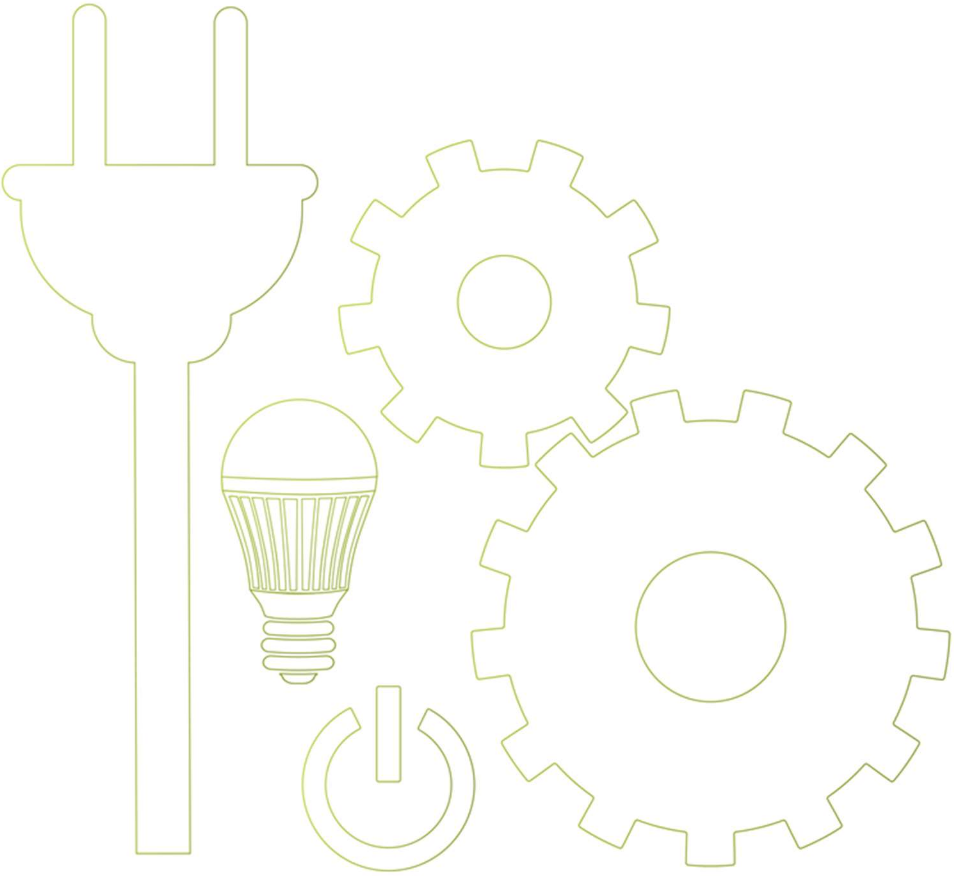

Solid State Lighting Annex:

Supplementary Technical Information regarding the Quality and Performance Requirements

LED Lighting Products

Energy Efficient End-use Equipment (4E)
International Energy Agency
SSL Annex Task 6

OCTOBER 2022

About the IEA 4E Solid State Lighting Annex

The SSL Annex was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement to provide advice to its member countries seeking to promote energy efficient lighting and to implement quality assurance programmes for SSL lighting. This international collaboration currently consists of the governments of Australia, Denmark, France, the Republic of Korea, Sweden and the United Kingdom. Information on the 4E SSL Annex is available from: https://www.iea-4e.org/ssl/

About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E)

Fifteen countries from the Asia-Pacific, Europe and North America have joined together under the forum of 4E to share information and transfer experience in order to support good policy development in the field of energy efficient appliances and equipment. 4E focuses on appliances and equipment since this is one of the largest and most rapidly expanding areas of energy consumption. With the growth in global trade in these products, 4E members find that pooling expertise is not only an efficient use of available funds, but results in outcomes that are far more comprehensive and authoritative. Launched in 2008, in view of its achievements during the first and second five-year terms, the IEA endorsed 4E's application for a third term that will run to 2024. https://www.iea-4e.org/

Disclaimer

The IEA 4E SSL Annex quality and performance requirements provide governments and market transformation programme managers with a basis on which to structure voluntary and mandatory programmes which are harmonised with other programmes around the world. This harmonisation will help to accelerate the market transition to SSL technology. The final decision to publish the quality and performance requirements is made by the Management Committee of the SSL Annex, following an expert review and public consultation. Neither the IEA 4E SSL Annex and its participating governments, nor the IEA 4E Implementing Agreement make any warranties or guarantees as to the accuracy of data presented herein, nor do they accept any liability for any action taken or decision made based on the contents of this document. Furthermore, it should be noted that this report is issued as advice for governments and does not necessarily reflect the views or policies of the governments who are part of the SSL Annex.

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1. Background

This is a supplementary technical support document that should be read in conjunction with the 2022 publication of the SSL Annex's Quality and Performance Requirements for LED Lighting Products[1]. This document offers explanations and insights into (a) the sources of product performance data analysed, (b) the methodology used to quantify and forecast the performance requirements, (c) the rationalised product categories, and (d) the updates and clarifications to the measurement quantities.

2. Revision of Quality and Performance Requirements

Two significant changes have been made in the 2022 release of the Quality and Performance Requirements for LED Lighting Products as a result of the latest review.

Firstly, and most importantly, the ***efficacy levels throughout the document are recommended for programmes with commencement dates expected in the year 2024***. This is an acknowledgement that programmes, once initiated, take several years to implement including providing enough notification period for the market supply chain to prepare.

Secondly, ***there has been a re-structure of the product scopes*** in the Product Quality and Performance Requirements publications to reflect the advancement of energy-efficiency across a broader range of product forms.

The revision of the performance requirements was a five-stage process.

1. Reputable sources of product performance data were identified, collected and incorporated into a combined product database (see Table 1) for detailed analysis.
2. Within the combined product database, yearly trends of specific percentiles that are used to define the performance tiers (20th Percentile for Tier 1, 80th percentile for Tier 2 and 95th percentile for Tier 3) for each product category within scope were examined. (See "Predicting yearly efficacy trends" for details)
3. A rationalisation of product categories was conducted by amalgamating appropriate product categories with similar trends or trend rates.
4. Released for public comment from 25th November 2020 to 25th January 2021
5. Consideration of comments received and further review of latest available data for changes in performance of products

[1] "Quality and Performance Requirements for LED Lighting Products" at https://www.iea-4e.org/wp-content/uploads/2022/11/Task-6-LED-Lighting-Product-Tiers-October-2022-final.pdf

2.1. Sources of product performance data

As part of the review of the performance requirements of different categories of LED lighting, a combined product database has been developed so that a statistical analysis can be conducted to propose the efficacy thresholds for each product category and each tier based on the database percentiles. There are two main functional categories of product performance data. The first is market data, obtained from market surveys and public databases with no performance requirements, such as minimum efficacy, for listing. This category also includes laboratory data from market-available products tested for benchmarking purposes. The second is registration data, obtained from databases of registered products that have performance requirements, most notably efficacy, for listing. The datasets accessed for the combined product database along with number of products and the year of product listings are provided in Table 1. Only details for those categories of products within each database that are relevant to the product scopes of the performance requirements are included.

