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REVIEW OF THE CURRENT STATE AND FUTURE DEVELOPMENT IN STANDARDISING ARTIFICIAL LIGHTING

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"It is with gratitude that I dedicate this paper to the memory of Lou Bedocs. Lou was a mentor throughout much of my professional life and also a good friend. He helped me write my first ever research report and collaborated with me on a number of research projects. He encouraged my involvement in the world of standards and regulations and was always ready to give help or guidance."

ABSTRACT

This paper discusses the organisations involved in the development of application standards, European regulations and best practice guides, their scope of work and internal structures. It considers their respective visions for the requirements for future standardisation work and considers in more detail those areas where these overlap, namely human centric or integrative lighting, connectivity and the Internet of Things, inclusivity and sustainability.

Keywords: artificial lighting, standardisation, application requirements, regulatory body, IoT

1. INTRODUCTION

When considering artificial lighting there are two main areas of standardisation, product requirements and application requirements. Product requirements are predominantly concerned with safety and performance whilst application requirements consider what criteria need to be satisfied when using a product within a lighting installation. This paper shall predominantly focus on the work of standardisation of application requirements.

As the development of standards may be performed to address specific regulatory requirements from an individual state such as the United Kingdom or Russia, or from a wider political body such as the European Union, there can also be close links between standards organisations and regulatory bodies. For instance the documents EN15193–1:2017 [1] and PD CEN TR15193–2:2017 [2] were developed under a European Union Mandate to support the European Energy Performance of Buildings Directive [3].

Professional and trade associations can also help drive the standardisation process as they develop concepts regarding best practice and solutions that provide more functions. They also tend to provide a large number of the experts working within standards development.

Fig. 1. Inter-relationships and inputs to standardisation

However standards need a solid scientific basis, and therefore make use of papers presented in academic journals and technical conferences. The academic input in terms of new research helps guide standards development to define/refine established best practice.

Therefore the standardisation landscape can be quite complex and confusing when viewed from the outside, Fig. 1.

Who works within these structures and organisations in developing standards and who they represent can be difficult to appreciate and can change depending upon the organisation they are a member of and their role within the organisation.

However within this arena, much valued work is produced to help guide lighting professionals in best practice.

2. STRUCTURES AND REPRESENTATIVES

At an international level standardisation is generally performed within the International Electrotechnical Commission (IEC) for product standards and the International Organization for standardisation (ISO) for application standards. Within Europe these equate to CENELEC for product standards, the European Committee for Electrotechnical Standardisation, and CEN for application standards, the European Committee for Standardisation.

International standards may also be produced by other organisations such as the International Commission on Illumination (CIE) or less formally by various industry consortia such as Zhaga, a global lighting-industry organisation that aims to standardise components of LED luminaires.

These organisations can roughly be split into four categories;

- Professional societies which generally concern a specific discipline and further the interests of professionalism within that discipline and their members.
- Trade associations and industry consortia which generally represent the interests of a specific industry with respect to standards and regulations and may also develop the market potential for that industry.
- Standards bodies, which develop technical standards giving requirements based upon good practice and acceptance.
- Law making or regulatory bodies such as governments who enact laws to enforce safety and standards and protect consumers.

When working across these organisations a person may be representing themselves, their employers or their country as shown in Fig. 2.

So within professional societies a person generally acts as an individual, unless they have a formally appointed position, in which case they tend to represent the society; within industry associations a person tends to represent a company; and within standards bodies they tend to represent a country. It is difficult for a person from academia or industry to be directly involved in law-making although they can influence the process through lobbying and informing politicians and government organisations on what is good practice and practicably achievable.

	Societies	Associations	Standards	Laws and directives
World	CIE	WTO	ISO, IEC	UN
Continents	IESNA, CIEChina, IESAustralia	NEMA CCI AMF	ANSI, ASTM CCC ASI..	Federal Governments
European	(Lux Europa)	LightingEurope	CEN, CENELEC	EU
National, in each country, f.e.	LiTG, SLL, ILP, LTG, SLG, AFE, NsVV, ...	ZVEI, FEEI, LIA, SdIE	DIN, BSI, ON, AFNOR, SNI,	National laws f.e. Building regulations, EnEV, ...
Representation	Dedicated lighting experts	Companies lighting experts	Appointed national delegates	Politicans, lobbyists

Fig. 2. National and International organisations and representation

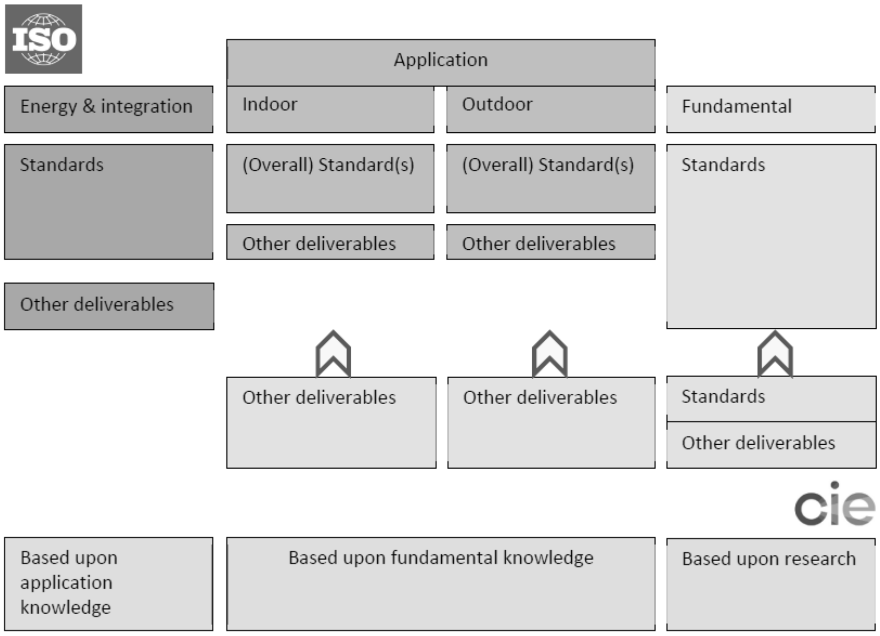

Fig. 3. Visualisation of horizontal cooperation between ISO/TC274 and CIE in lighting [36]

To help coordinate work between committees and organisations formal liaison arrangements may be agreed, and in this case a person will represent the organisation they are liaising for. So, for example, a liaison officer for ISO/TC274 to the CIE would represent ISO/TC274 within the CIE.

National standards bodies, such as BSI, will shadow the standards work, being performed at an international level, propose national experts to help in the work and submit comments on proposed work items and draft documents. They will also vote on the acceptance of documents submitted for approval and publication. For example, BSI shadows the work being performed within CEN/CENELEC and also ISO/IEC.

Each of these categories and their component organisations are considered below.

