True specs for dimmed and colour tuned LED luminaires

C Dam-Hansen[1,4], A Thorseth[1], D D Corell[1], A Bay[2], C Krause[2], and C Kofod[3]

[1] Department of Electrical and Photonics Engineering, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark
[2] Viso Systems, Vesterbrogade 12, 1., 1620 Copenhagen V, Denmark
[3] Energy Piano, L. F. Cortzensvej 3, 2830 Virum, Denmark

[4] Corresponding author e-mail: cadh@dtu.dk

Abstract. Colour tunable and dimmable LED lamps and LED luminaires are used increasingly in both domestic and professional lighting sector. The documentation of energy and light quality performance are often very limited for only for a single setting of multiple possible settings. Fifteen LED lamps and eight LED luminaires that are dimmable and tuneable white have been selected for demonstration of the variations in these parameters and possible errors in lighting design simulations. These have been tested in over twenty modes of operation including dimming from 100% to 25%, and correlated colour temperature (CCT) settings from 2200K to 6500K. The inherent standby power of these colour tuneable devices is measured, and the overall efficacy is evaluated in normal usage situations. In average for all tested LED lamps and luminaires 49% and 33% of the energy consumption is used in standby mode for 1h and 2h on time pr. day, respectively. The extensive set of test results show that there can be very large variations in e.g. the luminous flux, luminous efficacy and stroboscopic visibility measure (SVM), while others are very consistent over the modes of operation. The luminous flux shows variations of down to 22% of the maximum and rated value, and these lowest values occurs at the lowest CCT. The best performing has over 90% at all CCT settings. For the luminous efficacy most test results show a maximum value at 4000K or at the maximum CCT, and variations down to 20-50% of the maximum efficacy. The SVM is shown to increase to values over 1 and up to 2.4 at low dimming levels or low light output, demonstrating that stroboscopic effect will be visible for the majority of people and hence a problem in such settings. This is seen for approx. half the tested while the others have SVM < 0.4 for all settings and will not be visible over all settings. These results demonstrate the need for testing over the possible modes of operation to be able to correctly design and simulate a lighting installation using dimmable and colour tunable LED lamps and luminaires. The needed new dataformats and adoption of these from test laboratories to lighting software, in order for lighting designers and energy engineers to be able to make use of the extensive test results, are discussed.

1. Introduction

Over the last decade, LED lighting products have proven to be reliable and energy-saving and are now the preferred choice over all traditional light sources. This is due to the high energy efficiency, long lifetime and high light quality achievable, but LED lighting technology also provides an unprecedented potential for adjustment and control of the light output. This is in terms of dimming i.e., control of the luminous intensity, but also in terms of control of the spectral power distribution (SPD) of the emitted light. This is based on color mixing systems using both various colored LEDs and/or white LEDs at different correlated colour temperature (CCT) This is used for tunable white light sources, where the white light emission can be controlled in CCT, but also for color tunable light sources emitting light over a large gamut also covering saturated, colored light. It is the former that is interesting for general lighting installations.

There is a rapid increase in the use of dynamic LED products and lighting controls from both household smart lamps with app-control and dynamic luminaires in office environments and health care institutions. They are e.g., used to make the light follow the rhythm of daylight and for stimulation of nonvisual effects of light, typically to support alertness and circadian rhythm [1].

Modern lighting installations in both new and renovated commercial buildings often consist of such controllable LED solutions. Where possible, installers prefer to use the same luminaire model throughout, and to meet local minimum illumination requirements by permanently dimming specific luminaires. Some installations also control the CCT during the day or for special purposes. However, dimming and colour/CCT controls affect both energy efficiency, colour quality and temporal light modulation (TLM) and the accompanying temporal light artifacts (TLA)[2].

The standby power consumption of these dynamic LED products will affect the overall energy consumption and efficacy of a light source or lighting system dependent on the usage pattern over time. A study of office lighting and of lighting control systems[3] has found that the standby energy consumption accounts for around 30% of the total energy consumption but it may rise to 55% in extreme cases. This was based on actual occupancy data and simulation-scenarios of the total yearly lighting consumption for different combinations of lighting control systems (LCSs) and lighting poser density including standby consumption. It was concluded that a complete switch off LCSs during unoccupied hours is needed to preserve savings from LCSs.

IEA 4E Solid State Lighting (SSL) Annex [4][5] has measured the energy consumption associated with the new features that are being incorporated into SSL products and specified a new measurement method, including settings and parameters to test. They have made indicative test measurements following the development over the last seven years with analysis including more than 200 LED lamps and luminaires. In this period some manufactures have lowered their standby consumption by better components and/or control strategy while others have not focused on this issue. The IEA 4E SSL analysis has revealed that the standby consumption varies substantially from 0.08 W to 2.71 W. The EU regulation[6] in force from September 2021 sets a maximum standby power of 0.5 W. In the rest of the world there is typically no standby power limitations except for California, USA, that already in 2019 demanded the standby power limited to a maximum of 0.2 W [7] .