Table 1: Datasets accessed and included in Combined Product Database

Dataset Source	**Number of lamps**	**Entry Years**	**Number of in-scope luminaires**	**Entry Years**
Market Data				
US Lighting Facts database	12,868	2009 – 2016	57,326	2010 – 2019
Australian Market Survey	3,196	2017 – 2018		
Benchmarking test data (international)	342	2016 – 2019		
Register data				
Energy Star database	9,671	2009 – 2019	19,200	2009 – 2020
Japan energy-saving product database	433	2017		
Thailand Label No. 5 product database	284	2019		
Korea high-efficiency certification system database	3,487	2017 – 2019	29,255	2017 – 2019
Design Lights Consortium (DLC) Quality Product Listing	30,821	2016 – 2020	27,578	2016 – 2020
India Star Rating Register	355	2019		
Total listing	**61,457**	**2009 - 2020**	**133,359**	**2009 - 2020**

Review subsequent to the public draft has included datasets (up to 2022) from the California Energy Commission, CLASP product testing, the European market, and Swedish Energy Agency product testing.

2.2. Method for establishing yearly trends for the performance requirements

The process of creating annual trends for each product category requires a large dataset, to minimise the influence of individual products, and a lengthy history to best establish the trend profile. The dataset also needs to have no limitation on product eligibility in terms of a minimum efficacy as this will arbitrarily inflate the efficacy value for the yearly percentiles.

Only the US Lighting Facts dataset best meets these criteria and is ultimately analysed to determine the efficacy yearly percentiles used for establishing trend projections to 2024. The remaining datasets listed in Table 1 were then superimposed as scatter plots over the percentile trend lines to validate or, if considered necessary, adjust/recalibrate the annual trend rates and the associated tier efficacy projected for 2024. Section 4. Predicting yearly efficacy trends, provides the detailed analysis for (a) non-directional lamps and (b) linear lamps.

2.3. Rationalised Product Categories

The SSL Annex has published the 2022 edition of Recommended Quality and Performance Requirements grouping product types within the following four (4) categories of LED lamps and luminaires for general lighting purposes:

Category 1. Residential Lighting Products (2022)

- Non-directional Lamps (revision of Version 2, November 2016)
- Directional Lamps (revision of Version 2, November 2016)
- Linear strip light (New)
- Downlight Luminaires (revision of Version 2, November 2016)

Category 2. Commercial and Industrial Lamps (2022)

- Linear LED Lamps (revision of Version 1, November 2016)
- Single capped high luminous flux lamps (New)

Category 3. Commercial and Industrial Indoor Luminaires (2022)

- Planar Luminaires (revision of Version 1, November 2016)
- High/Low Bay LED Luminaires (revision of Version 1, November 2016)
- Linear batten and troffer luminaires (New)
- Commercial retrofit kits (New)

Category 4. Outdoor Luminaires (2022)

- Street Lighting (revision of Version 2, November 2016)
- Outdoor Area Lighting (New)

3. Updates and Clarifications to Measurement Quantities

Since November 2016, several countries/regions have introduced, or are well progressed in developing, regulations for Minimum Energy Performance Standards (MEPS) for lighting products, mainly lamps intended for the domestic sector. Higher Efficiency Performance Standards (HEPS), some in conjunction with an Endorsement Label and subsidy programs, have also been developed for promoting higher quality lighting products in several countries. Procurement specifications for energy efficient streetlight luminaires have been adopted by local governments and other providers of public lighting (e.g. energy distribution businesses, energy service companies) for the purposes of reducing energy and maintenance costs.

In relation to technical parameters, some of those used in previous versions of this document have been superseded. In addition, new metrics have been included in recently renewed fields of interest with links to health matters. There are also other technical parameters which are important, for example, electromagnetic immunity and radio frequency emissions, but these are generally dealt with in broader regulations applying to electronic equipment. Those covered in this document relate specifically to lighting product energy efficiency, functional performance, and health aspects.

The following sections document changes which endeavour to facilitate greater coverage and clarity of matters pertaining to the provision of good quality lighting service from energy-efficient lighting products.

3.1. Displacement Factor

Historically, power factor has been the metric used in performance standards and regulations to describe the phase shift (*i.e.* alignment) between the current and voltage waveforms for the mains power supplied to the product. This metric incorporates two different electrical phenomena: the effects of harmonics on the shape of the current waveform (expressed as distortion factor) and the phase shift of the mains frequency (fundamental) component of the current waveform (expressed as displacement factor) caused by the reactive impedance (caused by the capacitive and inductive elements) of the LED driver.

The relationship between these three metrics is:

$$\lambda = K_{displacement} \times K_{distortion}$$

Where $\lambda = power\ factor$

$$K_{displacement} = displacement\ factor$$

$$K_{distortion} = distortion\ factor$$

Limits on the current harmonics are generally applied through other metrics so their inclusion, by using power factor, is unwarranted. Changing the metric to displacement factor is in line with current recommendations within relevant international standards. Displacement factor provides an indicator of any increased current requirements due to the fundamental current phase shift. The effects of changing displacement factor on the current required by a lamp are illustrated in Figure 1 and a comparison of the effects for different lamp technologies is provided in *Figure 2*. It should be noted that the overall effect of displacement factor on the electricity transmission system is the collective result of all connected appliances and equipment to the system.

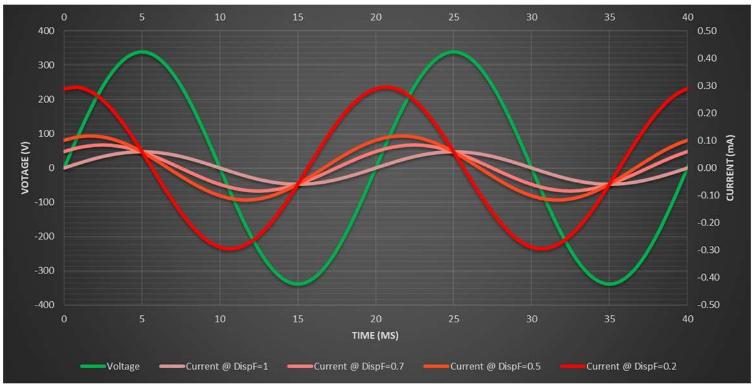

Figure 1: Fundamental currents for different Displacement Factors providing the same lamp power

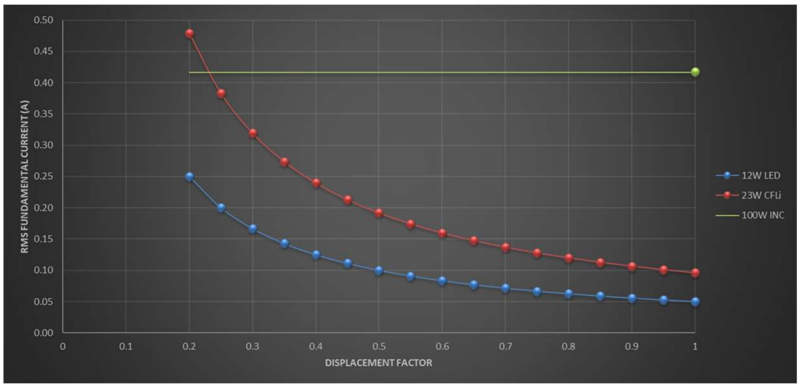

Figure 2: Fundamental Current vs Displacement Factor for three lamp technologies with equivalent light output: 12W LED, 23W Compact Fluorescent Lamp (CFLi) and 100W Incandescent (INC)

3.2. Temporal Light Modulation

Light output from LED chips is very sensitive (i.e., responsive) to fluctuations in delivered electrical power in ways not observed with conventional light source technologies such as incandescent and fluorescent. This variation in light output with time is defined as temporal light modulation (TLM), and if levels are too high can produce unwanted changes in visual perception, known as temporal light artefacts (TLAs). This exposed a gap in lighting product performance standards and regulations that since 2016 has seen the defining of specific TLAs and their metrics by the CIE, the development of test methods by the IEC, and proposed limits by regulators. Two TLA metrics are included in this current revision, short term flicker (P_{st}^{LM}) for effects from lower frequencies, Figure 3, and stroboscopic visibility measure (SVM) for effects from higher frequencies, Figure 4. More information on TLAs is provided in CIE Technical Notes, TN 006-2016 and TN 008-2017 and guidance on measurement of TLM is provided in TN 012:2021.