3. STANDARDS ORGANISATIONS

3.1. ISO/TC274: Light and Lighting

At the level of international standardisation ISO/TC274 is the main technical committee with a scope of standardisation in the field of application of lighting. It is a relatively new technical committee, previously at ISO level lighting was considered as a factor within a diverse set of technical committees producing non lighting specific standards. For example, lighting was considered within the work of ergonomics standardisation committees. To ensure lighting was considered correctly by dedicated lighting experts, and that the chain of national shadow committees commenting and voting on lighting related standards corresponded correctly, the topic of lighting was centralised within ISO/TC274. It works closely with the International Commission on Illumination (CIE) and coordinates work programs. This cooperation results in three possible routes for new work items depending upon the level of cooperation that is considered relevant:

- Informative relation – One organization is fully entrusted with a specific work item and keeps the other fully informed of all progress.
- Collaborative relation – One organization takes the lead in the activities, but the work sessions and meetings may receive delegates from the other organisation who have observer status and who ensure the technical liaison with the other organization. These delegates may also make written contributions were considered appropriate during the progress of this work.
- Integrated liaison – Joint Working Groups ensure integrated meetings for handling the realisation of standards under a principle of total equality of participation.

This is visualised in Fig. 3, taken from the Strategic Business plan of ISO/TC274, where the work of CIE is identified as concerning fundamental knowledge and based upon research whereas the work of

ISO/TC274 is based upon application knowledge. Joint standards use both of these areas of expertise in their development.

ISO/TC274 is responsible for the existing standards:

- ISO 8995–1:2002 Lighting of work places – Part 1: Indoor;
- ISO/CIE 8995–3:2018 Lighting of work places – Part 3: Lighting requirements for safety and security of outdoor work places;
- ISO 30061:2007 Emergency lighting.

At the time of writing this paper ISO/TC274 has four standards, technical specifications or reports under development as work items:

- *ISO/CIE FDIS20086* Light and lighting – Energy performance of lighting in buildings. This draft standard specifies the methodology for evaluating the energy performance of lighting systems for providing general illumination inside non-residential buildings and for calculating or measuring the amount of energy required or used for lighting inside buildings. It is closely related to EN15193–1:2017[1];
- *ISO/WD TR21783* Light and lighting – Integrative lighting – Non-visual effects. This draft Technical Report shall include a summary of the published scientific studies on non-visual effects of light on humans, plus an evaluation of related material that is suitable for use in practice or an indication where more knowledge and validation is necessary for safe and beneficial lighting applications;
- *ISO/CIE PRF TS22012* Light and lighting – Maintenance factor determination – Way of working. This draft Technical Specification specifies a standardised way of working for determining the maintenance factor for both outdoor and indoor lighting installations using the methodologies as described in CIE154:2003 [37] and CIE097:2005 [38];
- *ISO/TC274 WG2* Commissioning process of lighting systems. This technical specification will give requirements on the commissioning of lighting systems.

The requirements will include procedures, methods, and documentation for the commissioning of the functionality of lighting systems. It will present details on the commissioning of lighting systems without focusing on technical characteristics of specific components.

One further working group is also active but currently has not raised their work to a formal work item.

- *ISO/TC274 JWG5* Lighting for work places.

This joint working group is to update the existing standard *ISO 8995–1:2002 Lighting of work places – Part 1: Indoor*.

When developing standards a view to possible future technologies and applications is always necessary to ensure relevant standards are available in a timely manner. ISO/TC274 identifies the path of technological development as shown in Fig. 4, where:

- Adaptive lighting is defined as lighting responding to circumstances or according to predefined conditions, while maintaining the lighting quality within the specified requirements for these circumstances or conditions [39];
- Integrative lighting is defined as lighting specifically designed to produce a beneficial physiological and/or psychological effect upon humans [39].

Additional key considerations identified are the aging population within society and energy performance, especially with respect to environmental concerns and global climate change. Climate

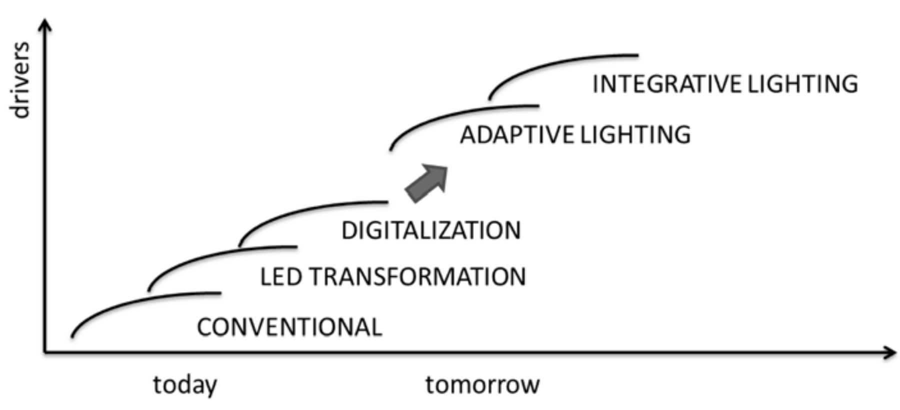

Fig. 4. Relevant technological developments and their evolution over time [36]

change is becoming an important regulatory driver within the lighting industry, as it is within all aspects of life, and this is reflected in its increased importance in standardisation. However, the lighting needs for an increasingly aging yet active population needs careful consideration within this energy aware scenario. The growth of digitalisation and the Internet of Things (IoT) should help lighting meet these requirements by efficiently providing light when needed and ensuring it is the correct light for the individual as opposed to purely lighting for the task.

3.2. CEN/TC169 LIGHT AND LIGHTING

At the level of European standardisation for lighting application CEN/TC169 is the main technical committee with a scope of standardisation in the field of vision, photometry and colorimetry, involving natural and man-made optical radiation over the UV, the visible and the IR regions of the spectrum, and application subjects covering all usages of light, indoors and outdoors, including environmental, energy and sustainability requirements and aesthetic and non-image forming biological aspects.

As such, it is responsible for many standards, technical specifications (TS) and technical reports (TR) (Table).

To manage the development and maintenance of such a list of documents covering a diverse set of subjects requires careful organisation. To help with this CEN/TC169 contains many working groups. Each working group is responsible for one or more of the standards given in the table:

WG 1 Basic terms and criteria;

WG 2 Lighting of work places;

WG 3 Emergency lighting in buildings;

WG 4 Sports lighting;

WG 6 Tunnel lighting;

WG 7 Photometry;

WG 8 Photobiology;

WG 9 Energy performance of buildings;

WG 11 Daylight;

WG 12 Joint Working Group with CEN/TC226 – Road lighting;

WG 13 Non-visual effects of light on human beings;

WG 14 ErP Lighting Mandate Management Group.

Each working group has a convenor who organises and acts as a facilitator for the work of the group and reports back to CEN/TC169 on progress a minimum of twice a year at the annual plenary meeting and also at a mid-term convenors meeting.

At the time of writing this paper, CEN/TC169 has seven work items in progress, updates to EN1837, EN13032–1, EN13032–4, EN12464–1 and EN15193–1, and also two new work items concerning "BIM Attributes for Luminaires and Sensors" and "Guidance Notes on the use of dynamic signage systems".

Again, similar to ISO/TC274, when developing standards a view to possible future technologies and applications is always necessary to ensure relevant standards are available in a timely manner. CEN/TC169 identifies the external factors that will influence lighting and therefore standards development work as:

- Urbanisation – the trend towards increased urban living and more densely populated urban areas;
- Sustainability – the need to reduce energy usage and preserve natural resources;
- Aging populations – the need for proper design of both indoor and outdoor spaces including lighting, to cater for aging occupants or those with reduced visual capacity;
- Connectivity / Internet of things – the increasing trend to link products and services;
- Glazing technologies – developments in window and shading technologies helping the move to near zero-energy buildings;
- Building Information Modelling – the requirement for data-rich virtual models to help throughout the entire building and components life cycles.