Since the EU regulation[6] only sets performance requirements for light sources at full load, manufacturers only report standby power and energy consumption at full load together with the photometric and colorimetric parameters, describing the efficiency and light quality. For tunable white lamps/luminaires the luminous flux may be very different depending on the choice of CCT. Anyhow the manufacturers typically only provide one luminous flux value without specification of the CCT.

The effects of dimming and CCT setting are typically not taken into account in light source documentation. Therefore, the actual performance parameters in dimmed and CCT settings are not known. Luminaire data is usually stored in IES and/or EULUMDAT files, and these typically contain information about luminous intensity distribution (LID), luminous flux, active power, CCT, and colour rendering index (CRI) for one setting only. These are then used in lighting design and simulation software, which can lead to large miscalculations of energy consumption and undesirable lighting quality at the used settings. As an example, temporal light modulation (TLM) issues typically increase when dimming is applied. If the energy consumption of lamps and luminaries are assumed to be linear with light output, control setting, or constant with colour temperature, the energy calculated energy consumption for lighting installations can be erroneous.

LED lamps and LED luminaires should generally be measured using the globally agreed methods contained in the international test standard CIE S 025/E:2015 [8]. The standard includes only limited information on the treatment of tunable and dimmable luminaries in terms of measurement methods. ANSI/IES TM-38-21[9] specifies a recommendation for measuring “tunable white” lamps, luminaires, and light engines. In 2022 CIE is beginning the process of revising CIE S 025/E:2015 [8] in technical committee TC 2-97, work that may include methods for more lighting devices with more advanced controls. The question is how these dynamic light sources should be characterised, by which and how many settings, and how to share the data to enable efficient and accurate lighting design and simulation of systems. And the next question is how should the data be exchanged from laboratories to lighting designers and energy engineers. ANSI/IES TM-33-18 [10] describes a new standard xml-format that allow for data at different settings, and adds new characteristics e.g., SPD, different color rendering parameters, and TLA metrics, like the stroboscopic visibility measure, SVM, to the normally used LID, active power and luminous flux. As this American standard has not been widely adopted, efforts are made in this work to support and influence Global Lighting Data Format (GLDF) [11] e.g., through organisations like IES, ISO and CIE.

In this work a selection of commercially available LED lamps and LED luminaires that are dimmable and tunable white have been selected for demonstration of the variations in performance parameters and possible errors in lighting design simulations. These are tested in over twenty modes of operation including dimming from 100% to 25%, and CCT settings from 2200K to 6500K.

2. Measurements of lamps and luminaires

A range of dynamically controllable LED lamps and LED luminaires was selected for extensive testing to demonstrate the problems mentioned. Models were chosen from different manufactures, and single artefacts of each were bought on the market in the period 2020-2022. The anonymized 23 artefacts covered a range of light sources primarily sold for the domestic sector and includes

- 15 LED lamps with nominal power ranging from 4.5 W – 12 W. The nominal luminous flux range covered 250 lm to 1000 lm with E27 or GU10 type sockets
- 8 LED luminaires including ceiling fixture (panel, cylinder, ring and build-in spot), wall fixtures, wall frameless panel and table lamps. The nominal power range covered 4.5 W – 24 W and the nominal luminous flux range was 300 lm to 2800 lm

All lamps/luminaires were controllable via a manufacturer specific apps communicating over a Bluetooth, Zigbee, or Wi-Fi connection protocol. All artefacts were dimmable and except for one they were all also tuneable white and/or colour-tunable. The apps for controlling the dimming and CCT settings used sliders set by touch control. Some of the apps had a numerical scale on these controls indicating dimming level and/or CCT values and others did not. On the former setting values had to be estimated.

2.1. Measurement methods

All artefacts or devices under test (DUT) were tested by measurements with an integrating spherespectroradiometer according to the international test standard CIE S 025/E:2015 [8]. All DUTs were powered at 230 V AC and 50 Hz using a stabilised programmable AC power supply (Elgar, CW1251P). The electrical parameters were measured using 4 wire connection at the DUT with a power analyser (WT3000, Yokogawa) and included RMS voltage, RMS current, active power and power factor.

The photometric quantities were measured in a Ø1.9 m integrating sphere (Instrument Systems, ISP2000) fibre connected to a spectroradiometer (Instrument Systems, CAS 140CT). The system was calibrated to total radiant flux and corrected for the change in sphere transmission caused by changing the DUT. The parameters of main interest here were: the luminous flux measured in lm [12, Secs. 17-21–039], the correlated colour temperature (CCT) measured in K [12, Secs. 17-23–068], and the luminous efficacy defined as the ratio of luminous flux and active power, measured in lm/W [12, Secs. 17-21–089]. In addition, the colour coordinates and colour rendering index[13] were calculated from the measured spectral power distribution.