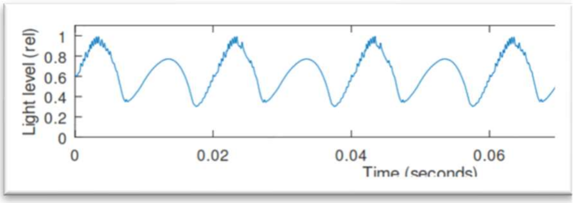

Figure 3: Different light levels of adjacent peaks creating a 50 Hz variation which is measurable in short term flicker (P_{st}^{LM})

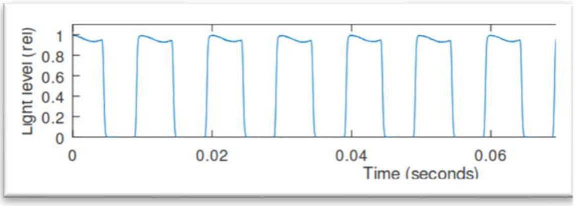

Figure 4: Light level varying at 100 Hz which is measurable in stroboscopic visibility measure (SVM)

3.3. Colour - chromaticity coordinate system

Colour quality metrics are important for describing the colour of the light emitted by a light source as well as colour consistency between samples of the same product and maintaining consistency of colour over the useful life of the product. Reporting, and even visualising, colour appearance, colour difference or colour shift is best presented by a colour space which has a uniform scale of perceived colour change in any direction in the described colour space.

Historically, the x,y chromaticity coordinate system, developed in 1931 by the CIE, has been used in regulatory programmes. This is a non-uniform colour space evidenced by the significant region of shades of green compared to other primary colours, Figure 5. The Uniform Colour Scale chromaticity coordinate system developed by the CIE in 1976 however provides a more balanced colour space, providing opportunity for colour variation metrics (u',v') where measured values throughout the space represent consistent change in colour appearance, Figure 6.

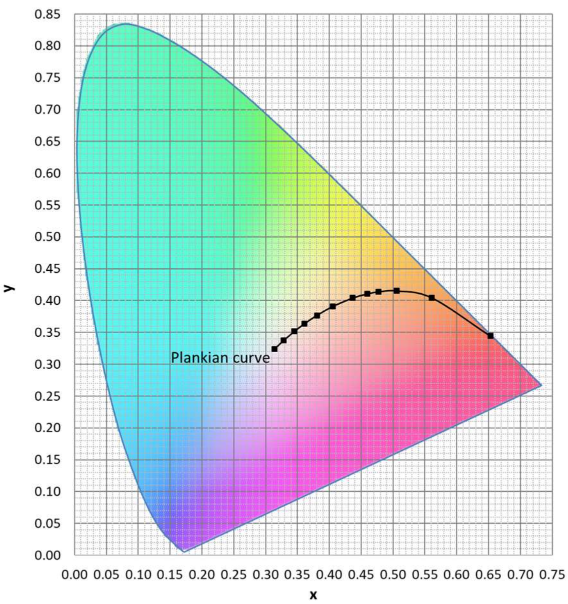

Figure 5: CIE 1931 (x,y) Chromaticity Diagram

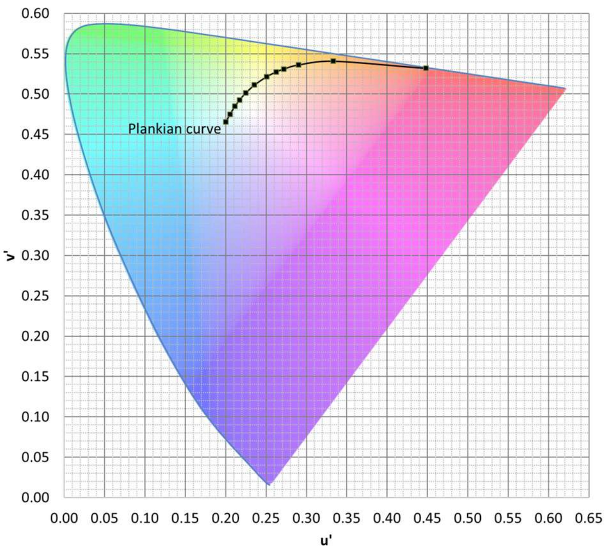

Figure 6: CIE 1976 (u',v') Uniform Colour Scale Chromaticity Diagram

In terms of white light colour appearance, Correlated Colour Temperature (CCT), is accepted and well recognised as a descriptor of the colour appearance of a light source. CCT is fundamentally based on the similarity (correlation) of the perceived colour of a light source, to the colour of the optical radiation emitted by the process of incandescence from a blackbody radiator of a particular temperature (in Kelvin, K).

The curve plotted on a chromaticity chart representing the change in colour appearance with the heating of a blackbody radiator is known as the Planckian curve, Figure 7. With increasing temperature, the colour appearance of the emitted light shifts from a reddish white to a bluish white.

Light sources with colour appearances that are deemed to be similar to a particular colour temperature on the Planckian curve are represented by the CCT isolines that cut across the Planckian curve, illustrated in Figure 7. A more precise designation of the appearance of light sources that have the same CCT but are located away from the Planckian curve is expressed by the metric Duv. This indicates the distance along the CCT isoline and whether above (+ sign) with a slightly greenish appearance or below (- sign) with a more pinkish appearance than the reference colour temperature on the Planckian curve, also illustrated in Figure 7.

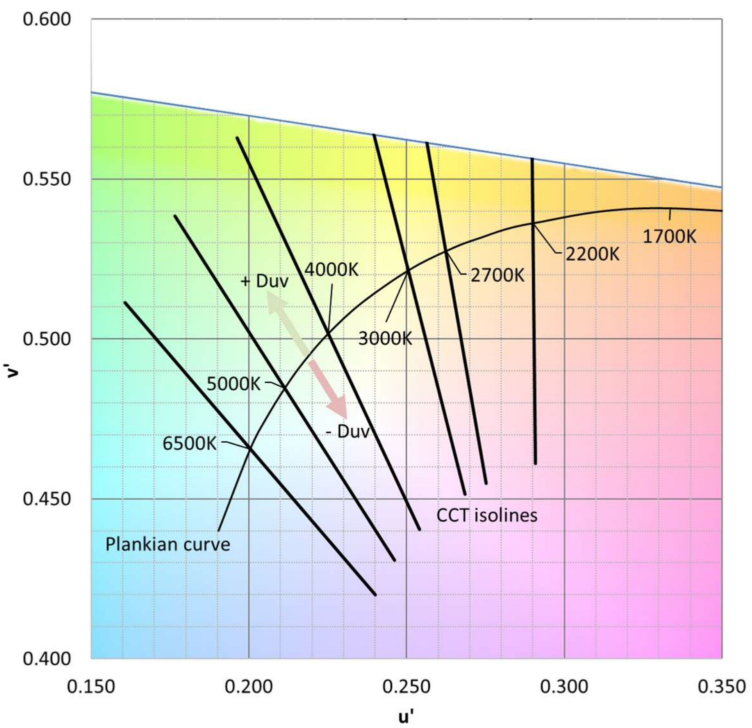

Figure 7: CIE 1976 (u',v') Uniform Colour Scale Chromaticity Diagram illustrating CCT isolines and Duv directions away from Planckian curve

In terms of lit environments, it is important that products (of the same or different model) which are intended to provide the same CCT should be close enough in colour appearance to provide that intended experience. This can be achieved by restricting the distance between the light sources' colour appearances when depicted on a chromaticity diagram.

