# Understanding LED performance:
# Evidence-based approaches to supporting stakeholders of energy-efficient lighting programmes

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## 1. ABSTRACT

The International Energy Agency's Energy Efficient End-use Equipment, Solid State Lighting (IEA 4E SSL) Annex takes an evidence-based approach to evaluating LED product performance. Using comprehensive market data from product registries, surveys, market product testing and by initiating leading edge research, the SSL Annex provides support to governments looking to implement energy-efficient policies in lighting. Key to this activity, is the development of recommendations on parametric limits for product performance and research into test methods that reduce the time and cost burden for government, industry and consumers.

This paper highlights several activities that exemplify the SSL Annex's evidence-based approach and the outcomes of that work. This begins with benchmarking results that provide a snapshot of product performance in precise markets and provides a basis for the prediction of future trends. Such benchmarking data show notable differences between claimed and tested data variation between regulated and unregulated markets.

Furthermore, the investigation and development of novel product test methods – critical to reducing testing burden while maintaining accurate measures of performance – are presented for LED product endurance and lifetime. This work developed a method for shortening predictive life testing by incorporating accelerated aging and pulse-soak testing.

Also highlighted is recent research on the human factors impact of Temporal Light Modulation (TLM). Such priority work allows for the advancement of performance measures for health and wellbeing of consumers.

The ongoing efforts of the SSL Annex activities aim to ensure that energy efficient lighting policy is driven by real data that accurately reflects a rapidly changing market.

## 2. INTRODUCTION

As LED technology has matured to dominate the lighting product market, the need for information that provides understanding of LED product performance has escalated. Assessing advances in product performance is centred on the ability to evaluate both existing products (benchmarking) and evaluating ongoing, innovative product research and development (streamlined product testing and predicting performance trends).

## 3. INVESTIGATING PRODUCT PERFORMANCE

An evidence-based approach to investigating LED product performance involves several modes of data collection. Claimed performance data, reported by product manufacturers and retailers, can be obtained through market survey or accessed directly from product registries or databases maintained by government and other organisations; such as the European Product Registry for Energy Labelling (EPREL) database[1] or the Design Lights Consortium (DLC) database[2]. Claimed performance data is useful but is not always verified by associated product testing. Test performance data is superior in terms of accuracy, but generally more difficult to find. Some databases may include full or partial test performance data that verifies claimed data (e.g. the DLC database includes some test data). In addition to this, product test data is also produced by governments as part of market surveillance and compliance activities, as well as by other organisations as part of benchmarking activities. The member countries of the SSL Annex do independently undertake regular product testing for market surveillance purposes.

Through claimed and tested product performance data, collected via market survey, online databases, lighting product registries, and from benchmarking and compliance resources; a forecast of LED product performance can be developed. Understanding product performance is critical for several reasons:

- Market surveillance: to determine compliance with existing lighting regulations (including safety, quality, minimum energy performance);
- Benchmarking: to determine current market performance and the need for policy intervention;
- Consumer protection: to assess gaps between claimed and actual performance of products;

[1] https://eprel.ec.europa.eu/screen/product/lightsources

[2] https://www.designlights.org/qpl/

- Market forecasting: to predict future market performance based on historical data; and
- Policy impact assessment: to evaluate the effect of product performance standards on the market.

Figure 1 shows the result of benchmark luminous efficacy testing of A-shaped LED lamps in the ASEAN region. In this graph, circular markers show results for the lamps selected from markets with no regulations on these products' performance at the time of testing; cross-shaped markers show data from markets with relevant performance regulations. A solid red line in this graph shows the efficacy level recommended by the SSL Annex for minimum acceptable performance of these products at the time of testing (65 lm/W, 2018). Comparing LED lamps from markets with and without regulation, it is clear that the products tested in unregulated markets generally had lower efficacies than those in regulated markets, and below the recommended level in 2018.