In relation to TLM and TLAs, the stroboscopic visibility measure (SVM) M_{VS} [14] and Short-term flicker index P_{st}^{LM} [15] were measured. This was done according to the guidelines in CIE TN 012 [16].

A custom built TLM measurement system was used. It was based on a Ø10mm Si-photodiode (United detector Technology, SN-19907) and the signal was amplified using a variable gain transimpedance amplifier (Femto, DLPCA-200) and digitized using an analog to digital converter (National Instruments, NI-USB-9162). Calculations are done using a custom-built LabVIEW routine.

One of the issues of measuring LED light sources is the stabilization of the light output and power consumption of the DUT. According to CIE S 025/E:2015 [8], the DUT must be on for at least 30 min. and the variation of measured parameters must be less than 0.5% over a 15 min time window. When measuring many different settings of a specific LED lamp or luminaire, stability should normally be achieved before measurement of each setting, however, a 15 min verification was not practically possible in this study, due to the need for manual control through an app. Consequently, stability was checked manually over 1-3 minutes before measurements. The measurement procedure used to test the DUTs was as follows:

- stabilizing the DUT at the nominal CCT setting at 100% dimming level by monitoring the luminous flux and active power as a function of time, in accordance with CIE S 025/E:2015 [8].
- Setting the dimming level to 100, 75, 50 and 25% consecutively and doing a measurement at each setting.
- Changing the CCT and repeating the measurement at each dimming level.

The CCT settings used were 2700 K, 4000 K, 5000 K and the minimum (typically 2200 K) and maximum CCT (typically 6500 K) possible for the specific DUT. This protocol was used as accurately as practically possible. Some DUTs could not be set to all the specified CCTs. By default, the CCT given in the apps was used to set the CCT during measurements, however in case CCT values were not given in the app the CCT setting was done through monitoring of the measured CCT. By default, the dimming level given in the apps by percentages was used for dimming the DUT during measurements. Some apps did not show any percentage indication on the dimming slider and in these cases the dimming setting was done by using the active power consumption relative to the full load active power.

Photometric and TLM parameters were measured in different setups and not at the same time. It was a difficult task to reproduce the same CCT and dimming level for these two measurements due to the resolution and sensitivity of the app and controls used. Effort was made to ensure this by using a spectral irradiance measurement along with the TLM measurement and monitoring the CCT and consumed electrical power to match earlier settings for photometric measurements.

2.2. Standby power

The investigated LED lamps and luminaires were all dynamically controllable via Bluetooth, Zigbee or Wi-Fi and had a power consumption even when not providing light, i.e. a standby power consumption. This affects the energy consumption of an installation over time, and the effective efficiency of a light source. Therefore, the IEA SSL Annex[4][5] has defined a new key term "overall efficacy":

$$\mu_{\text{overall}} = \frac{\phi_v t_{\text{on}}}{P_{\text{on}} t_{\text{on}} + P_{\text{standby}}\, t_{\text{standby}}} = \frac{\phi_v}{P_{\text{on}}}\left(\frac{1}{1+\frac{P_{\text{standby}}}{P_{\text{on}}}\frac{t_{\text{standby}}}{t_{\text{on}}}}\right)\ [\text{lm/W}], \qquad (1)$$

which describes the effective efficiency over an evaluation time $t_{on} + t_{standby}$ where the light source is only on for a time period of t_{on} while being in off-state for t_{standby}. Here, ϕ_{v} is the luminous flux emitted. P_{on} and $P_{standby}$ are the powers in the on and off states. When there is no standby power or no standby time period the overall efficacy equation reduces to the luminous efficacy, i.e. ϕ_{v} divided by P_{on},. It is worth noticing that the overall efficacy can become much lower than the luminous efficiency in case t_{on} is much lower lower than t_{standby}, and especially if $P_{\text{standby}}/P_{\text{on}}$ is high. That means that this is of higher importance for low power LED lamps than for high power LED luminaires. The standby power consumption P_{standby} was measured using a power analyser (Yokogawa WT3000) when the DUT was powered on at 230 V AC 50 Hz using a stabilised power supply (Elgar, CW 1251P), but set to the off-state in the app and emitting no light. The procedure for measuring standby power consumption is described in IEC 62301 [17].

3. Results

In this section the measurement results on the LED lamps and luminaires are presented with an emphasis on the parameters that shows a large and significant variation as a function of the CCT and dimming settings. Here, the luminous flux and luminous efficiency are most important to lighting design and energy calculations. In regard to temporal light modulation, the measured SVM values are of highest importance and shows the largest variations.

3.1. Luminous flux and efficacy

The measurements of luminous flux as a function of CCT setting showed large variations for the majority of the DUTs. In Figure 1, this variation is illustrated by the measured luminous flux at the five CCT settings, relative to the maximum luminous flux for the DUT which may be at any of the CCT settings. These values are measured for each DUT at full load, 100% dimming level.