Previously, different sized ellipses (based on number of unit steps, where lower number indicates smaller size, e.g. 7-step ellipse) around the target colour for a limited set of reference colour temperatures[2] have been used, Figure 8. These are defined within IEC 60081 and are based on

[2] See IEC 60081:2002 Double-capped fluorescent lamps- Performance specifications

ellipses defined by MacAdam[3]. However, in a uniform colour space (i.e. u’,v’ chromaticity diagram), the shape of the restriction boundary, centred on the target reference colour, should be a circle due to perceived change in colour appearance being equal in all directions. This is not the situation with the MacAdam ellipses.

Additional to this, IEC 60081 only defines six target reference colours, effectively limiting the range of colour appearances of light sources within lighting products that have been published in international standards. Ultimately, this forces a rejection of LED packages with colour appearances outside of the MacAdam ellipses but still adjacent to the Planckian curve, from use in general lighting products, Figure 8.

From both commercial and sustainability perspectives, it is reasonable to expect manufactured LED packages with colour appearances near the Planckian curve to be able to be utilised in general lighting products. This philosophy is supported by the defining of ANSI[4] quadrangles[5] centred on ten target reference colours which encompass the region adjacent to the Planckian curve from approximately 2100 K to 7000 K, Figure 8.

For situations where colour appearance is required to be very uniform (from multiple light sources) or precise (from a single light source), a more restrictive requirement can be specified based on a set of small circles (with the radius stated as a number of unit steps) inside the ANSI quadrangles. The circles are known as n-step u’,v’ circles (e.g. 4-step u’,v’ circle). The smaller the number of steps, the smaller the circle.

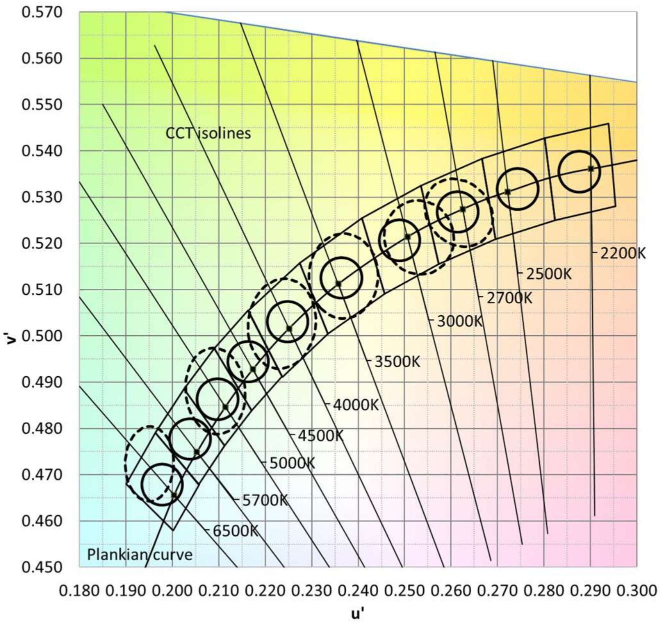

Figure 8: CIE 1976 (u',v') Uniform Colour Scale Chromaticity Diagram illustrating ANSI quadrangles, 4-step u'v' circles (solid lines) and 7-step MacAdam ellipses (dashed lines)

Another colour performance quality is for a product to maintain an acceptable shift in colour appearance over its life. It can be readily determined within the uniform colour space (i.e. u’,v’

[3] D.L. MacAdam, JOSA, 1, 18-26 (1943)
[4] American National Standards Institute
[5] ANSI/NEMA C78.377-2017

chromaticity diagram) using the chromaticity difference, $\Delta_{u',v'}$, between the colour appearance at the beginning and the end of an operating period. This is represented by a move from an initial position on the chromaticity diagram (i.e. the initial colour appearance, u'_1,v'_1) to a position after the designated operating period (i.e. the maintained colour appearance, u'_2,v'_2). An example is provided in Figure 9.

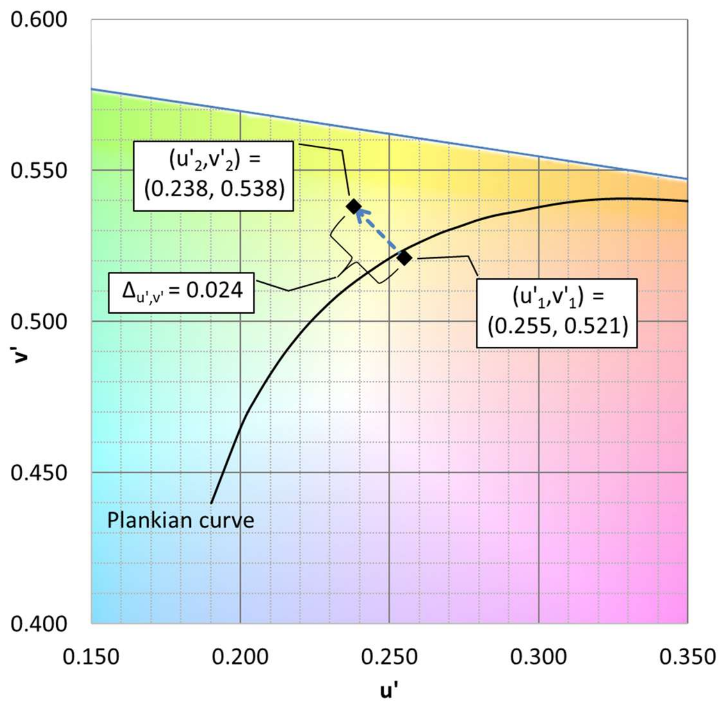

Figure 9: CIE 1976 (u',v') Uniform Colour Scale Chromaticity Diagram illustrating chromaticity difference, $\Delta_{u',v'}$, between initial and maintained colour appearance

The metrics described above:

- u',v' for chromaticity coordinates
- CCT and D_{uv} for colour appearance
- n-step u'v' circles for colour consistency
- $\Delta_{u'v'}$ for colour shift

are used for the recommended colour performance requirements in this document. They have been selected as the most appropriate for assisting and understanding the designation of colour appearance and appreciating quantitative differences. Further details see CIE Technical Note, TN 001-2014 and ANSI/NEMA C78.377-2017.

3.4. Product lifetime

The life of a product is determined by the time until it cannot provide a useful amount of light for its intended purpose. This may be either by (a) catastrophic failure, that is the inability to produce any light by the lamp, or (b) parametric failure, wherein some light is still produced by the lamp but is too dim or is otherwise unsatisfactory for the intended purpose. Typical causes of catastrophic failure are electronic component or electrical connection failures, while typical parametric failures are deterioration of the LED die (manifested as colour shift and/or light loss) and LED driver performances (manifested as flicker and/or light loss). The rated lifetime of a product is generally intended to represent the median lifetime of multiple units of the same product (F_{50}). This means, by definition, that half the units will have a lifetime shorter than this rated value and the remainder will exceed it. As well as the typical lifetime of a product complying with the rated lifetime, the spread of the lifetimes of samples of the product (around the rated value) is important in appreciating the likelihood of the consumer purchasing a sample of a product and ultimately receiving a service near to the rated lifetime.

This is clearly illustrated for two products which have the same lifetime of 15,000 hours but one is a poor quality product, Figure 10, with many early failures (nearly 30% of samples at 6,000 hours operation) whereas the good quality product, Figure 11, has virtually no failures (3%) at 6,000 hours. Appropriate test methods need to be able to expose the relatively high probability of early failure of poor products, Figure 12, while having a low probability of causing failures of the good products, Figure 13.