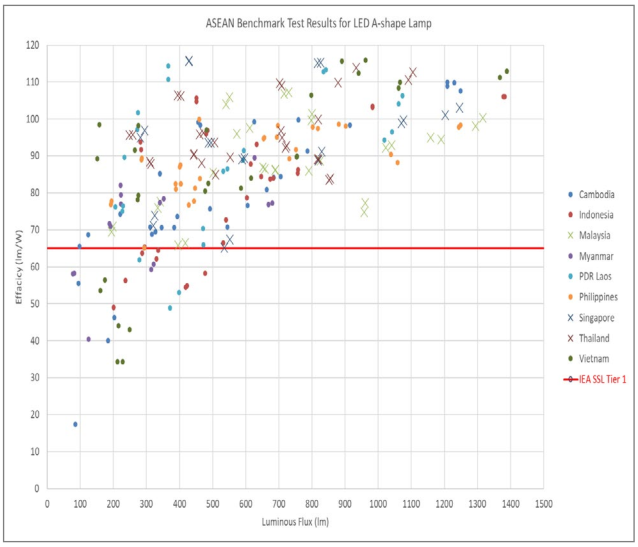


**Figure 1: Benchmark testing of luminous efficacy and luminous flux for A-shaped LED lamps in ASEAN region**

This type of benchmarking data can demonstrate the effect of policy on market performance trends and provide concrete evidence to assist in regulatory decision-making processes.

Test data can also be used in comparison with claimed product data to evaluate the need for verification testing in a market. Figure 2 and Figure 3 show luminous efficacy test data for 2 similar product groups in different markets:

- 19 omnidirectional LED lamps in Australia, (Figure 2), and
- 22 A-shaped LED lamps in Kenya, (Figure 3).

Each product tested is represented by 2 markers on the graphs. The hollow marker shows the claimed value of efficacy and flux, the solid marker shows the corresponding tested value, and each related claimed/tested data marker is connected by a line. The data are colour-coded, so that black markers show products where the difference between claimed and tested values are less than 10%. Green markers show products with tested values more than 10% greater (i.e. the purchaser gets a better performing product) than claimed; while red markers show products with tested values more 10% lower (i.e. the purchaser gets a worse performing product) than claimed values.

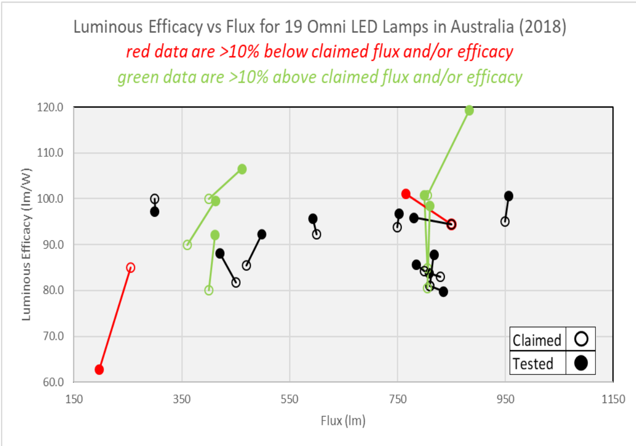


**Figure 2: Claimed and tested luminous efficacy and luminous flux data for 19 omnidirectional LED lamps from Australia in 2018.**