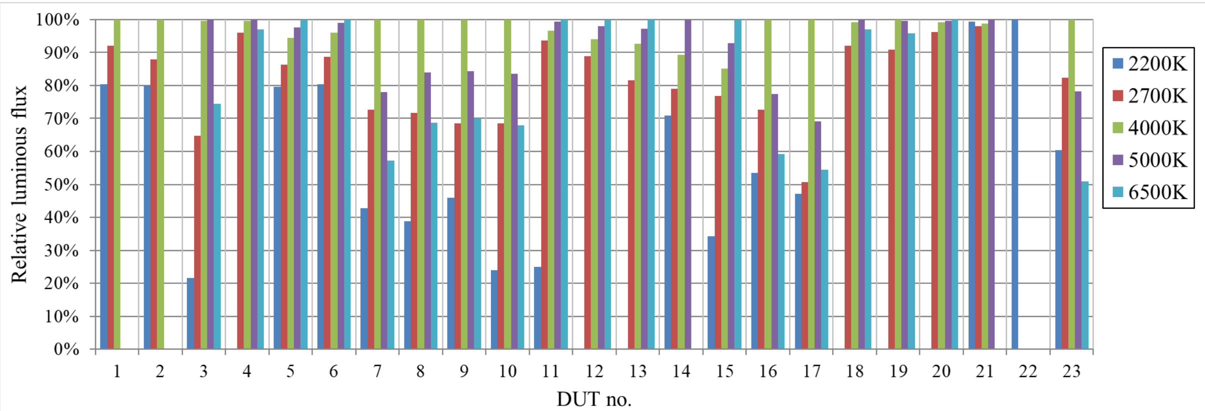

Figure 1. Luminous flux, Measured luminous flux for the five CCT settings relative to the maximum luminous flux for each of the 23 DUTs.

It is observed that the majority of the DUTs can be changed in CCT over 4 or 5 settings, while one cannot be changed in CCT. The maximum luminous flux is often at the rated CCT, informed by the manufacturer, and is seen to be at 4000 K for the majority of DUTs, and the relative luminous flux for the other settings are below 85%. The minimum relative luminous flux is found at 2200 K for all DUTs except for one. For one third of the DUTs, the luminous flux at 2200 K is very low at 22 – 53% of the maximum luminous flux. Four LED luminaires and one LED lamp shows a much higher consistency and has more than 90% relative luminous flux at all CCT settings.

In Figure 2, the measured luminous efficacy at full load or 100% dimming level as a function of the measured CCT is shown for the 14 LED lamps and the 8 LED luminaires. It is observed that the measured CCT are not exactly at the set CCT values. There are three types of variation of the measured luminous efficacy as a function of CCT. The first is characterised by having the highest efficacy at the highest CCT and it decreases for lower CCTs. These are shown with solid lines in Figure 2. The second type exhibit the highest efficacy at 4000 K, corresponding to the results in Figure 1 where the luminous flux decreases for both lower and higher CCT around peak at 4000 K. These are shown with dashed lines in Figure 2. A relative change in luminous efficacy from the maximum value 20-50% is observed for both the first and second type of variation.

The third type shows almost no variation in the efficacy, these are shown as dotted lines and corresponds to the results seen in Figure 1 that showed almost no variation in the luminous flux. It is observed that the luminous efficacy of the LED lamps is generally higher than for the LED luminaires.

The maximum efficacy of 132 lm/W for LED lamps is found at a high CCT of 6500 K and the average efficacy is around 90 lm/W for the tested DUTs. For the LED luminaires the maximum efficacy is 100 lm/W, while the average efficacy is around 70 lm/W.

