediacy of accessing those savings, and the scope for stimulating wider smart services. We seek to drive and support actions that can help accelerate LED adoption and realize our **2020 Call to Action** on energy efficient indoor corporate lighting.

However, The Climate Group also wants to ensure the urgent drive for energy efficient lighting is not compromised by low quality, sub-standard LED products being allowed to enter the market, nor result in inappropriate replacement of fixtures, unnecessary over-lighting, or lack of flexibility in light adjustment. We recommend early consultations and, where necessary, sample trials to confirm and demonstrate lighting needs, and to aid in refining procurement specifications for large scale LED roll-out.

Finally, The Climate Group seeks to encourage collaborative efforts and interoperability between manufacturers and suppliers to help standardize smart approaches and facilitate the roll out of IoT innovations. However, a balance must be maintained between increasing accessibility and flexibility and maintenance of control and asset security.

As part of the suite of low carbon and energy efficient actions corporations can explore, connected LED lighting solutions are ready today, delivering on savings and should be prioritised alongside wider actions on building renovations. If you have not yet actioned a review of the potential benefits and savings from energy efficient lighting – do so today.

CONTACT INFORMATION

For further information on this activity, related events and how to participate please contact The Climate Group team. **Email:** LED@theclimategroup.org

The document is intended to be a working document and a supporting summary to The Climate Group's ongoing LED consultations activities as part of their LED Scale-up programme (see www.theclimategroup.org in partnership with Signify www.signify.com.

This document was prepared by Toby Morgan and Dr Peter Curley, with background research by Arianna Tozzi. Many experts and consultation participants have provided insights and guidance, and we would like to thank all those that have supported our efforts.

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Appendix:

CHANGING MIND-SETS: LUMENS AND WATTS [62]

The advent of LEDs has prompted a need for wider awareness of how light performance is specified. In the past, light lamps were defined according to type (e.g. incandescent, high intensity discharge etc.) and power Wattage (e.g. 40W, 60W, 100W, 250W, 400W etc.). Each delivered a known light level, color and quality of light, over a known area.

LEDs can deliver the same light output as traditional lights but using far fewer Watts of power. This means that the level of illumination of a traditional household 40W incandescent lamp can now be achieved using, for example, a 5W LED lamp. In future, as lights become more efficient, the specified Wattage may reduce even further for the same level of light output. So end users should select lighting solutions according to the amount of light needed – measured in Lumens[63] – and not by Wattage. The efficiency of the lamp is defined by how many lumens are delivered, divided by the number of Watts consumed, or in Lumens per Watt (lm/W).

Manufacturers may provide 'conversion' tables, for near-equivalent traditional lights to LED products, however caution is advised. In some cases, this approach has led to examples of 'over-lighting' and 'under-lighting', and examples of procured LED luminaires providing different or insufficient lighting coverage. For the avoidance of doubt we would encourage trials and/or product samples to be tested to ensure that adopted solutions satisfy the requirements for the lighting applications.

REFERENCES

[1] IPCC and WRI – Accelerating Building Efficiency – Eight Actions for Urban Leaders; http://www.wri.org/publication/accelerating-building-efficiency-actions-city-leaders
[2] https://www.carbontrust.com/resources/guides/energy-efficiency/lighting/
[3] https://www.energyinst.org/media-relations/media-centre/1718
[4] http://www.wri.org/blog/2016/05/4-surprising-ways-energy-efficient-buildings-benefit-cities
[5] Illuminated, Integrated and Intelligent: Reinventing the Workplace – Philips Smart Buildings.
[6] https://raconteur.uberflip.com/i/845148-future-workplace-special-report-2017
[7] https://hbr.org/2017/06/a-new-way-to-think-about-office-lighting
[8] https://www.theclimategroup.org/sites/default/files/led_consultation_handout-2017-update.pdf
[9] http://united4efficiency.org/
[10] http://united4efficiency.org/wp-content/uploads/2015/11/U4E-Savings-Assessment_IND.pdf
[11] http://www.iop.org/news/14/oct/page_64180.html
[12] Philips Lighting, The LED revolution booklet, 2015. http://www.philips.com/consumerfiles/newscenter/main/standard/resources/corporate/press/2015/COP21/Booklet-LED-lighting-revolution-2015.pdf
[13] http://economictimes.indiatimes.com/articleshow/57789646.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst
[14] http://www.iea.org/textbase/npsum/lll.pdf
[15] https://www.eia.gov/outlooks/ieo/world.php
[16] https://www.fgould.com/uk-europe/articles/uk-building-stock-carbon-reduction-commitments/
[17] http://www.iea.org/textbase/npsum/lll.pdf
[18] http://www.telegraph.co.uk/business/energy-efficiency/why-leds-are-good-for-businesses/
[19] http://www.gereports.com/worlds-largest-led-retrofit-will-cut-chase-banks-lighting-bill-in-half/
[20] http://luxreview.com/article/2015/10/royal-mail-delivers-on-energy-savings
[21] http://www.volkerfitzpatrick.co.uk/en/projects/detail/royal-mail-uplift-programme
[22] http://optics.org/news/5/4/5
[23] http://luxreview.com/article/2016/07/ten-human-centric-lighting-stories-you-must-read
[24] http://luxreview.com/article/2017/01/how-to-design-human-centric-lighting-by-scientist-who-discovered-it-
[25] http://www.ledsmagazine.com/articles/print/volume-13/issue-8/features/tunable-lighting/explore-and-control-led-based-tunable-white-lighting.html
[26] http://www.telegraph.co.uk/business/energy-efficiency/why-leds-are-good-for-businesses/
[27] http://ukenergylighting.co.uk/benefits-of-led-lighting-in-offices/
[28] http://www.smartbuildingsmagazine.com/features/office-lighting-now-is-the-time-for-retrofitting-leds
[29] https://raconteur.uberflip.com/i/845148-future-workplace-special-report-2017
[30] http://www.breeam.com/index.jsp?id=804
[31] https://www.bloomberg.com/features/2015-the-edge-the-worlds-greenest-building/
[32] *http://www.spectral-lighting.co.uk/news/leadenhall.html*
[33] http://officeagenda.britishland.com/assets/pdfs/smart-offices.pdf
[34] https://www.autodesk.com/redshift/al-bahr-towers/
[35] For example: US DoE, *Solid State Lighting, Technology Fact sheet*, 2015 http://www.energy.gov/eere/ssl/technology-fact-sheets
[36] Note: The separate LED elements are a very small of the electronic components and may not warrant separate recycling.
[37] For example: US DOE, *Solid State Lighting Fact Sheet: Lifetime*, 2013 http://www1.eere.energy.gov/buildings/publications/pdfs/ssl/life-reliability_fact-sheet.pdf
[38] Note: For a typical LED operating 10-12hr/day, 50,000 hrs would be equivalent to ~11 to 13 years of operation.
[39] US DoE, *LED Lighting Facts*, 2015 http://energy.gov/eere/ssl/led-lighting-facts