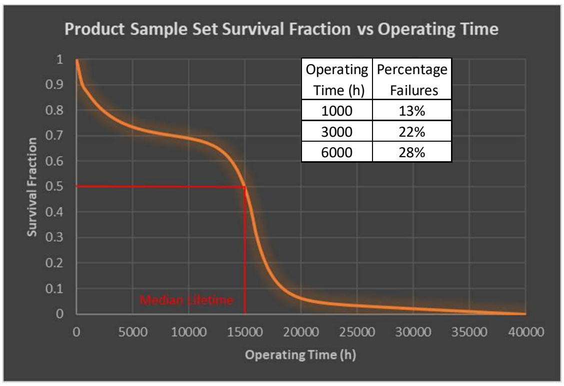

Figure 10: Poor product survival fraction profile

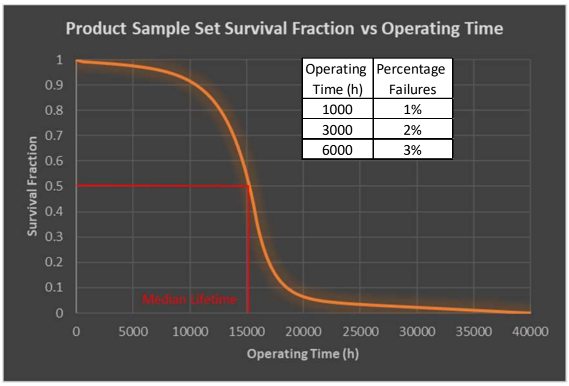

Figure 11: Good product survival fraction profile

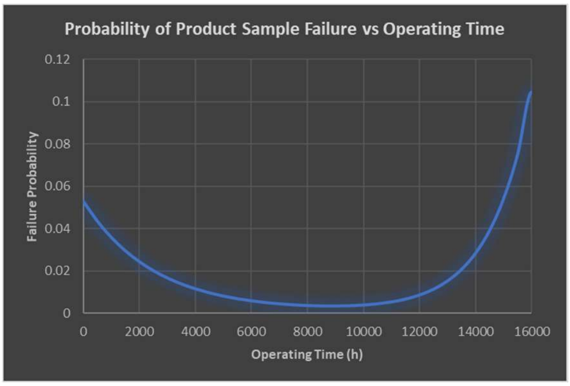

Figure 12: Poor product failure probability profile

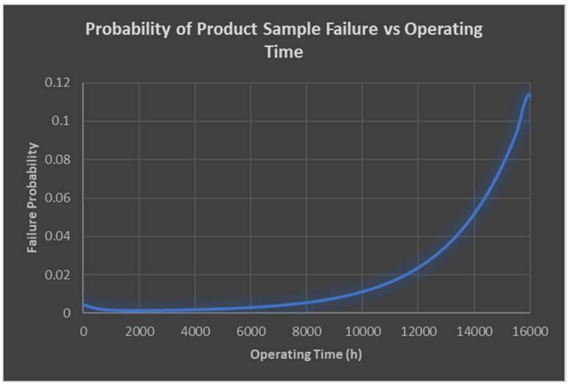

Figure 13: Good product failure probability profile

To protect consumers, metrics that guard against very early (i.e. premature) failure are required. There are typically two reasons for premature failure, both of catastrophic nature:

1. failure of components under the operating electrical and/or thermal conditions, and
2. mechanical failure of electrical connections due to stresses created from the impact of different thermal expansion rates between materials when subjected to large variations in temperature.

This requires subjecting product samples to conditions that would either be reasonably expected to be encountered in typical installations (e.g. switch cycling at typical ambient temperature), or extreme conditions that may accelerate the same failure mechanisms that can then be identified after relatively short test durations (e.g. exposure to temperature extremes in unpowered or cycling switched states). The impact of operating time and switching cycle on lamp component temperatures is illustrated in Figure 14. With the ambient temperature remaining near 20°C, the temperature variation at the lamp's Temperature Measurement Point (TMP) changes significantly from approximately:

- 5°C for switch cycling of 1 minute on and 1 minute off, (as shown in Figure 14 in the region of the Relative Time scale from approximately 15-60 minutes),
  to
- 45°C for switch cycling of 2.5 hours on and 0.5 hours off, (as shown in Figure 14 in the region of the Relative Time scale from approximately 100-450 minutes).

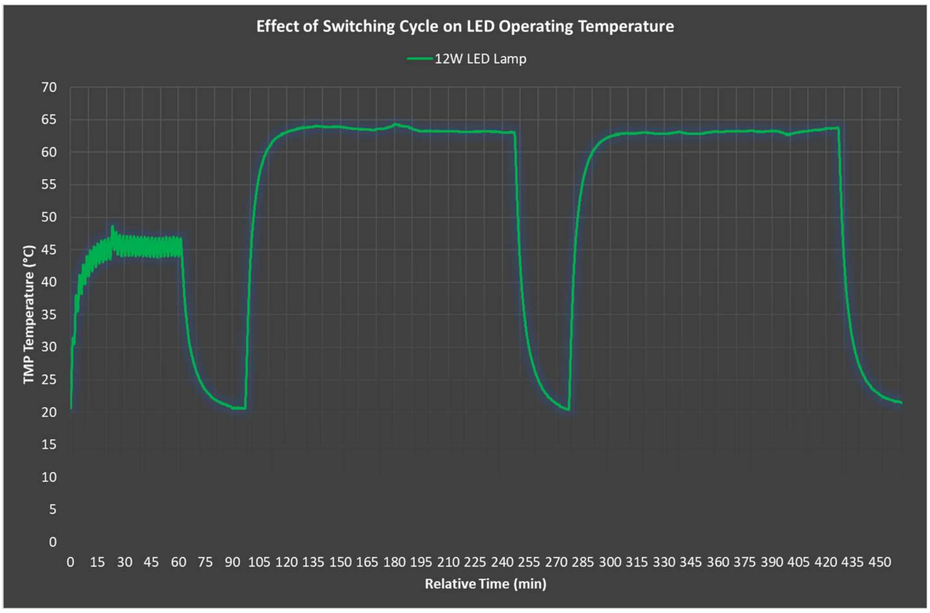

Figure 14: Effect on lamp operating temperature at the Temperature Measurement Point (TMP) of short and long switching cycles

These are known as endurance tests and they identify a product's early failure rate and generally do not include any early indication of reduction in luminous flux output, although there are ongoing research activities in this area.

Checking that the typical lifetime (which accounts for catastrophic and parametric failures) of the samples of a product comply with the rated lifetime is a more complex process given the extremely long operating life of LED products and the lack of an accepted theoretical model and associated test method for long-term catastrophic failure prediction rates. There is however a generally accepted theoretical model for the long-term parametric failure mode of luminous flux depreciation. This requires use of a performance testing method able to be conducted over a duration considerably shorter than the product's lifetime and then combining these test results with an accepted algorithm, which models the depreciation in luminous flux output of LED products, to confirm the rated lifetime of the product. The calculations within this type of test only ascertain the predicted median lifetime due to the luminous flux depreciation of the samples and not from any operational failures. The commonly used defined metric for the value that is determined from this test is the median time for the luminous flux maintenance of samples of a product to drop to 70%, $L_{70}B_{50}$. An illustration of the test and prediction process is provided in Figure 15.