4. PROFESSIONAL SOCIETIES

4.1. CIE

The International Commission on Illumination (CIE) is a professional organisation that advances knowledge on topics concerning the science and art of light and lighting, colour and vision, photobiology and image technology. It has a strong tradition of technical and scientific excellence and is recognized by ISO as an international standardisation body (see section 3.1 and Fig. 3).

The work of the CIE is split between six divisions and each division may establish a technical committee (TC) to carry out a specific work item, such as producing or updating a technical report or standard. When the work item is complete the TC

Table

EN1837	Safety of machinery – Integral lighting of machines;
EN1838	Lighting applications – Emergency lighting;
EN12193	Light and lighting – Sports lighting;
EN12464	Light and lighting – Lighting of work places Part 1: Indoor work places Part 2: Outdoor work places;
EN12665	Light and lighting – Basic terms and criteria for specifying lighting requirements;
EN13032	Light and lighting – Measurement and presentation of photometric data of lamps and luminaires Part 1: Measurement and file format Part 2: Presentation of data for indoor and outdoor work places Part 3: Presentation of data for emergency lighting of work places Part 4: LED lamps, modules and luminaires Part 5: Presentation of data for luminaires used for road lighting;
CEN/TR13201–1	Road lighting – Part 1: Guidelines on selection of lighting classes
EN13201	Part 2: Performance requirements Part 3: Calculation of performance Part 4: Methods of measuring lighting performance Part 5: Energy performance indicators;
EN14255	Measurement and assessment of personal exposures to incoherent optical radiation Part 1: Ultraviolet radiation emitted by artificial sources in the workplace Part 2: Visible and infrared radiation emitted by artificial sources in the workplace Part 3: UV-Radiation emitted by the sun Part 4: Terminology and quantities used in UV-, visible and IR-exposure measurements;
CR14380	Lighting applications – Tunnel lighting;
EN15193–1	Energy performance of buildings – Energy requirements for lighting – Part 1: Specifications, Module M9;
CEN/TR15193–2	Energy performance of buildings – Energy requirements for lighting – Part 2: Explanation and justification of EN15193–1, Module M9;
EN16237	Classification of non-electrical sources of incoherent optical radiation;
EN16268	Performance of reflecting surfaces for luminaires;
EN16276	Evacuation Lighting in Road Tunnels;
CEN/TR16791	Quantifying irradiance for eye-mediated non-image-forming effects of light in humans;
EN17037	Daylight in buildings;
CEN/TS17165	Light and lighting – Lighting system design process.

is closed, unlike, for example, CEN/TC169 where the working group still exists after a particular work item is completed. The divisions cover:

Division 1 Vision and Colour;
Division 2 Physical Measurement of Light and Radiation;
Division 3 Interior Environment and Lighting Design;
Division 4 Transportation and Exterior Applications;
Division 6 Photobiology and Photochemistry;
Division 8 Image Technology.

Each division has a division director, division secretary, division editor and a number of associate directors who ensure the divisional work program continues.

The CIE has a vast range of technical reports and standards, many of which contain the fundamental knowledge that is used to define requirements within standards and regulations. It is continually striving to understand the next key issues and uses this to define a research strategy which currently include:

– Recommendations for Healthful Lighting and Non-Visual Effects of Light;

– Colour Quality of Light Sources Related to Perception and Preference;

– Integrated Glare Metric;

– Adaptive, Intelligent and Dynamic Lighting;

– Visual Appearance: Perception, Measurement and Metrics;

– Support for Tailored Lighting Recommendations;

and other fundamental issues including those concerning photometry and colorimetry.

4.2. Lux-Europa

Lux-Europa is the European Lighting Society and its members are representatives from national European lighting societies.

Lux-Europa does not give professional status or produce codes of practice but it has importance in standards work in that every 4 years it hosts the Lux-Europa Conference. This provides an arena for the presentation of much research and also Euro-centric topics such as new or upcoming legislation and standards.

4.3. Society of Light and Lighting and Institution of Lighting Professionals (UK)

Many countries have their own professional organisations and these organisations produce best practice guides on many aspects of lighting. Within the UK the two main professional organisations for lighting are the Society of Light and Lighting (part of the Chartered Institute of Building Services Engineers) and the Institution of Lighting Professionals.

The Society of Light and Lighting (SLL) is the descendant of the UK Illuminating Engineering Society that was formed in 1909. The Institute of Lighting Professional has its origins in the Association of Public Lighting Engineers, founded in 1924. The organisations to a large extent complement each other with relatively little overlap in work. They aim to promote the benefits of good lighting, good practice in lighting design, and the development of lighting as an integral part of a low-energy and sustainable future. They also liaise with the UK Government on lighting matters and provide members with a recognised professional standing.

Both organisations produce a range of publications covering individual application areas, relevant legislation and information on the technology of light. In general the content of these documents is driven by lighting standards but on occasions the content may drive standards work. An example is the guidance on obtrusive light that is found in CIE150 [4]. For a period the requirements specified by the Institution of Lighting Professionals [5] was more proscriptive than those in the CIE150 document but with the latest edition of CIE150 they have become harmonised again.

It should be noted that The Society of Light and Lighting is the UK member of Lux-Europa.

5. INDUSTRY ASSOCIATIONS

5.1. LightingEurope

LightingEurope is the industry association that represents the lighting industry within Europe. Its mission is to advocate and defend the lighting industry in Brussels, working with European agencies and the European Commission to reconcile EU policy with lighting best practice. It aims to promote efficient lighting practices for the benefit of the global environment, human comfort and the health and safety of users.

To help in this, LightingEurope brings together industry experts with local and European policy experts in Working Groups covering specific areas of lighting policy. The Working Groups are:

– LEDification – LEDs have enabled energy efficient solutions, which allow more ambitious energy targets to be written into legislation. It is, however, important to preserve the balance between energy efficiency and lighting best practice and to protect the basic quality requirements for LED luminaires;

– Intelligent Lighting Systems – As buildings become smarter lighting will become the backbone of an intelligent building, and through increasing use of sensors and controls intelligent lighting systems will provide users and building owners more control over the quality, flexibility, and scalability of a lighting system. Similarly, the development of smart city concepts based upon intelligent systems will provide a city-wide matrix of network points for data gathering and control;

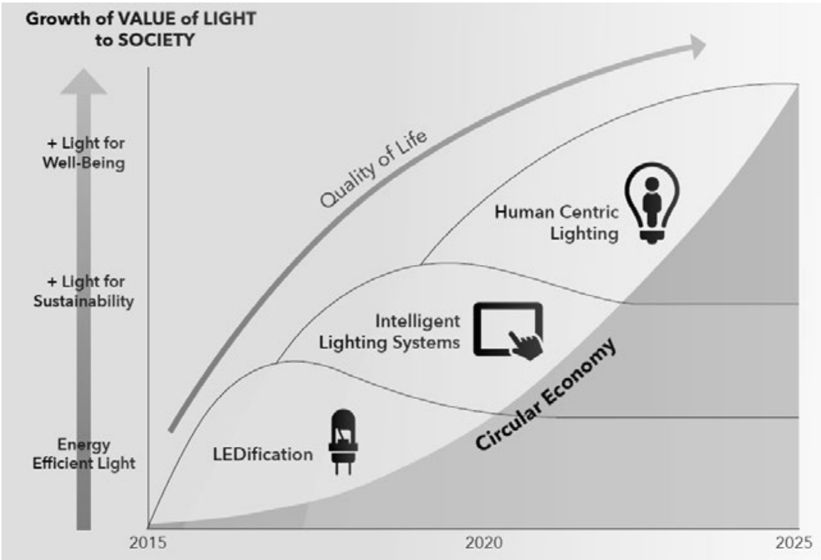

Fig. 5. Developments in the lighting market [35]