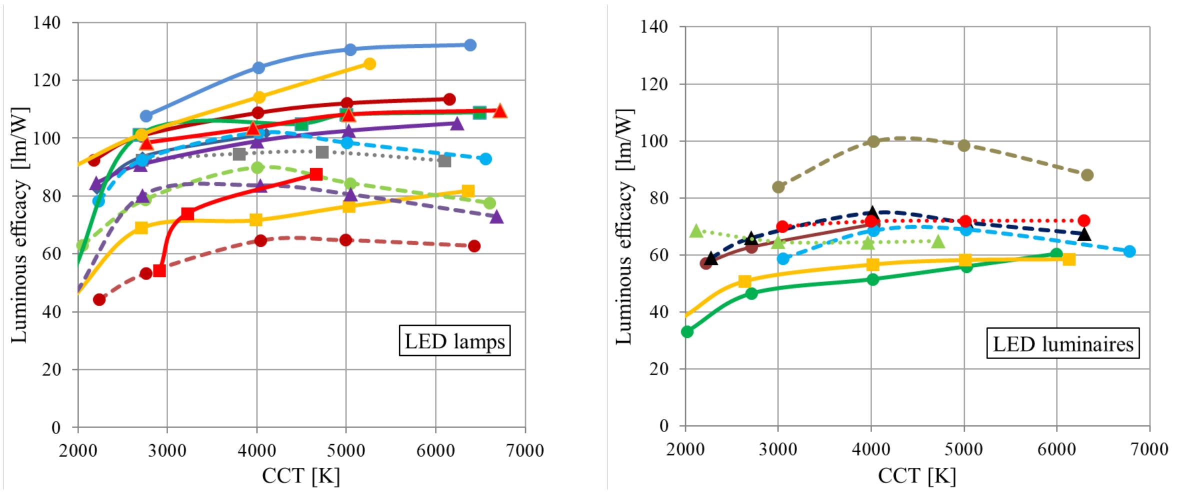

Figure 2. Efficacy, Measured luminous efficacy at full load as a function of measured CCT for 14 LED lamps (left) and 8 LED luminaries (right).

3.2. Stroboscopic visibility measure

The TLM has been measured for a representative selection of the DUTs, and the measured SVM are presented for five LED lamps and three LED luminaires, which demonstrates the large differences in variation pattern of the SVM values as a function of dimming level.

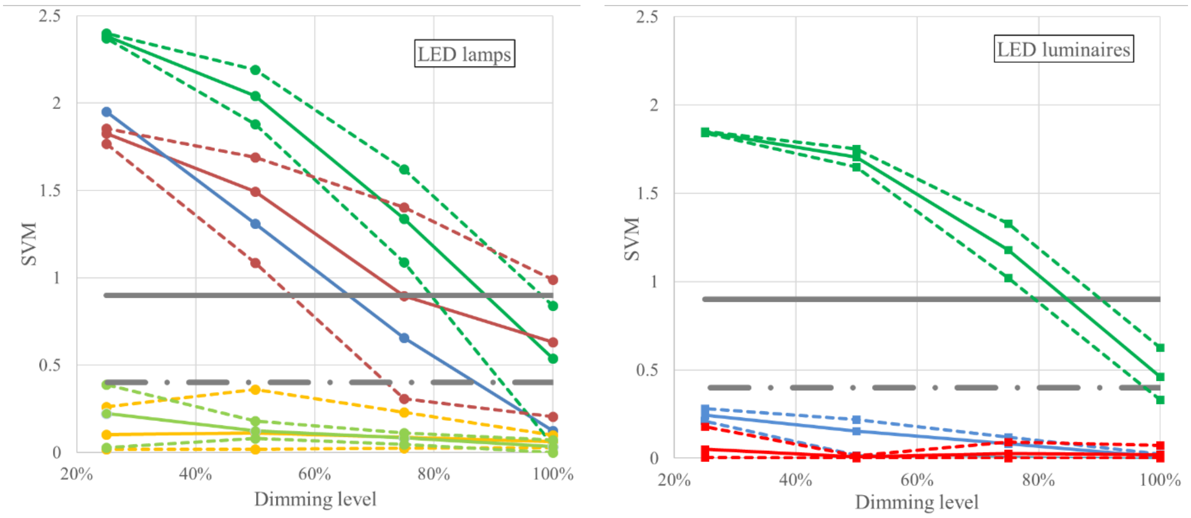

Figure 3. SVM, Measured average SVM (solid line and markers) for the different CCT settings of the DUT as a function of the dimming level, maximum and minimum SVM values are shown with same colour dashed lines and markers. Left: 5 LED lamps, right: three LED luminaires. The EU requirement for SVM is shown with grey solid and dashed-dotted line.

The SVM was measured at up to five CCT settings for each DUT and for the four dimming levels. The variation observed as a function of dimming level does not change much for each CCT setting. Therefore, the variations for CCT settings are not explicitly showed. In Figure 3, the average, maximum and minimum measured SVMs at each dimming level are shown. To the left this is done for five LED lamps and to the right this is shown for 3 LED luminaires.

The EU regulation[6] requirement for SVM is that it must be below 0.9 at full-load and this requirement will be lowered to 0.4 from September 2024. These two values are shown in Figure 3, as grey solid and dash-dotted lines. Requirements only apply at full load, i.e. at 100% dimming level.