Metrics and testing are required to provide indicative lifetime information on

- Endurance
- Lumen maintenance

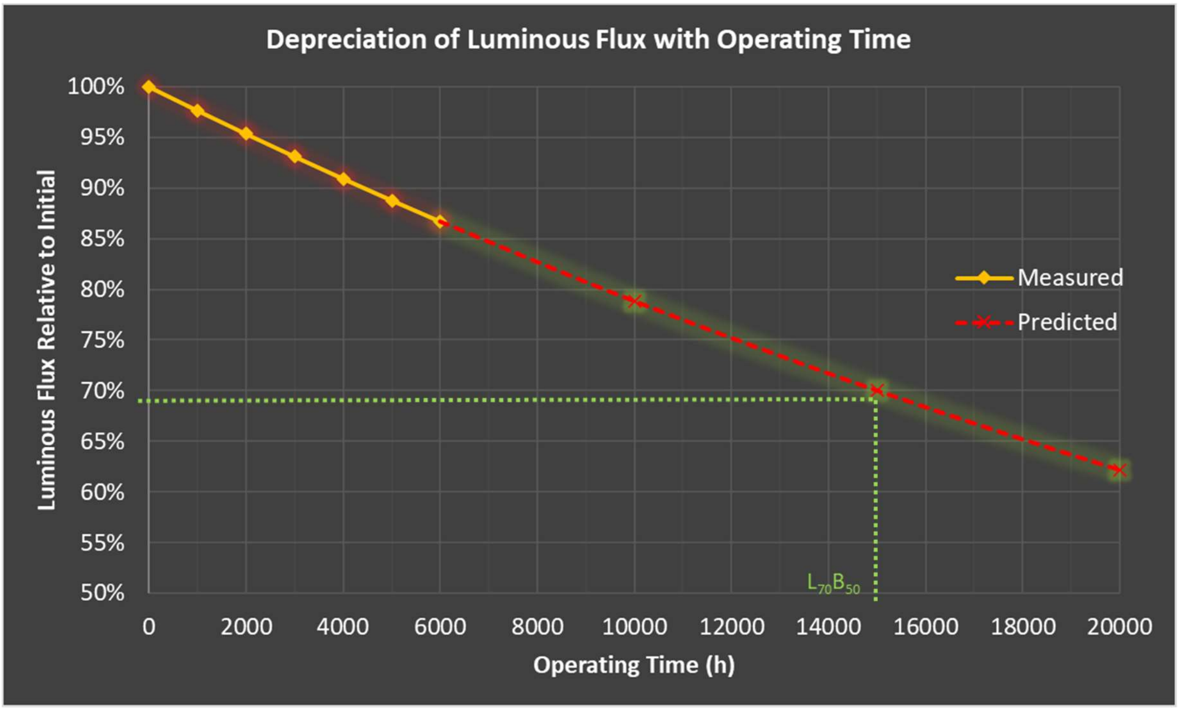

Figure 15: Modelling of luminous flux depreciation and determination of the $L_{70}B_{50}$

In 2020, the SSL Annex continued investigations into lifetime testing of LED products, by commissioning a study to review the latest literature and research on the topic. Published in June 2021[6], based on the evidence collated, the study provides, recommendations on the perceived best approach(es) to lifetime testing for LEDs and LED products, which may then facilitate further targeted research verifying and refining the relationship and test methodology.

This body of work may ultimately contribute to redefining metrics and test procedures for product lifetime; but until then, existing published metrics and test procedures continue to be recommended by the SSL Annex and are presented in Annex 2, Quality and Performance Requirements for LED Lighting Products (2022)[7].

4. Predicting yearly efficacy trends

[6] Accessed 5th October 2021: https://www.iea-4e.org/ssl/news/new-iea-4e-ssl-annex-literature-review-offers-insights-into-complex-area-of-led-lifetime-testing/

[7] "Quality and Performance Requirements for LED Lighting Products" at https://www.iea-4e.org/wp-content/uploads/2022/11/Task-6-LED-Lighting-Product-Tiers-October-2022-final.pdf

Luminous efficacy trends over time were obtained based on the US Lighting Facts database for lamps and luminaires in relevant product categories. These trends were extrapolated using linear and logarithmic trendlines. With very similar results obtained over the relatively short projection period, for simplicity of explanation, the linear trendlines were used to obtain estimates of projected tier efficacy targets for 2024 (with 95% confidence interval illustrating upper and lower estimates).

N.B. The US Lighting Facts Database is used for the analyses as it, in comparison to other data sources:

1. *contains a large volume of data and can be considered representative of the general market as a voluntary product register with no minimum luminous efficacy requirements;*
2. *lists the initial date products are registered – unlike many other data sources where the date is associated with the year available for sale, or the year data was accessed (which may be several years after the product entered the market); and,*
3. *is sufficiently detailed to enable the LED products to be cohesively grouped by type, size and application.*

The US Lighting Facts Database is therefore the most suitable choice for observing and extrapolating LED product efficacy trends over time.

The extrapolated luminous efficacy trends for each of the product categories were then compared with recent data from a range of other data sources (mostly international LED product registers) in order to observe the fit of these actual product efficacy data with projected efficacy trends.

An example of this data analysis is shown here in Figure 16 for non-directional lamps. This figure shows the US Lighting Facts data for this lamp category in the years the lamp database was active. Highlighted are the trends for a total of 1,381 lamps from 2010 to 2016:

- Tier 1 – 20th percentile of data
- Tier 2 – 80th percentile of data
- Tier 3 – 95th percentile of data

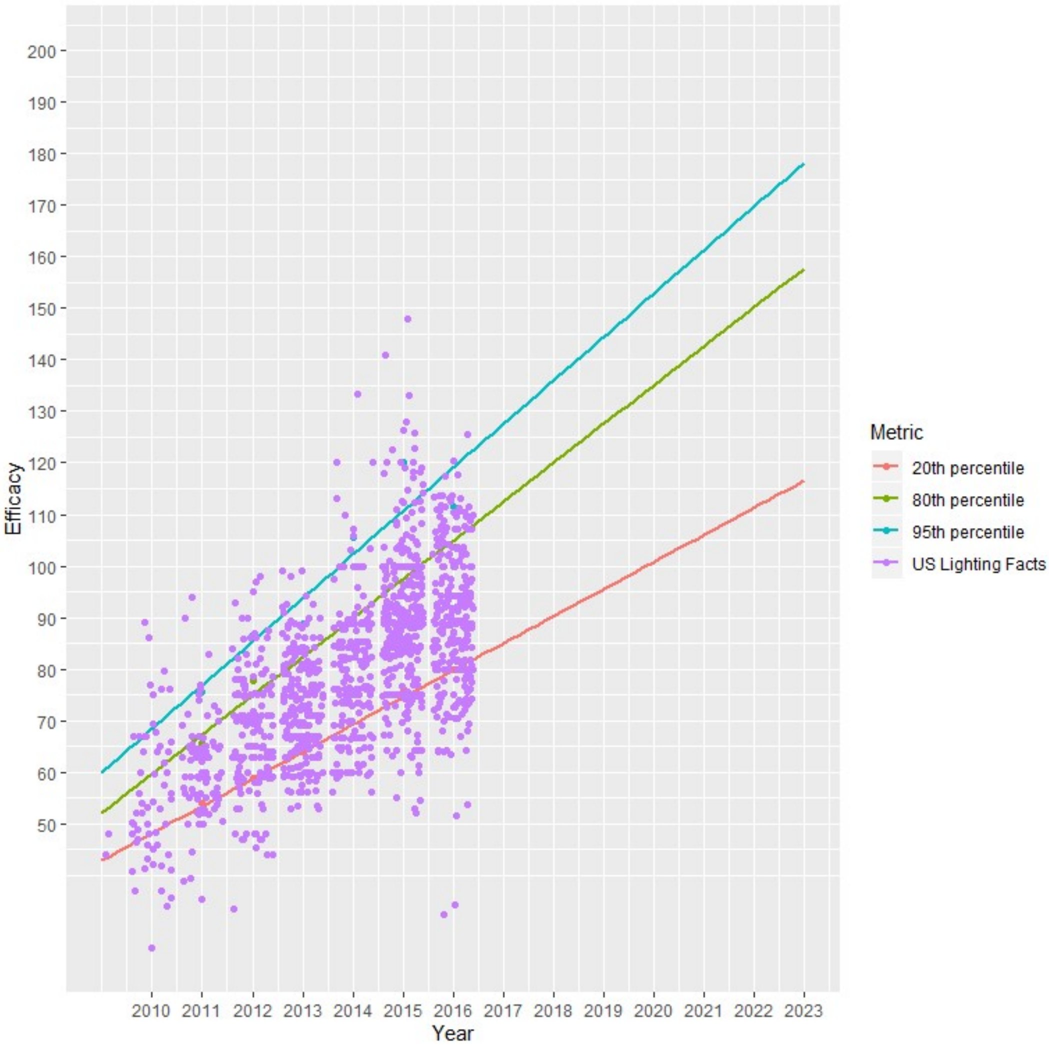

Figure 16: Efficacy trend (in lm/W) projections for 20th, 80th and 95th percentiles based on US Lighting Facts data for non-directional LED lamps (n=1,381)