– Human Centric Lighting – Light has the power to energize, to relax, to increase alertness, cognitive performance and mood, and to improve the sleep-wake cycle of people. This WG aims to promote the idea of human centric lighting by making information available, initiating scientific studies and organizing events targeted at legislative and business decision makers. Note in this sense, the term human centric lighting is equivalent to the term integrative lighting used by CIE and ISO;

– Circular Economy – The principle of the circular economy is to minimize the ecological footprint of products that means elements of circular economy include refurbishment, remanufacture and reuse, and re-distribution.

Industry associations need a view to the future to ensure relevant standards are available in a timely manner, to educate legislators and the market in the potential new markets and to prevent legislation from inadvertently interfering with new ideas and applications. LightingEurope has a strategic roadmap showing how it expects the lighting market will develop and how this will add to the value of light and the quality of installations (Fig. 5).

This shows that LEDification, the adoption of LED technology, is considered well established, allowing increased use of controls. The digital nature of solid-state lighting technology will aid in the growth of intelligent lighting systems and the IoT which in turn will open the way to human centric solutions. All the while sustainability in terms of the circular economy will increase in importance.

Fig. 4, showing the vision of ISO/TC274, and Fig. 5 show obvious parallels, so both organisations see lighting application and technology developing in a similar way.

5.2. Lighting Industry Association (UK) and ZVEI (Germany)

National trade associations aim to represent their trade within the country to the marketplace and to legislators. A fundamental difference between the LIA and ZVEI is that the LIA is purely concerned with lighting whereas ZVEI represents the German electrical and electronics industry, and therefore has much wider concerns. However, within ZVEI different divisions address different industry sectors and there is a division dedicated to lighting.

Both, the LIA and the lighting division of ZVEI are members of LightingEurope, representing their member's rights in the European arena and they are heavily involved in standards committees, both nationally and worldwide.

The LIA and the lighting division of ZVEI have a number of working groups made up of experts from member companies. These tend to monitor any relevant legislation and liaise with and submit comments to legislators, and also address technical topics to provide a resource of technical information and guidance that members may use to develop the lighting market. Therefore, to an extent national trade associations mirror LightingEurope, although on a national level. However national associations may identify key issues and these may be developed at a national level, promoted up to LightingEurope for a more European approach, or both as is considered appropriate.

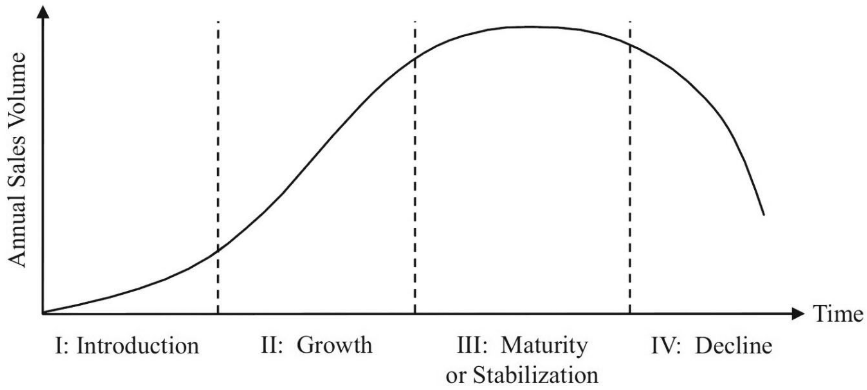

Fig. 6. A typical technology life-cycle curve

6. STANDARDS INTO THE FUTURE

Lighting is in a time of change, not just in terms of technologies such as light sources and solid-state devices but from the practice of lighting for the task to now lighting for people and individuals, from lighting purely for vision to lighting for vision, wellbeing and communication, and into the world of connected devices and the Internet of Things where lighting moves from being a source of light to being a data point.

This is a challenge for standards. Standards are not guides or research documents but factual documents based upon evidence and proven fact. They give established best practice metrics and criteria without necessarily defining how these criteria should be achieved. This creates a problem as radically new concepts and techniques need researching and proving before they are likely to be incorporated into a standard. In addition, to develop a standard normally takes at least three years. This means that standards can lag the development of new products and application techniques, at times significantly. In terms of a typical technology life-cycle, such as shown in Fig. 6, this means that a standard on the application of a technology might only be published during the growth phase of the technology life-cycle and the introduction phase is used to gain enough experience with the technology to define standard criteria. An example of this could be human-centric lighting, where products and applications have been produced but recommendations and design criteria within standards are still very limited.

However, as has been shown above, each organisation within lighting standardisation has a view to the future, be it a standards body, trade association or professional organisation. These viewpoints show a large amount of overlap and in terms of lighting application they cover: – Human centric or integrative lighting; – Connectivity and the Internet of Things; – Inclusivity, in terms of visual capabilities; – Sustainability.