It is observed that there are two types of markedly different behaviours of the measured SVM as a function of the dimming level. The one is characterised by low SVM values at full load or 100% ranging from under 0.4 to close to 1 for the different CCT settings, i.e., a large variation. It is observed that the SVM values increase for each lower dimming level and ends at SVM values from 1.8 to 2.4 at 25% dimming level. This behaviour is observed for three of the LED lamps, of which two were of filament type and one an LED luminaire. The stroboscopic effect is pr. definition visible for 50% of the observers at a value of SVM = 1. This means that for these devices SVM will be visible at dimming levels of 50% or lower. This is not the case for the other type of behaviour. It is characterised by a very low SVM value of 0.1 or less at full load or 100% and only a small increase in the SVM value at lower dimming levels. This is observed for two of the LED lamps, where the maximum SVM values measured are below 0.4, and for two of the LED luminaires where the maximum SVM values measured are below 0.3. That means that a majority of observers will not be able to observe a stroboscopic effect in the light from these LED lamps and luminaires. For these, the stricter EU 2024 requirement is fulfilled at all settings. And these will also be able to comply with the recommendation of the European workplace lighting design standard EN 12464[18] stating that “lighting systems should be designed to avoid the negative effects of flicker and stroboscopic effect throughout the full dimming range”, but without establishing maximum limits. It is the power supply and the electronic driver that determines the behaviour of the TLM and hence the SVM values. Luminaries have room for larger and more complex drivers which can deliver this low SVM behaviour at all settings. But it is seen in a E27 A60 bulb where the available space for electronic drivers is limited. The TLM waveforms measured for these are characterised by low modulation at high frequencies, at 2000 Hz and 4000 Hz for the LED luminaires tested. For the other type of behaviour, the TLM waveforms are pulse width modulation (PWM) waveforms with 100% modulation depth, at frequencies lower than 2000 Hz up to which people are sensitive to the stroboscopic effect. This gives rise to high SVM values.

3.3. Standby power
The standby power was measured for 23 of the artefacts, covering 15 LED lamps and 8 LED luminaires. The majority shows a standby power in the range from 0.19 to 0.47 W, which comply with the EU requirement. However, a single LED lamp has a standby power of 0.61 W and four of the LED luminaires have standby powers in the range from 0.76 to 0.96 W, which are not compliant.

In Figure 4 the rated efficacy is shown together with the calculated overall efficacy for two on time situations of 1 h and 2 h over a day of 24 h. These are typical ON time for lamps/luminaires used in the domestic sector [19]. This is shown for each of the 23 LED lamps and luminaires The DUTs have been sorted to show the DUTs with the highest rated efficacy to the left.

It is observed that the overall efficacy is much lower for both 1h and 2h on time than the rated efficacies. The lowest overall efficacy is found for is a 4.5 W LED luminaire (DUT no. 20) with a high standby power of 0.76W. In this case the overall efficacy is only 14 lm/W and 23 lm/W for 1h and 2h on time, respectively. This is close to the luminous efficacy of incandescent lamps which have been banned from the market due to low efficacy. Best performance is observed for a linear LED luminaire (DUT no. 6) with a low standby power of 0.19W giving overall efficacy of 82 lm/W and 91 lm/W for 1h and 2h on time, respectively. On average for all tested LED lamps and LED luminaires 49% and 33% of the energy consumption is used in standby mode for 1h and 2h on time pr. day, respectively.

Non-compliance does not seem to adhere from technical obstacles, as interestingly the California Energy Commission’s so-called Modernized Appliance Efficiency Database System [20] [21]_shows that more than 300 smart lamps/luminaires on the USA market have standby power lower than 0.2 W and a large part is also below 0.1 W.

A way to obtain substantial reduction of the standby power was described by IEEE [22], which was first developed for IoT connected devices on a battery. In this concept, a low power radio receiver is added to the lighting product and is the only thing that stays connected but only for 2 milliseconds out of every 100 milliseconds. Use of this concept for a product with standby power 0.2 W thus reduce the standby power to 0.004 W.

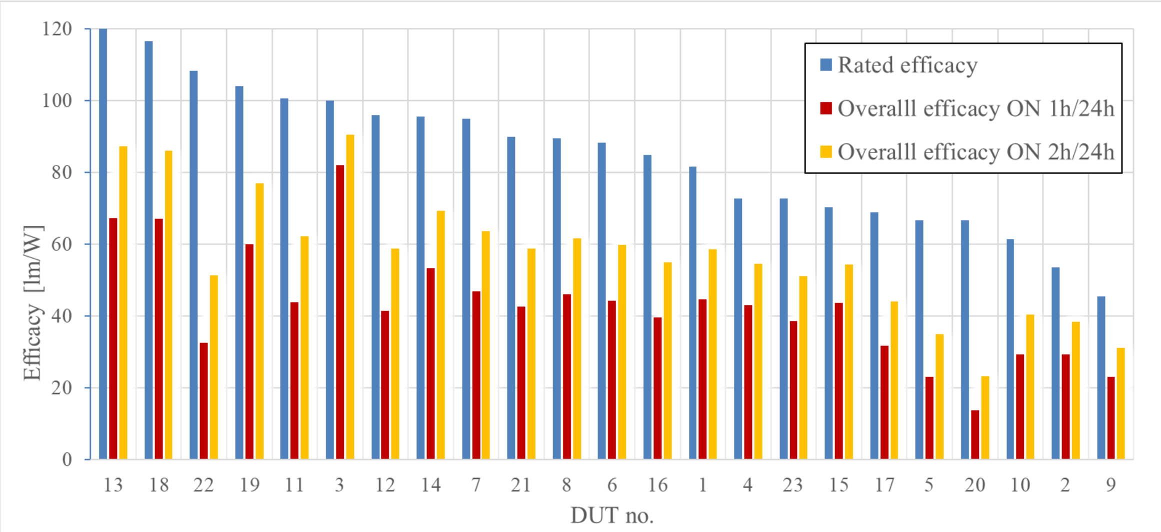

Figure 4. Overall efficacy, rated and calculated overall efficacy corresponding to 1 h and 2 h on time over 24 h for 23 of the LED lamps and luminaires, ordered according to rated efficacy.