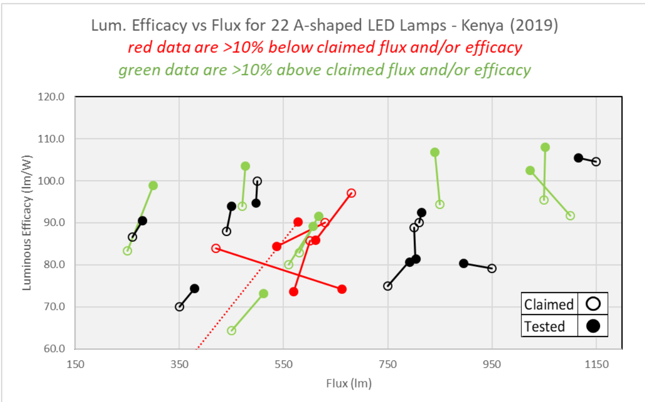


**Figure 3: Claimed and tested luminous efficacy and luminous flux data for 22 A-shaped LED lamps from Kenya in 2019**

Figure 2 shows 2 of the 19 lamps (approximately 10%) tested with claimed values more than 10% higher than their tested values. In Figure 3 this proportion rises to approximately 23% of tested products (5 out of 22 lamps).

Data of this type can be used to assess the need for compliance and verification testing to protect consumers and to ensure that policies are being effective in transitioning markets.

While benchmarking data can offer a snapshot of current LED product performance, data accumulated over time can offer broader insights into performance trends over time. Such trends can allow for some prediction of future product performance, which is critical for policy planning.

Starting in 2020, a multi-year review of historical data on luminous efficacy of LED products was undertaken by the SSL Annex, in order to provide recommendations on reasonable product performance standards for the coming years. In 2022, the Annex published its latest update on Quality and Performance Requirements for LED Lamps and Luminaires. The performance requirements designate recommended values across a range of performance measures at 3 levels:

- A minimum acceptable performance level (MEPS) – around 80% of the (unregulated) market should be able to achieve this level;
- A high performance level (HEPS) – around 20% of the (unregulated) market should be able to achieve this level; and
- A Top Performer level – this level is achieved by the top 5% of the (unregulated) market.

In terms of efficacy, LED products must be separated into categories of similar products for comparison and trend prediction.

For example, Figure 4 shows how grouping historical efficacy data for omnidirectional LED lamps (< 3,000 lumens) from 2011 to 2017 produced efficacy trends for the MEPS (20th percentile), HEPS (80th percentile) and Top Performing (95th percentile) lamps – shown using trend lines with confidence intervals in grey shading. Also illustrated on this graph using coloured circular markers is historical data taken from a range of sources between 2013 and 2019, including test data, market surveys and national product registers. These data were used to validate the predictive trends, and the recommended efficacy levels set out in the 2022 publication of the Quality and performance requirements for LED lamps and luminaires [1].

The most recent data added to Figure 4 was taken in 2022 from product information published in the European EPREL database. From this database, the efficacy rating (A-G) for the EU regulated Energy Label [2] of 18,909 non-directional LED lamps with E27/B22 bases and a minimum flux of 400 lumens was compiled. Note that, some lamps have advanced features such as dimmability or colour adjustment that receive efficacy concessions for MEPS but not for the Energy Label. This 2022 data shows available products with efficacies across the range from below the predicted MEPS levels to above the Top Performer levels. It should be noted that the EPREL data is categorical in nature, with seven categories:

| | | |
|---|---|---|
| A: | $210 \leq \eta$ | lm/W |
| B: | $185 \leq \eta < 210$ | lm/W |
| C: | $160 \leq \eta < 185$ | lm/W |
| D: | $135 \leq \eta < 160$ | lm/W |
| E: | $110 \leq \eta < 135$ | lm/W |
| F: | $85 \leq \eta < 110$ | lm/W |
| G: | $\eta < 85$ | lm/W |

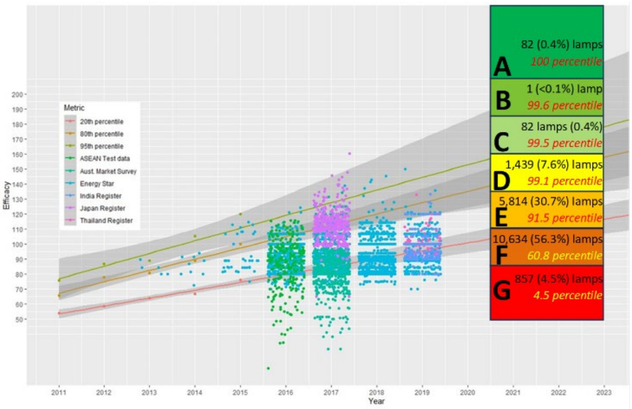


**Figure 4: Luminous efficacy vs year of registration/survey for omnidirectional lamps, showing efficacy trends based on US Lighting Facts data (2011-2017), individual product data from registers, test data and market surveys (2013-2019) and 2022 EPREL data with energy classes A to G**