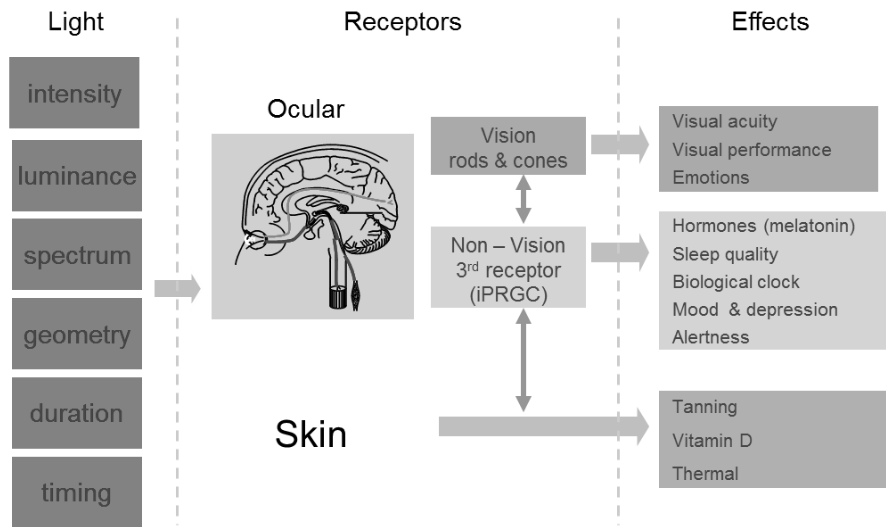

Fig. 7. Simplified overview of impacts of light on humans

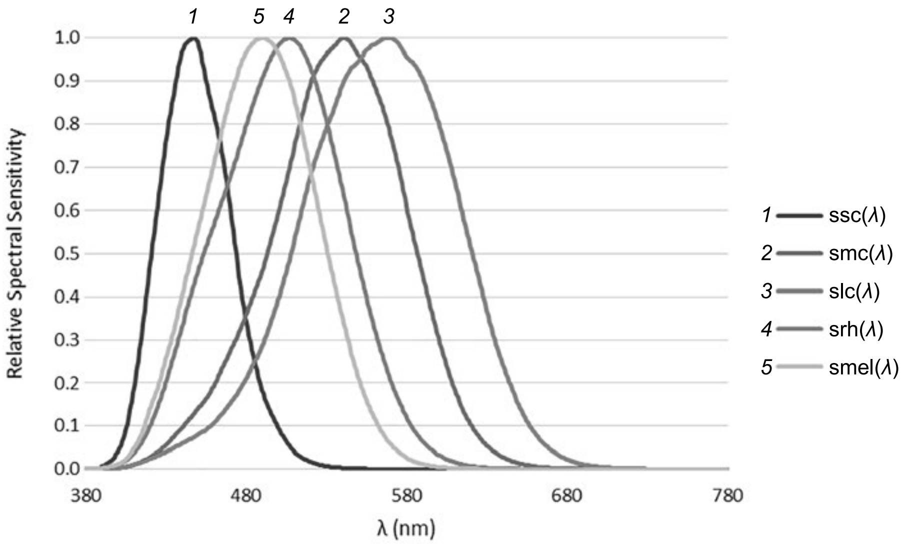

Fig. 8. The α-opic action spectra [6]

These topics provide challenges in terms of practice, metrics and usage and can lead into discussion about additional topics such as colour.

6.1. Human-centric/Integrative Lighting

As shown in Fig. 7, humans interact in many complex ways with light. Light itself has many properties and these create the visual scene, the emotional response and also the biological response. These different responses require new metrics as existing units no longer reflect what is being measured. The units of lumen, candela and lx are visual metrics based upon the eye photopic response curve, which itself is a compromise whose validity is openly questioned due to it not correctly accounting for the S-cone response (amongst other issues). These metrics are not really valid for a photo-biological response based upon both visual and non-visual receptors.

In Fig. 8 the melanopic sensitivity function is shown as a function of wavelength (smel), as defined by Lucas et al [7]. It is significantly different to the 3 CIE short (ssc), medium (smc) and long (slc) cone sensitivity functions for the 10° observer, nor does it correspond to the CIE scotopic rod sensitivity function (srh). Therefore any measure using conventional cone-based (photopic) or rod-based (scotopic) metrics cannot correctly account for the human biological response to light. Fig. 8 does demonstrate that the circadian effect will be impacted by spectral content in addition to flux density, or in very simplistic terms the light level and colour temperature.

A number of proposals have been made for metrics to measure this non-visual impact from lighting.

The WELL Building Standard [8] uses the unit of Equivalent Melanopic Lux (*EML*). This is calculated from the visual illuminance within a space (*L*) and the melanopic ratio (*R*), a weighting factor based upon the light source. The visual illuminance is measured vertically 1.2m above floor level.

The WELL Building Standard provides a spreadsheet to calculate this based upon the melanopic action spectrum given in CIE S026.E:2018 and the CIE $V(\lambda)$ curve, the spectral luminous efficiency function for photopic vision (https://www.wellcertified.com/en). Based upon the spectral content of the light source the melanopic response and spectral response is calculated and then the total melanopic response is divided by the total visual response and this value is then multiplied by 1.218.

Then

$$EML = L \times R \text{ (unit: equivalent melanopic lx).} \quad (1)$$

A second proposal came from the Lighting Research Centre, Rensselaer Polytechnic Institute.

M.S. Rea et. al. [9] proposed the metric Circadian Light which is the irradiance at the cornea weighted to reflect the spectral sensitivity of the human circadian system as measured by acute melatonin suppression after a one-hour exposure. A second metric, the Circadian Stimulus (CS) is the effectiveness of the spectrally weighted irradiance at the cornea from threshold (CS = 0.1) to saturation (CS = 0.7).

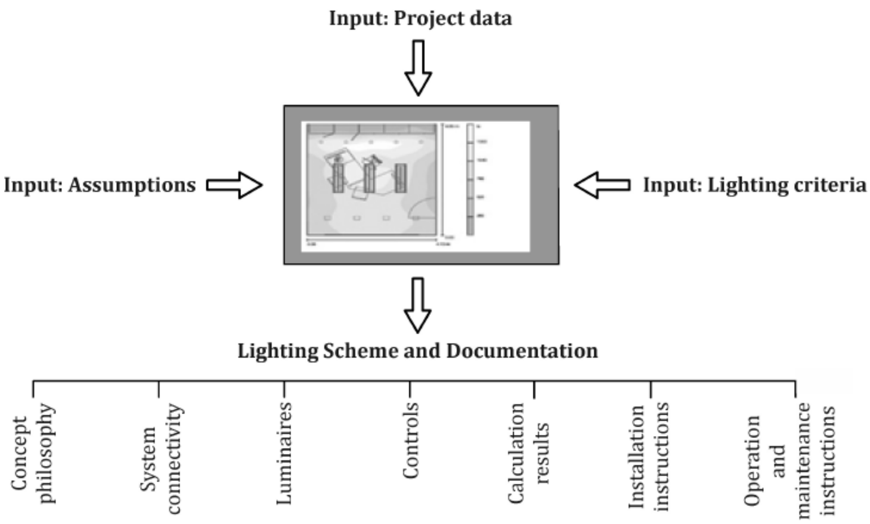

Fig. 9. Lighting system design process and documentation [11]

Similar to EML a spreadsheet is freely available to download and calculate these values or a web-based on-line tool may be used (https://www.lrc.rpi.edu/cscalculator/).

This demonstrates that there is no universally accepted measure to allow human centric design, let alone accepted limits.

Even assuming accepted metrics and limits are agreed upon there is then the question of timing. When discussing biological rhythms we have to understand these are not the same as the physical day/night rhythms of our planets 24 hour cycle. The wake/sleep cycle of an individual may be removed from the natural cycle of day and night to a greater or lesser extent due to work patterns, social habits, and age, gender or chrono-biological traits. There is no universal clock that people are in time with; everyone has their own personal clock which is synchronised to their own wake/sleep cycle.

The implication of this is that human-centric design involves not only some measure of circadian flux but also biological time and light history. Therefore, unless a relatively uniform population exists with complimentary needs, such as a care home for Alzheimer's patients, or at least relatively uniform day/night timings, such as an office with single shift fixed working hours or a factory which may have multiple shift patterns but with only 1 shift in operation at any one time, human-centric design will potentially require a careful approach to avoid penalising some occupants in preference to others.

The WELL Building Standard provides an attempt at accounting for this by stipulating the required level of 200 EML should be present at least between the hours of 9:00 until 13:00. However, this makes the assumption that a person is working a normal daytime shift pattern synchronised with the natural day/night cycle. This is not valid in many situations and could result in applying a circadian lighting design out of step with the occupant biological time.

Therefore without effective lighting controls, human-centric lighting can only be applied with a broad brush on a generic level.

6.2. Connectivity and the Internet of Things

Whilst we discuss the benefits of increased connectivity and the Internet of Things it must be accepted that despite lighting sensors and controls being widely available for many years many lighting installations, both old and new, still do not use any but the more basic control techniques, generally a manual switch.