In relation to the stroboscopic visibility measure, an analysis of the measured standby power and SVM, does not reveal any correlation between the two for the LED lamps and luminaires tested in this work.

4. Discussion

The results of this study show that dimming and colour tuning affect efficiency and light quality (in terms of SVM) of all artefacts – but also with considerable differences. This study is primarily based on household light sources. Assuming that conclusions may also apply to professional light sources the results underline that there is a real risk that power consumption in full-scale professional lighting installations is miscalculated and TLA effects underestimated. As building codes in many countries set more and more strict limitations on building energy consumption, it is evident that data like the ones provided by this study is critical to avoid excessive building energy consumption and unacceptable TLA. More data is also important to make true comparisons between alternative lighting products and solutions. This study also points to some of the practical difficulties of producing data and making such data available in the whole value chain:

- Performing an extended suite of measurements across several dimensions is highly time-consuming work. Rigorously studying combinations of all parameters cause the workload to and testing costs increase exponentially. Further, regulating both CCT and dimming levels in the lab proved to be very difficult to perform systematically because of inconsistent control systems. Thus, improved light measurement control systems and software automated measurement protocols are essential components in more detailed characterisation
- Existing light measurement standards such as CIE S 025/E:2015 [7] do not specify how to interpret the term dimming and do not advise on light measurement protocols for dimming/colour tuning during measurements, and which steps are necessary. IES TM-38 [8] lays out a possible framework for specifically characterising white tunable light sources.

- Once measured, the detailed data needs to be stored in formats that can be shared with downstream users such as consumers, lighting desingers and specifiers and energy engineers. The well-known text formats EULUMDAT and IES LM-63-19[18] are not suited. Major standardization bodies have already worked for some time on new XML-based formats: IES [10], CIE TC-2.83, ISO 274/JWG 1/TF BIM, CEN/TC 169/WG 1/TF BIM). XML-formats are machine-readable and in general much more flexible and allows for addition of more data.

- Design and energy calculation software such as DIALux and Relux must be able to use the more detailed tested performance data as a function of colour tuning, dimming and use pattern. Consequently, collaboration has been started with the GLDF initiative [10] aiming at a much more comprehensive dataformat for lighting design software.

- Conscious product selection by both consumers and professional lighting specifiers relies on awareness of the possible negative effects of dimming, colour tuning, and standby consumption. The purpose for bringing more details into the planning stages is obviously to make energy calculations of whole buildings as accurate as possible, while maintaining awareness of light quality.

5. Conclusion

A wide selection of dimmable and tunable white LED lamps and LED luminaires have been selected for demonstration of the variations in performance parameters. These have been tested in over twenty modes of operation including dimming from 100% to 25%, and correlated colour temperature (CCT) settings from 2200K to 6500K. The inherent standby power of these colour tunable devices have been measured, and the overall efficacy have been evaluated in normal usage situations. In average for all tested LED lamps and luminaires 49% and 33% of the energy consumption is used in standby mode for 1h and 2h on time pr. day, respectively.

The extensive set of test results show that there can be very large variations in the luminous flux, luminous efficacy and SVM, while others are very consistent over all modes of operation. The luminous flux shows variations of down to 22% of the maximum and rated value, while the best performing has over 90% at all CCT settings. For the luminous efficacy most test results show a maximum value at 4000K or at the maximum CCT, and variations down to 20-50% of the maximum efficacy. The SVM is shown for some devices to increase to values over 1 and up to 2.4 when applying dimming levels, demonstrating that stroboscopic effect will be a problem in such settings. Some had SVM < 0.4 for all settings and will not pose a problem with stroboscopic effect.

These results demonstrate the need for testing over the possible modes of operation to be able to know the performance and correctly design and simulate a lighting installation using dimmable and colour tunable LED lamps and luminaires. The needed new data formats and adoption of these from test laboratories to lighting software, in order for lighting designers and energy engineers to be able to make use of the extensive test results, have been discussed.

Acknowledgement

This work was mainly supported by ELFORSK through the project 353-014 International standards for lighting, global energy savings. This project runs until 2023 and includes various activities of standardisation to support energy savings in lighting. For more information see the project website [23].