Figure 5 shows a similar graph for linear LED lamps, again showing the most recent EPREL data for 3521 linear LED lamps (with flux greater than 1,200 lumens) overlaid on data used to generate and validate efficacy trends for products in this category.

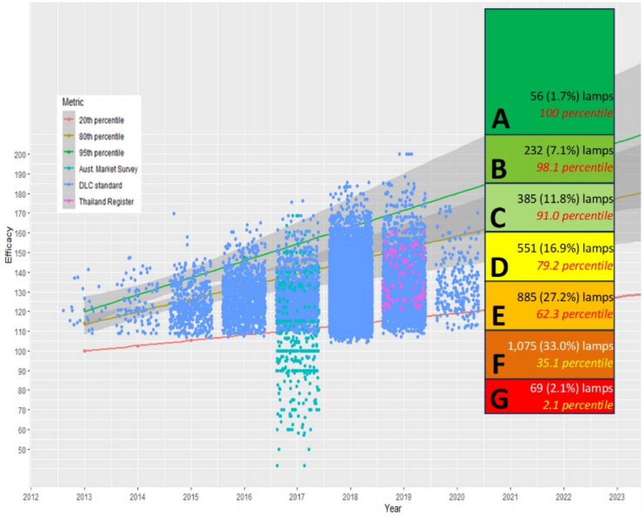


**Figure 5: Luminous efficacy vs year of registration/survey for omnidirectional lamps, showing efficacy trends based on US Lighting Facts data (2013-2017), individual product data from registers and market surveys (2013-2020) and 2022 EPREL data with energy classes A to G**

Collecting and presenting the historical and current data shown in Figures 4 and 5 demonstrates the value of efficacy predictions. The range of individual product data presented on these graphs shows how different types of data sit within the predicted levels: e.g. test data and market data that lags below the predicted MEPS (20$^{th}$ percentile) level may indicate the need for enhanced regulation or compliance activity.

## 4. INVESTIGATION OF LED PRODUCT ENDURANCE AND LIFETIME

Product lifetime – along with price and running costs – is a key economic factor in the assessment of the cost-benefit of investing in a product. Therefore, businesses and consumers would benefit from some assurance that an LED product will deliver the claimed service life (rated lifetime). If there is accuracy in lifetime claims, this will provide confidence to the market and boost the rate of adoption of LED.

The rated lifetime of a product is defined as the median lifetime of multiple units of the same product, thereby half the units will have a lifetime shorter than this rated value, and the remainder will exceed it.

The ability of a product to endure typical operating conditions, including realistic switching cycles, is one of the most basic requirements of product performance. Investigation into the ability of a product to endure these conditions can be used to provide an indication of the model's likelihood of reaching its intended (claimed median) lifetime. The SSL Annex investigated the relationship between variation in LED chip temperature of products and switching cycles concluding that more suitable indicator of a products survivability required 1200 cycles of 2.5 hours on and 0.5 hours off, Figure 6.