The European Commission highlighted this in their "Preparatory study of lighting systems Lot 37", produced by consultants VITO [10]. This concluded that:

- The maximum EU-28 total savings for optimised lighting system designs with controls are depending on the reference light source scenario;
- The maximum EU-28 total annual electricity savings due to lighting system measures are 20–29 TWh/a in 2030 and 48–56 TWh/a in 2050;
- This is approximately 10 % (2030) or 20 % (2050) of the total EU-28 electricity consump-

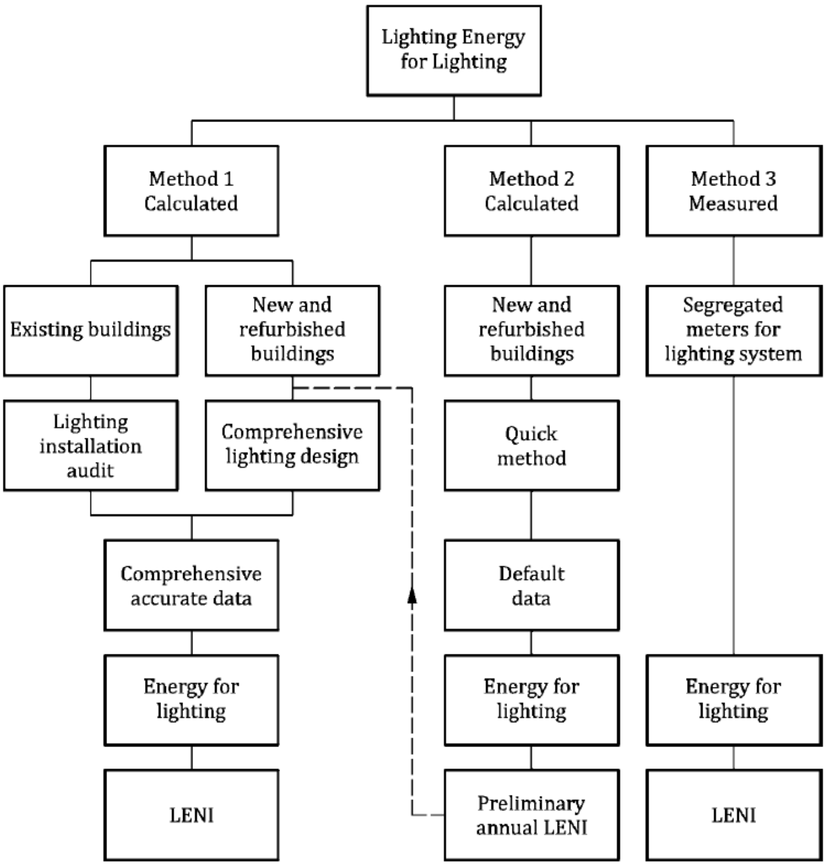

Fig. 10. Flow chart illustrating methods to determine energy for lighting [1]

tion for non-residential lighting in the BAU-scenario for light sources[1].

To support this, CEN produced a new technical specification PD CEN/TS17165:2018 [11] which sets out the general framework of a lighting system design process that can be applied to lighting of any project including smart buildings. It describes the expected inputs into producing a lighting system design and the expected outputs, as shown in Fig. 9.

To produce energy efficient lighting systems and to support the use of lighting controls it is necessary to demonstrate energy savings. Standards exist for both: for buildings and roads. EN15193–1:2017 [1] details the calculation for *LENI*, the Lighting Energy Numeric Indicator. This calculation is shown in equation 2 below.

$$LENI = \frac{\{(F_c \times \frac{P_i}{1000} \times F_o[(t_D \times F_D) + t_N]\} + +\{[t_y - (t_D + t_N)] \times (P_{ci} + P_{em})\}}{A}, \quad (2)$$

where

LENI is the lighting energy numeric indicator (kWh/(m² year)),

F_c is the savings from constant illuminance controls for the area,

P_j is the power density of the area (W/m²),

F_O is the savings from occupancy controls for the area,

t_D are the daylight operating hours for the area (h),

F_D is the savings from daylight controls for the area,

t_N are the night time (non-daylight) operating hours for the area (h),

ty are the annual operating hours for the area (h),

P_{ci} is the total luminaire control standby power,

P_{em} is the total emergency standby power,

A is the room area (m^2).

Techniques for calculating the savings from control technologies are given within the standard. A LENI value may also be produced for existing lighting installations either through metering of the electrical supply to the lighting or by estimation based upon a lighting installation audit. The 3 methods are shown in Fig. 10.

[1] Note: BAU means "Business as Usual" or in effect we continue as we are.

An equivalent energy calculation exists for road lighting, as specified within EN13201–5:2015 [12]. This defines the Annual Energy Consumption Indicator (AECI), which is given in equation 3 below.

$$D_E = \frac{\sum_{j=1}^{m}\left(P_j \times t_j\right)}{A}, \quad (3)$$

where

D_E is the annual energy consumption indicator for a road lighting installation (Wh/m²),

P_j is the operational power associated with the j^{th} period of operation (W),

t_j is the duration of the j^{th} period of operation (h),

A is the size of the area lit by the same lighting arrangement (m²),

m is the number of different operational periods.

When lighting controls are in use an operational period would also include the period during daylight hours when the lighting was not active to account for the controls standby power. When presence detection is used it is necessary to assume the probability for each of the lighting levels.

Given that we can calculate energy usage and the impact of lighting controls, more widespread use of control technologies is required. There is much additional help and advice available for the use of lighting controls. CIE222 [13] provides guidelines in order to balance lighting quality, user comfort and energy efficiency in lighting controls solutions for lighting in non-residential building. It describes the background to lighting control strategies, contains an extensive literature study on application of controls and 12 tables that evaluate the influence of controls in applications. The report allows an appropriate control strategy to be chosen either starting from the application and working forward to predicted outcomes, or starting with desired outcomes and working back to the required control strategies to achieve these.

An alternative resource is the Lighting Control Guide from the UK Lighting Industry Association [14] which provides an appreciation of the benefits of lighting controls, helps match lighting controls and light sources with application and provides a decision tree to assist in the selection of the most suitable lighting controls.

A major consideration with the use of a more advanced control systems is commissioning, ensuring that the system operates correctly. This is where the work of standards committees such as ISO/TC274 WG2 Commissioning process of lighting systems is very important to give a good practice yardstick to work to.

With the development of more advanced concepts such as the IoT and smart cities many more possibilities are being developed and considered. For a smart city this could include aspects such as social profiling of application spaces, for example in terms of:

- Expected age profile of users across time of day and time of week;
- Expected social activities across time of day and time of week;
- Expected transportation modes;
- Prevalence and type of any crime;
- Area category, such as inner-city/urban/rural, retail/entertainment/residential, etc.

As the usage and occupant profile changes within a space so should the lighting.

Similarly for buildings a profile may be developed on space or energy usage. Sensors and system software can detect when rooms or single desks are occupied and this data can be visualised, allowing space usage to be optimised. In addition utilising daylight, presence and time-based controls allows energy usage to be minimised. So lighting within buildings should complement the people performing a task, and not just consider the task requirements as if they were being performed by a "standard" person with "standard" visual capacity and no emotional needs.