[40] Note: In many cases the cost of a maintenance needed to replace a complete luminaire can far exceed the cost of the luminaire itself.
[41] Note: Color Temperature is defined in degrees Kelvin (e.g. 3000K may be termed a 'warm' white, 4000K a neutral white, and >4500K a cool white. The precise upper and lower Kelvin boundaries for these general LED colors may vary by manufacturer).
[42] http://luxreview.com/article/2016/05/two-minute-eplainer-tunable-white-leds
[43] New Scientist, *Lighting Cities with cheap Glaring LEDs is a dim move*, 2015 https://www.newscientist.com/article/dn26383-lighting-cities-with-cheap-glaring-leds-is-a-dim-move
[44] http://www.lighting.philips.co.uk/support/support/faqs/led-light-fittings/luminaire-design-to-reduce-glare.html
[45] For example: Us DoE, *SSL Fact Sheet – Flicker*, 2013 http://www1.eere.energy.gov/buildings/publications/pdfs/ssl/flicker_fact-sheet.pdf
[46] Gigaom, *Can E-Readers really harm sleep?* 2014 https://gigaom.com/2014/12/23/do-e-readers-really-harm-sleep-depends-what-you-call-an-e-reader/
[47]https://ec.europa.eu/health/sites/health/files/scientific_committees/scheer/docs/scheer_o_011.pdf
[48] http://www.ledsmagazine.com/articles/2017/07/european-union-organization-says-leds-have-no-direct-adverse-health-effect.html?eid=339482905&bid=1844184
[49] http://www.iea.org/textbase/npsum/lll.pdf
[50] http://www.breeam.com/index.jsp?id=583
[51] Solid State Lighting *SSL Annex, Product Performance Tiers*, 2016 http://ssl.iea-4e.org/product-performance
[52] The Climate Group, *LED workshop addresses Energy Efficiency Lighting Solutions*, 2016.
[53] Frost and Sullivan, *Global Smart cities market reach US$ 1.5 trillion by 2020*, 2014. http://ww2.frost.com/news/press-releases/frost-sullivan-global-smart-cities-market-reach-us156-trillion-2020
[54] https://raconteur.uberflip.com/i/845148-future-workplace-special-report-2017
[55] http://www.telegraph.co.uk/business/sme-library/managing-your-business/office-of-future/
[56] https://journal.thriveglobal,com/the-future-of-workplaces-499c2010173e
[57] http://luxreview.com/article/2016/06/world-s-first-li-fi-office-to-open-in-paris
[58] https://raconteur.uberflip.com/i/845148-future-workplace-special-report-2017
[59] Martin Valentine, Lighting Expert, Abu Dhabi, private communication
[60] https://www.ellenmacarthurfoundation.org/case-studies/selling-light-as-a-service
[61] http://luxreview.com/article/2015/04/pay-as-you-go-lighting-arrives-at-amsterdam-s-schiphol-airport
[62] https://www.gladiatorlighting.com/light-bulbs/led.html
[63] Note: Lumens per Watt then defines the efficiency; i.e. how many Lumens of light per Watts of energy used.