This work was partly supported by EMPIR 19NRM02 RevStdLED, Revision and extension of standards for test methods for LED lamps, luminaires and modules and EMPIR 20NRM01 and MetTLM, Metrology of Temporal Light Modulation. The projects (19NRM02 RevStdLED and 20NRM01 MetTLM) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme."

References

[1] CIE, “CIE statement on non-visual effects of light recommending proper light at the proper time,” CIE - International Commission on Illumination, 2019.

[2] CIE, “CIE 249:2022 Visual Aspects of Time-Modulated Lighting Systems,” Vienna, Austria,

2022.
[3] N. Gentile and M. C. Dubois, “Field data and simulations to estimate the role of standby energy use of lighting control systems in individual offices,” *Energy Build.*, vol. 155, pp. 390–403, Nov. 2017.
[4] IEA, “SSL Annex Task 7: Smart Lighting – New Features Impacting Energy Consumption,” IEA 4E SSL Annex, 2016.
[5] C. Kofod, “Solid State Lighting Annex: Task 7: Smart Lighting – New Features Impacting Energy Consumption, Second Status Report (Unpublished),” 2022.
[6] European Commission, “Commission Regulation (EU) 2019/2020 of 1 October 2019 laying down ecodesign requirements for light sources and separate control gears - Document 02019R2020-20210901,” 2019. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2019/2020/2021-09-01. [Accessed: 02-May-2022].
[7] CALIFORNIA and ENERGY COMMISSION, “CALIFORNIA CODE OF REGULATIONS Title 20. Public Utilities and Energy Division 2. State Energy Resources Conservation and Development Commission CALIFORNIA ENERGY COMMISSION,” 2021.
[8] CIE, *CIE S 025/E:2015: Test Method for LED Lamps, LED Luminaires and LED Modules*. CIE - International Commission on Illumination, 2015.
[9] IES, “ANSI/IES TM-38-21, Photometric and Electrical Measurements of Tunable-White Solid-State Lighting Products,” IES - Illuminating Engineering Society, 2021.
[10] IES, “ANSI/IES TM-33-18 Standard Format for the Electronic Transfer of Luminaire Optical Data,” 2018.
[11] DIAL GmbH and RELUX Informatik AG, “GLDF | Global Lighting Data Format.” [Online]. Available: https://gldf.io/. [Accessed: 01-Apr-2022].
[12] CIE, *CIE S 017:2020 ILV: International Lighting Vocabulary*, 2nd editio. Vienna, Austria: CIE - International Commission on Illumination, 2020.
[13] CIE, “CIE 13.3-1995, Method of measuring and Specifying Colour Rendering Properties of Light Sources,” 13.3, 1995.
[14] CIE, “CIE TN 006:2016 Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models,” Vienna, Austria, 2016.
[15] IEC, “IEC TR 61547-1:2020 Equipment for general lighting purposes - EMC immunity requirements - Part 1: Objective light flickermeter and voltage fluctuation immunity test method,” International Electrotechnical Commission, 2020.
[16] CIE, “CIE TN012:2021 Guidance on the Measurement of Temporal Light Modulation of Light Sources and Lighting Systems,” CIE (Commission International d’Eclairage), Vienna, Austria, Jan. 2021.
[17] IEC, “IEC 62301:2011 Household electrical appliances - Measurement of standby power,” IEC, 2011.
[18] CEN/TC 169, “EN 12464-1:2021 Light and lighting - Lighting of work places - Part 1: Indoor work places,” 2021.
[19] C. Kofod, “PremiumLight IEE/11/941/SI2.615944 Assessment of the initial situation in the participating countries, Final version,” 2013. [Online]. Available: https://www.visosystems.com/wp-content/uploads/2022/05/Assessment-of-the-initial-situation-in-the-participating-countries-PremiumLight-IEE11941SI2.615944-Energy-piano-30-06-2013.pdf. [Accessed: 12-May-2022].
[20] California Energy Commission, “Modernized Appliance Efficiency Database System,” 2016. [Online]. Available: https://cacertappliances.energy.ca.gov/Pages/Search/AdvancedSearch.aspx. [Accessed: 02-May-2022].
[21] CALIFORNIA and ENERGY COMMISSION, “CALIFORNIA CODE OF REGULATIONS Title 20. Public Utilities and Energy Division 2. State Energy Resources Conservation and Development Commission CALIFORNIA ENERGY COMMISSION,” 2021.

[22] D. K. McCormick, “IEEE technology report on wake-up radio : an application, market, and technology impact analysis of low-power/low-latency 802.11 wireless LAN interfaces,” 2017.

[23] A. Thorseth and C. Dam-Hansen, “ELFORSK project 353-014 International standards for lighting, global energy savings — DTU Research Database,” *DTU Orbit*. [Online]. Available: https://orbit.dtu.dk/en/projects/elforsk-project-353-014-international-standards-for-lighting-glob. [Accessed: 12-Apr-2022].