Another potential application of advanced control techniques is in emergency lighting. Current practice provides lighting to allow the evacuation of a building but has no knowledge of the state of the building and escape routes. Therefore it is up to individual occupants to ascertain if an escape route is safe to use, the lighting and signage is constant irrespective of the true condition. Linking the emergency lighting to other building services such as smoke or heat detection systems, would allow occupants to be directed around areas of potential danger, whilst the use of monitors that can detect occupant density within spaces and escape routes could allow routing around congested areas, smoothing the evacuation process in the quickest possible time. However these systems have their own particular considerations and concerns.

Testing the functionality of the intelligent emergency lighting system through life becomes more complex with numerous interdependencies and links with external systems. Automatic testing would be essential and would require careful configuration. Security of communications would be essential. Loss of communication with internal or external system components would compromise the system ability to direct occupants safely, of especial concern when these types of systems become established and people start to rely on them to keep them safe. Cybersecurity will also be an issue as any connected system introduces security risks. These are not just at the level of the emergency lighting system, although a third-party being able to activate evacuation alarms whilst simultaneously disabling evacuation systems is a concern, but any connected system is a potential gateway into more sensitive areas of an IT network. Therefore parts of the functionality of lighting systems may become under the remit of IT departments and specialists.

In recognition of the increased risks posed by the IoT and enhanced connectivity a new document being prepared is the EU Cybersecurity Act [15] which will provide schemes to certify products for Cybersecurity. Certification will be to either basic, substantial or high levels where:

- Basic – minimises known basic risk;
- Substantial – minimises known security threats from actors with limited skills and resources;
- High – minimises state of the art attacks by actors with significant skills and resources.

National governments and organisations are also developing guidance, for example a publication from the UK CIBSE [16], a white paper from the German ZVEI [17] and the UK Department for Digital, Culture, media and Sport [18].

However, as data collection and usage increases through the IoT and intelligent lighting systems, individual rights are in danger of being compromised. Therefore developments both in technology and in standards and application are tempered by legal regulation. In the European Union this is principally covered by the General Data Protection Regulation (GDPR) [19]. This covers the processing of personal data in the context of the activities of an establishment of a controller or a processor in the European Union, regardless of whether the processing takes place in the European Union or not, and it covers the monitoring of the behaviour of individuals within the EU. Key definitions include:

– Personal data – any information relating to an identified or identifiable natural person;.

An identifiable natural person – A person who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person.

Therefore any information that allows a specific identifiable occupant to be located, and even more so if this allows information to be gathered about their current mental state (think personalised human-centric lighting concepts) is covered. This will extend to areas such as smart phone applications that allow users to move through a smart city or building easier, permissions on data gathering and usage and how they are granted and accepted must be very carefully considered.

6.3. INCLUSIVITY

The concept of a standard person has existed for a long time. Leonardo da Vinci's painting of Vitruvian Man (1490) showed a standardised representation of the proportions of a human body but this was based upon the much earlier work of an architect from Ancient Rome, Vitruvius, who published a correlation of ideal human proportions with geometry in book III of his treatise "De architectura" [20]. A standard person is important because it allows the principle of "one size fits all", in workplaces, homes, public buildings, furniture, appliances, transport and lighting. Chairs, desks, stairs, doors, etc. all benefit from the availability of a standard person to design around. However the standard person also indirectly promotes discrimination in that those who do not conform to the norm are either forced to comply or disadvantaged.

And this exists in lighting as much as in any other profession. Lighting installations are designed to provide the correct lighting condition for the majority of the population, but those with particular physical, mental or visual requirements are generally not considered.

Inclusive design (alternatively termed as universal design) ensures all people are included by quality of design, irrespective of their capabilities, and designers have to accept responsibility for the impact of their designs. This quality of design should consider multiple impacts from the relatively obvious, such as wheelchair users have a different eyeheight and therefore experience glare differently, to issues requiring more consideration. If we explore sight loss there are three main generic types of sight loss, such as:

- Residual sight users is the group, which makes up the majority of people with sight loss; typically their sight will be bad enough to be registered blind or partially sighted but still of considerable use;
- Long cane users when long canes are a mobility aid used primarily by people with very little useable sight and allow changes in levels and texture to be perceived as well as detection and identification of obstacles;
- Guide dog users group represents a small fraction of the sight loss population; they are often amongst the most mobile.

Inclusivity is not just how we light a space but also where we position lighting fixtures and fittings. For example, if we consider how these people move through a space and how the siting of lighting fixtures will impact this (based upon Sight Line [21]).

- Residual sight users

Tonal contrast is the most important source of information. Residual sight users feel more comfortable on wide, spacious, uncluttered footways and pedestrian areas.

Sight, and therefore light, is still is a major factor.

For lighting, fixtures that have little contrast with the background can render them almost invisible.

- Long cane users

Rely predominantly on tactile and audible sources, and will usually attempt to walk along the building line.

Careful siting of lighting furniture away from the building line can aid these users

- Guide dog users

Guide dogs are trained to walk down the centre of a footway or corridor and avoid obstacles. They are also trained to locate crossings and entrances. If a guide dog cannot detect a space big enough to fit through it will just stop, leaving its owner stranded.Careful siting of lighting fixtures and furniture at key points such as crossing areas and building entrances helps the guide dog navigate these spaces

Lighting standards frequently only address these issues with relatively basic comments. The European Standard EN12464–1 [22] states that lighting levels may be increased when "the visual capacity of the worker is below normal". However, like most standards, it gives little advice on what this means in application. For more in-depth information publications such as CIE227:2017 [23] gives valuable advice, both on the causes of reduced visual capacity and what this means and also lighting requirements to help counteract these issues. This includes recommendations on lighting requirements for older occupants to move through escape routes, a safety issue that is frequently forgotten. It also discusses some applications of integrative / human-centric lighting in a section on the non-visual effects of light on older people and people with low vision.

Lighting not only has an impact based upon the visual capacity of an observers eye, it also has a mental impact based upon the ability of an observer to decode the visual scene. Observers with dementia may have good eyesight but their ability to understand common features and effects that we take for granted may not function correctly. Shadows become holes in the ground, or giant spiders, etc., the direction of shadows may be disturbing, for example light from below an object, and glare sources disorientate and confuse. Sources of information for this include papers by Torrington et al [24]

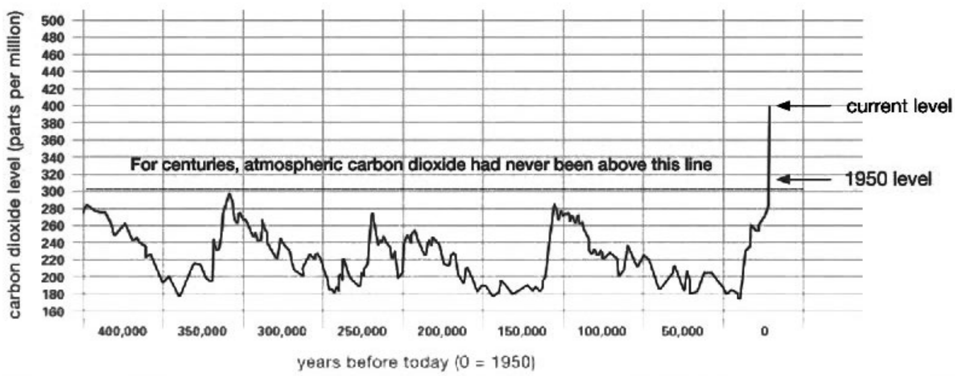

Fig. 11. Atmospheric CO_2 levels through time (source: NASA https://climate.nasa.gov/evidence/)

and Sloane et al [25], IES CG-1–09 [26], or the University of Stirling [27].