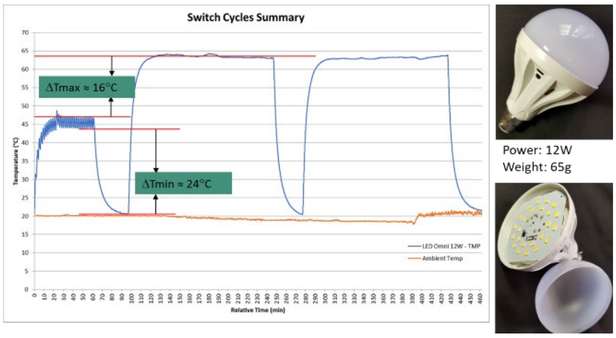


**Figure 6: Lamp temperature variation adjacent to an LED chip on PCB board with 1 min switching on & off followed by 2.5 hours on and 0.5 hours off.**

This test method also provides an opportunity to measure the luminous flux depreciation over 3,000 hours of operation which can be compared to the expected depreciation based on the rated lifetime. The findings of this work were incorporated as a combined endurance test method with luminous flux depreciation requirements in the current EU Ecodesign Regulation for light sources [3].

Determining the lifetime of an LED product by conventional testing of products until actual end of life is, unfortunately, not practical given their typically long lifetimes (25,000 hours would require testing for nearly 3 years) and the requirement to test a large sample set of a product for statistical purposes.

Before undertaking its own investigative pathway, the SSL Annex commissioned a review of published literature to summarise and objectively assess mainstream and novel approaches to lifetime testing of LED products which may lead to a robust testing solution for regulatory purposes [4].

Subsequent to the findings of this report, the SSL Annex has been investigating whether the influence of temperature on the combination of luminous flux parameters of (a) instantaneous output, (b) stabilised output, and (c) depreciation over time, can be used for to predict a product's lifetime.

Items (a) and (b) are acquired through a pulse (start-up) - soak (stabilised) test. Figure 7 illustrates an approximate 30% reduction in light output between start-up and stabilised conditions.

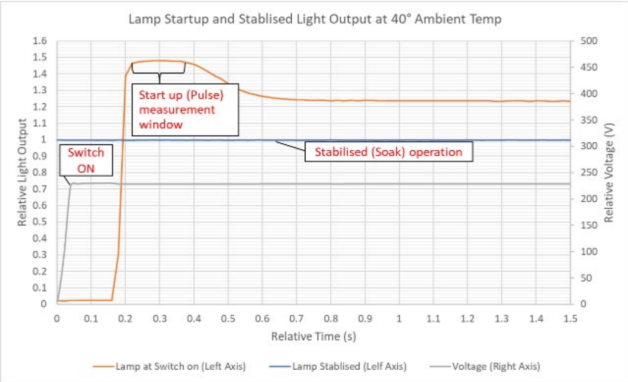


**Figure 7: Pulse-soak results for a lamp at 40°C ambient**

Item (c) is an accelerated ageing test at an elevated ambient temperature as illustrated in Figure 8.

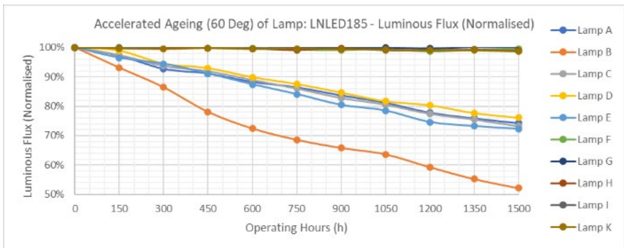


**Figure 8: Accelerated ageing test for a lamp model at 60°C (Lamps A-E turned on, Lamps F-K turned off)**

Early results are positive, and investigations are ongoing.

## 5. HUMAN FACTORS AND TLM

The term Temporal Light Modulation (TLM) refers to any change in light quantity or spectral content of light output by a light source over time. The associated term Temporal Light Artefact (TLA), sometimes referred to as "flicker", is used to describe the human visual perception of TLM.

LEDs have beneficial technological properties for lighting products, including: "instant" start, rapid colour adjustment, smooth and responsive dimming, and improved signalling and communication capabilities. However, without a complete understanding of the sensitivities of humans to rapid temporal lighting variations, there is the potential for a long-term legacy of installed LED products that negatively affect the health and well-being of many people. In this context, it is critical that the TLM of LED sources can be reliably measured, and that their effects on vision, neurophysiology, behaviour, and health can be predicted consistently within the broad population.