In order to validate the projected trends, a comparison was conducted with the most recent available data from other international sources. Figure 17 shows again the three trend lines, derived from the US Lighting Facts data, but now overlaid only with a scatterplot consisting of data from:

- Test data from 236 non-directional lamps available for sale in SE Asia in 2016.
- Australian Market data obtained from a 2017/18 survey of LED lamps available for sale online and in-store – lists 2141 non-directional lamps.
- US/Canada's Energy Star database – lists 3486 non-directional LED lamps (active at July 2019). This register has a minimum efficacy requirement implemented in 2017.
- India's Star Rating Register – lists 355 GLS equivalent LED lamps (listed as registered in 2019). This registration has tiered efficacy requirements for 1-5 star ratings.
- Japan's Top Runner Program register – lists 433 'GLS-shaped' LED lamps (listed registration year 2017). This register has a minimum efficacy of 100 lm/W.
- Thailand's Label No.5 product database – lists 95 A-shape LED lamps (data download year 2019).

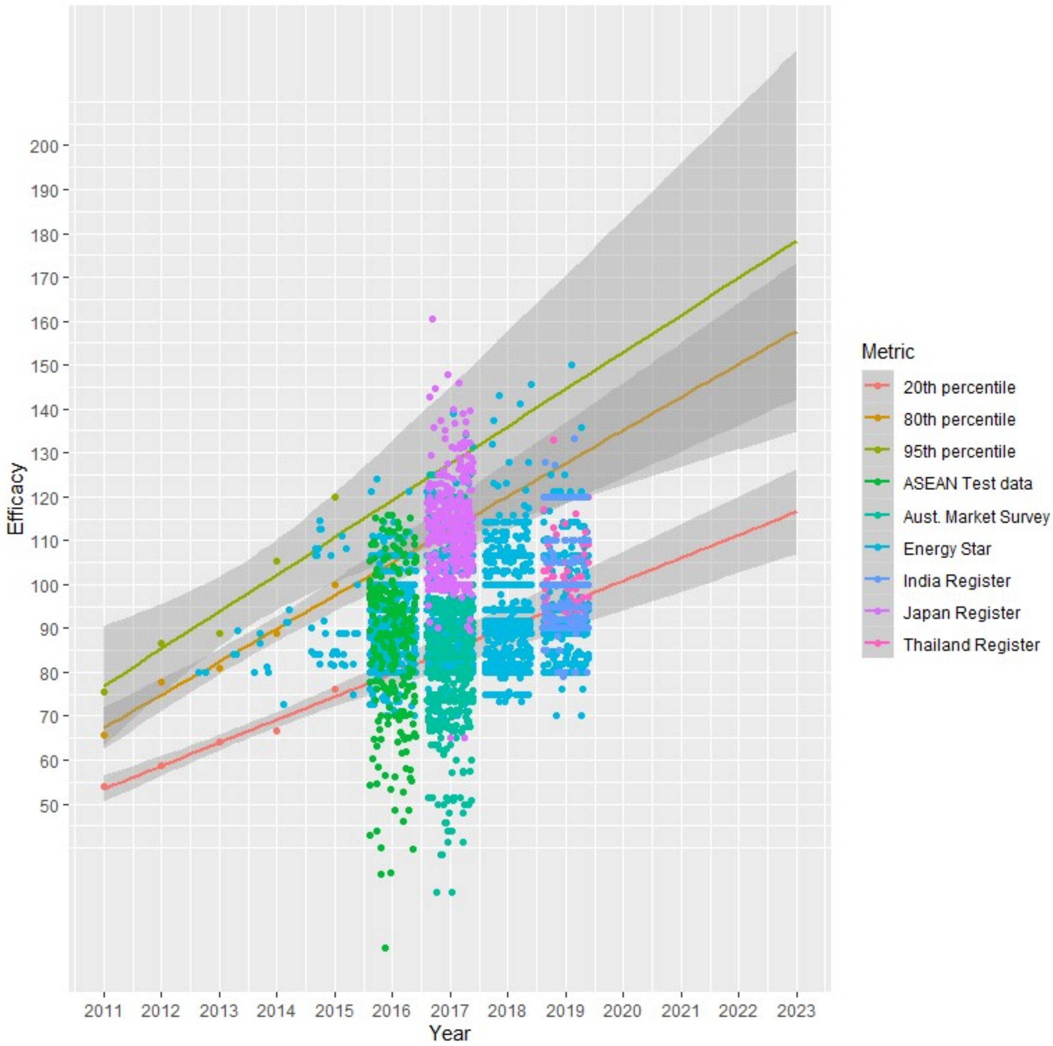

Figure 17: US Lighting Facts-derived efficacy projections (lm/W, shown with 95% confidence interval in grey), overlaid with international test, market survey and efficient product registry data for non-directional LED lamps

Figure 17 shows that the Tier 1 projection is consistent with register data from Energy Star and the Japanese, Indian and Thai energy efficient product databases (note that the Energy Star set its efficacy requirement in 2017, for Tier 1 reference).

Tier 2 and 3 projections beyond 2016 (where the US Lighting Facts data on LED lamps ends) show that there are products achieving these levels in quantities consistent with the expected performance level.

The data also shows that in the absence of minimum efficacy requirements (market survey and test data), the spread of data ranges from well below the Tier 1 projection to in line with and above the Tier 3 projection. It must be noted that the market and tested product data incorporates products which entered the market in years prior to their data entry date.

A second example of this efficacy trend analysis is provided for linear LED lamps. Highlighted for this lamp category in Figure 18 below are the trends for US Lighting Facts data for a total of 4,966 lamps from 2013 to 2016:

- Tier 1 – 20th percentile of data
- Tier 2 – 80th percentile of data
- Tier 3 – 95th percentile of data