6.4. SUSTAINABILITY

Lighting performs a balance in that people need lighting to live, however lighting has a global impact on our climate. Fig. 11 shows the levels of CO_2 in the atmosphere through a period of time and it is obvious that levels have increased and are still increasing dramatically.

In a 2013 report [28], the United Nations Environment Programme (UNEP) stated

"*Electricity for lighting accounts for almost 20 % of electricity consumption and 6 % of CO_2 emissions worldwide. According to the International Energy Agency, approximately 3 % of global oil demand can be attributed to lighting. If not addressed immediately, global energy consumption for lighting will grow by 60 % by the year 2030.*"

In addition in a report from the Organisation for Economic Co-operation and Development (OECD) [29] Angel Gurria, OECD Secretary-General stated

"*Growth in materials use, coupled with the environmental consequences of material extraction, processing and waste, is likely to increase the pressure on the resource bases of our economies and jeopardise future gains in well-being.*"

These facts are driving regulation and legislation to push for more energy efficient and sustainable solutions and a move to a circular economy as shown in Fig. 12.

After collection as we push the product, its components or its materials back into the manufacturing chain we can see that the further up the chain we go the greater the environmental impact. So we can see that the preferred options at product end-of-life are to reuse or to refurbish the product or its individual components. Recycling has a larger environmental impact as more processes are required to turn the waste into a new usable product.

Fig. 12. Principle of the circular economy [35]

However, as identified by UNEP and illustrated in Fig.13, whilst the end-of-life phase is important to preserve the environmental investment in the existing product, the in-use phase before this is critical. Fig.13, from an environmental product declaration produced according to EN ISO 14025 [30] and EN15804 [31], shows that 99 % of the global warming potential for this product is in the use phase. Therefore it is critical that the product is as efficient in use as possible, and is also used as efficiently as possible.

Within Europe eco-design regulations exist to remove less efficient products and components from the market. Current regulations are

- Regulation (EC) No 244/2009 with regard to ecodesign requirements for nondirectional household lamps [32].
- Regulation (EC) No 245/2009 with regard to ecodesign requirements for fluorescent lamps without integrated ballast, for high intensity discharge lamps, and for ballasts and luminaires able to operate such lamps [33].

Assessment parameter	Unit	Production Stage	Construction Process Stage	Use-stage	End-of-Life Stage	Benefits and loads beyond the system boundary
		A1-A3	A4, A5	B4, B6	C2-C4	D
Acidification Potential (AP)	[kg SO_2 eq]	6,02E-02	1,33E-03	1,45E+00	2,95E-03	-2,91E-02
Eutrophication Potential (EP)	[kg PO_4^{3-} eq]	5,90E-03	2,66E-04	1,30E-01	3,69E-04	-2,06E-03
Global Warming Potential (GWP100)	[kg CO_2 eq]	2,08E+01	1,23E+00	5,22E+02	5,35E+00	-7,83E+00
Primary energy, renewable	[MJ]	4,75E+01	8,25E-01	2,55E+03	3,52E+00	-1,56E+01
Primary energy, non renewable	[MJ]	3,48E+02	7,41E+00	9,10E+03	1,36E+01	-9,78E+01

Fig.13. Extract from Environmental Product Declaration (source: Thorn Lighting Ltd, Product code 96628133)

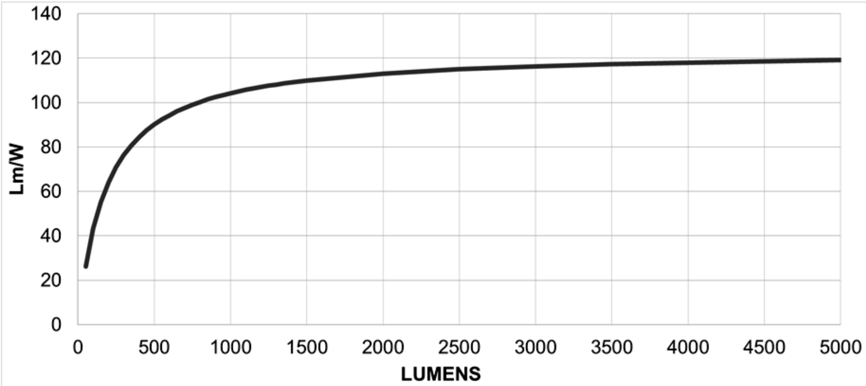

Fig. 14. Graphical representation of efficacy limits based upon equation 4

- Regulation (EU) No 1194/2012 with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment [34].

However these are in the process of being replaced by a single regulation which will come into effect on 1st September 2021. Efficiency limits will be calculated using equation 4.

$$P_{onmax} = C \times \left(L + \frac{\Phi_{use}}{F \times \eta} \right) \times R, \quad (4)$$

where

P_{onmax} is the maximum on-mode power (in W);

η is the threshold efficacy (in lm/W, light source type dependant);

L is the end loss factor (in W, light source type dependant);

C is the correction factor for light source characteristic;

F is the efficacy factor (1.0 for Non-Directional Light Sources, 0.85 for Directional Light Sources);

R is the CRI factor (0.65 for CRI≤25, (CRI+80)/160 for CRI>25).

Equation 4 results are shown in Fig. 14 with light source efficacy limits approximately between (100–120) lm/W.

It must be recognised that increasing the efficiency limits for lighting sources and luminaires will have diminishing returns. As more high-efficiency luminaires are installed, less significant gains will be made by more efficient product replacing already efficient product. Therefore the focus will move towards lighting systems as opposed to individual lighting products. This is demonstrated by a document produced by consultants VITO [10] that concluded:

"*The maximum EU-28 total savings for optimised lighting system designs with controls are depending on the reference light source scenario and the maximum EU-28 total annual electricity savings due to lighting system measures are 20–29 TWh/a in 2030 and 48–56 TWh/a in 2050. This is approximately 10 % (2030) or 20 % (2050) of the total EU-28 electricity consumption for non-residential lighting in the BAU-scenario for light sources.*"

So efficiency will move towards the regulation of full lighting systems with sensors and controls and sustainability will move towards maintainable luminaires with replaceable LED light sources and reusable components.

7. CONCLUSIONS

As has been described the world of standards and regulations is complex and attempts to address the needs of changing and evolving markets and technologies. They aim to provide a measure against which solutions may be compared for suitability but increasingly also address issues such as environmental and security concerns.

As our world changes in the future, automation increases along with connectivity, social demographics and expectations change, tasks and functions develop to meet the requirements of a 21st Century society, so will standards and regulations have to evolve to meet the needs of new generations. Research will be required to understand possibilities and impacts and the results will have to be embodied into documents that describe codes of practice.

As our predecessors in lighting struggled with how to quantify and codify basic principles so will the next generation of lighting professionals in an ever changing and exciting environment where boundaries between professions blurs and vision becomes only one aspect of design.

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