TLM can affect individuals in different ways depending on the modulation waveform. Some TLM waveforms result in the visual perception we call flicker are visible (such as flicker), while others are not visually perceptible but still may have detrimental behavioural and health effects (disrupted eye movements during reading, for example). Susceptibility to different TLM varies between individuals. This makes the development of meaningful and reliable metrics and limits challenging and is the focus of many ongoing research efforts.

The Stroboscopic Visibility Measure (SVM) is used to predict the likelihood of detecting the stroboscopic effect under a light source with temporal modulation. A light source with a measured SVM of 1 would create stroboscopic effects detected 50% of the time by an average observer. To make well-informed and constructive recommendations on appropriate SVM limits for LED products, the IEA SSL Annex identified the need for more research on the sensitivity of people to the stroboscopic effect.

Research on the detection of stroboscopic effect of sources with different levels of SVM was conducted in an IEA Annex initiative at the National Research Council of Canada (NRCC, Canada) and the Centre Scientifique et Technique du Bâtiment (CSTB, France), and published by Veitch and Martinsons in a report, 2019 [5] and a peer reviewed journal, 2020 [6].

Eighty-five people were tested in a small windowless room, observing rotating discs (horizontally and vertically) and metronome tasks illuminated by a single light source. The five groups of light sources selected were commercially available products, covering a broad range of measured SVM values (~0, ~0.4, ~0.9, ~1.4, ~3.0). Figure 9 shows the horizontal rotating disk task observed under different sources.

The results of this experimental showed the average rotating disc detection rates was lower than expected for the test groups at SVM ~0.9 – where it is expected that the detection rate should be nearly 50%.

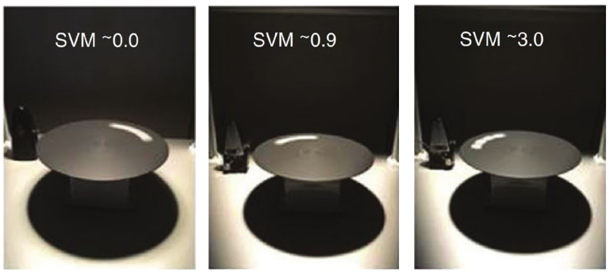


**Figure 9: Images showing conceptually the effect of increasing the SVM on the detection of the stroboscopic effect on a rotating disc [2].**

For increasing values of SVM above ~0.9, the stroboscopic effect detection increased in a strongly nonlinear way, suggesting that small increases above ~0.9 can substantially increase the likelihood of detection.

Interestingly, in evaluation of populations that may be potentially more sensitive to the impacts of TLM (specifically those susceptible to visual stress assessed by pattern glare sensitivity), it was found that this group did not perform significantly better at detection of the stroboscopic effect; but they did report higher levels of annoyance with higher SVM conditions.

This research was submitted by EU member states representatives from the SSL Annex to the European lighting ecodesign regulatory process in 2019 and was used as part of the evidence base for establishing maximum levels of SVM in Europe. The SSL Annex continues to look at this topic and is continuing to assess the links between lighting and health.

This research contributed to the understanding of the human impacts of the stroboscopic effect and the sensitivity of the SVM as a predictive tool.

## 6. CONCLUSION

Understanding LED performance first requires robust measurement methods and metrics, so that the data collected on available and developing products can be reliably evaluated, compared and presented to show market performance and trends.

The IEA 4E SSL Annex recognises the need for globally harmonised efforts to build consensus on the way LED products are evaluated, so that the goals of energy efficient lighting programmes are realised without sacrifice to economic and human factor considerations.

## 7. ACKNOWLEDGEMENT

These investigations have been supported either individually, or collectively, by the Governments of member countries of the IEA 4E SSL Annex, https://www.iea-4e.org/ssl/about/.

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