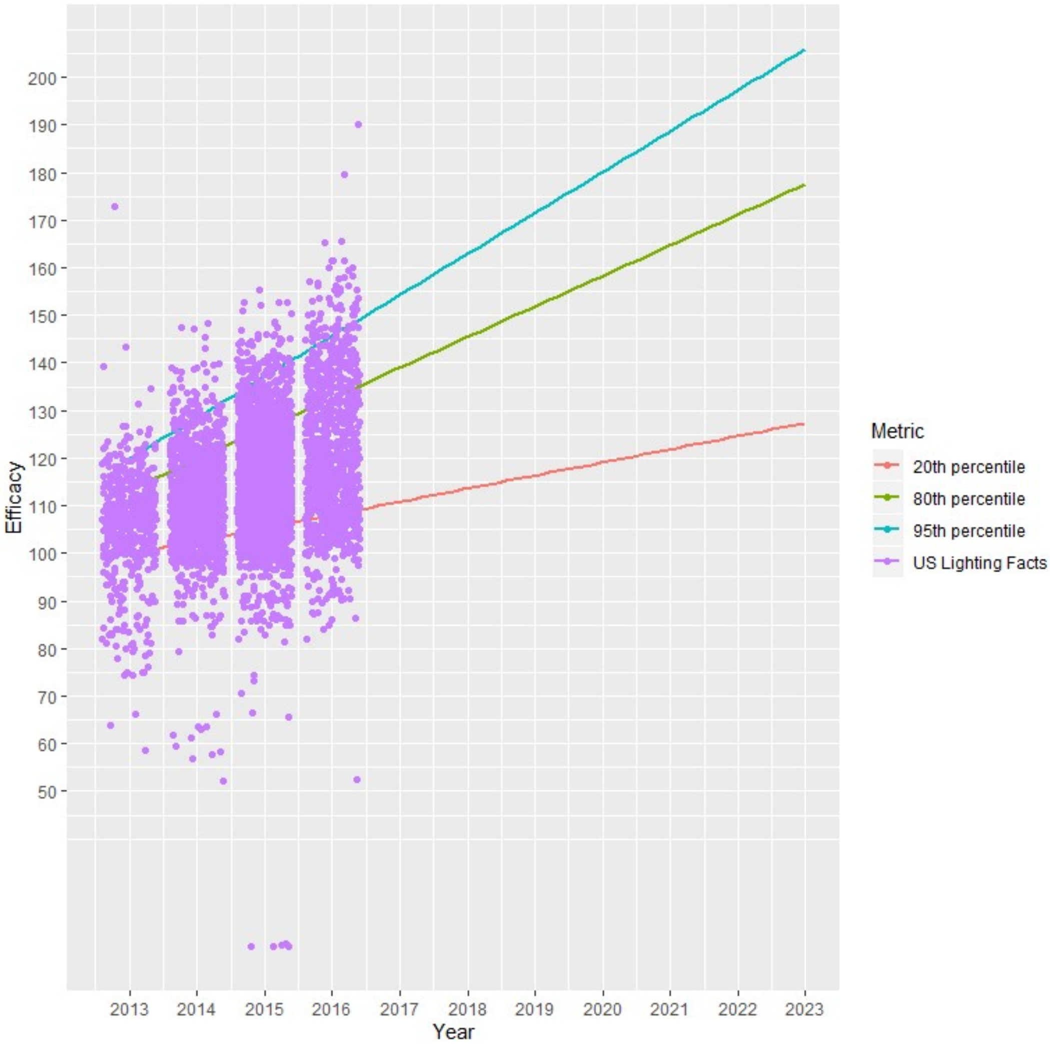

Figure 18: Efficacy trend (in lm/W) projections for 20th, 80th and 95th percentiles based on US Lighting Facts data for Double-Capped Linear LED retrofit lamps, (n=4,966)

Again, to validate the projected trends, a comparison was conducted with the most recent available data from other international sources, Figure 19 shows comparison (scatter) data from:

- Australian Market data obtained from a 2017/18 survey of LED lamps available for sale online and in-store – lists 372 linear lamps.
- Design Lights Consortium (DLC) Standard register – lists 30,821 linear LED lamps (active at April 2020). This register has a minimum efficacy requirement.
- Thailand's Label no.5 Program product register – lists 101 LED tubes (linear lamps), (data download year 2019).

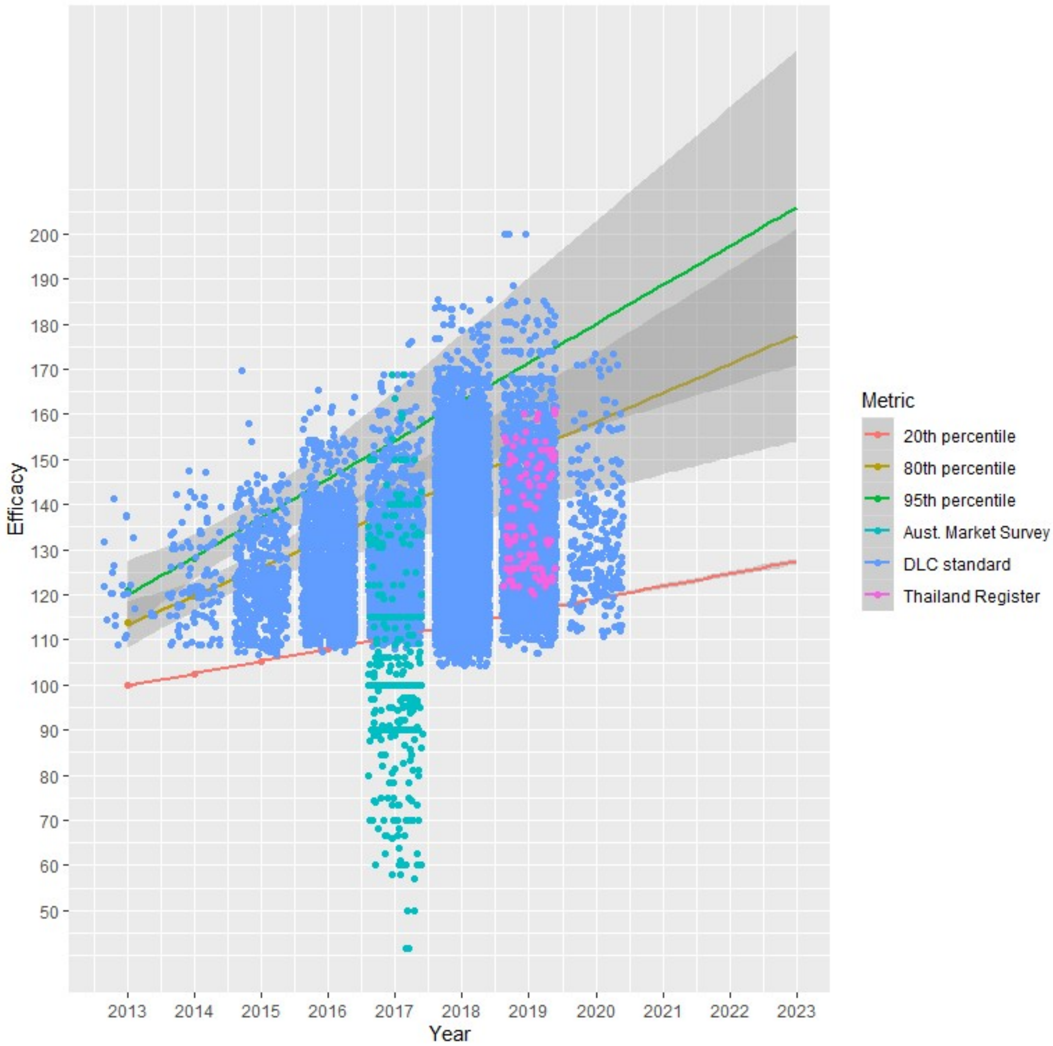

Figure 19: US Lighting Facts-derived efficacy projections (lm/W, shown with 95% confidence interval in grey), overlaid with market survey and efficient product registry data for linear LED lamps.

In this comparison, we see the DLC standard and Thai Label No.5 register data is consistent with all efficacy projections. The market survey data displays a spread of efficacy, ranging from well below the Tier 1 projection to in-line with and above the Tier 3 projection – again it is noted that this survey would include products which entered the market in years prior to the survey date.

The efficacy levels set out in the main document are recommended for regulations or market transformation programmes with commencement dates in the year 2024. This marks a one-year advancement of the commencement date of 2023 as proposed in the public draft (released 2020) and illustrated in the projections above (Figure 17, Figure 19). This change accounts for delays in issuing final documentation and is consistent with performance data reviewed in the period of 2020 to 2022.