Slutrapport

Projektinformation

Projekttitel	DoLEDLast - Holder LED produkter til at give de lovede energibesparelser?
Journalnummer	352-015
Projektansvarlig organisation	DTU Electro
Projektpartnere	David Super-Light A/S og Fischer Lighting Aps.
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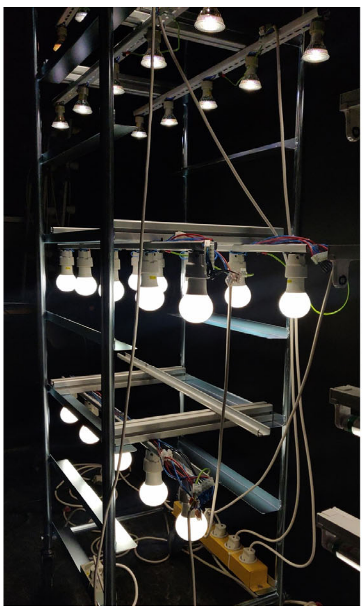
Final report for

DoLEDLast

Does LED products last to give the promised energy savings?

ELFORSK 352-015

28-2-2023



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1 Project summary

LED lighting products don't always meet their rated lifetime and may fail prematurely, reducing the expected energy savings in installations. The project aimed at obtaining new knowledge about the lifetime of LED products, using the new EU endurance test introduced in 2021. The on/off power cycling introduced should stress the product and catch early failures, compared to established test methods using continuous operation for longer durations. The project has established new laboratory test facilities and procedures for running the lifetime tests and comparing the results of the test methods. A new monitoring system has been developed and tested in the laboratory for continuous logging of temperature and light output of individual lamps. An automatic test system has been developed for the partners to be able to run the EU endurance test on single LED lamps in their own facilities.

Multiple samples of different types of LED lamps and retrofit modules have been tested in parallel using the two test methods. The results have been analyzed and compared, showing good correlation for maintenance at 3000 h. The LED lamps and modules tested in the project period all passed the EU endurance test with only a single catastrophic failure. Both tests showed very high luminous flux maintenance factors making it difficult to estimate the actual lifetime by extrapolation, for this longer testing would be needed.

The results are of a wide general interest and have been disseminated to the lighting industry and the research community, through trade magazine articles, conferences, international collaboration, and a thematic day on LED lighting technology with laboratory demonstration. The knowledge and facilities will be used in teaching, impartial testing for industry, and in research. Further testing on the LED products, will provide comparison data for research on a new 1500 h lifetime test at elevated temperatures, leading the way for a faster and better lifetime test method.

1.1 Dansk resumé

LED-belysningsprodukter opfylder ikke altid deres nominelle levetid og kan fejle tidligt, hvilket ødelægger de forventede energibesparelser i installationer. Projektet havde til formål at opnå ny viden om LED-produkters levetid ved brug af den nye EU-holdbarhedstest, der blev introduceret i 2021. Den indførte on/off-cyklus der stresser produktet og fanger tidlige fejl er sammenlignet med etablerede testmetoder, der bruger kontinuerlig drift af længere varighed. Projektet har etableret nye laboratorietestfacilitet og procedurer til levetidstestene og har sammenlignet resultaterne af testmetoderne. Et nyt monitoreringssystem er udviklet og testet i laboratoriet til kontinuerlig logning af temperatur og intensitet fra individuelle LED produkter. Der er udviklet et automatisk testsystem, så partnerne kan køre EU-holdbarhedstesten på enkelte LED produkter i deres egne faciliteter.

Flere enheder af forskellige typer LED-lyskilder og moduler er blevet testet parallelt ved hjælp af de to testmetoder. Resultaterne er blevet analyseret og sammenlignet, hvilket viser god korrelation for vedligeholdelse ved 3000 timer. De LED-lyskilder og -moduler, der blev testet i projektperioden, bestod alle EU's holdbarhedstest med kun en enkelt katastrofal fejl. Begge test viste meget høje lysstrømsvedligeholdelsesfaktorer, hvilket gjorde det vanskeligt at estimere den faktiske levetid ved ekstrapolering. Her ville længere test være nødvendig.

Resultaterne er af bred almen interesse og er blevet formidlet til belysningsindustrien og forskningsmiljøet gennem fagbladsartikler, konferencer, internationalt samarbejde og en temadag om LED-belysningsteknologi

med laboratoriedemonstration. Opnået viden og faciliteter vil blive brugt i undervisning, uvildig test for industrien og forskning. Yderligere test på LED-produkterne vil give sammenligningsdata til forskning i en 1500 timers levetidstest ved forhøjede temperaturer, hvilket kan vise vejen for en hurtigere og bedre levetidstestmetode.

2 Aim of the project

The purpose of the project is to create and disseminate new knowledge about LED products' lifetime and durability in relation to the new endurance test published in the EU's new eco-design regulation [1] and to convey this knowledge to the industrial partners in the project, the lighting industry in general and to the research community.

A number of different LED lighting products/light sources are selected for the studies, so that the project's results are relevant to as many stakeholders as possible. The starting point is the two partner companies' own products, which will be LED boards and LED modules with driver electronics that are included in their luminaires. In addition, a number of LED products such as LED filament bulbs and LED tubes to replace fluorescent tubes are being investigated.

The hypothesis is that the EU endurance test over 3600 hours [1] with on/off power cycling is better at predicting the actual lifetime of the LED products and will stress them more than the LM-84 (6000 hour) test [2] where they are continuously switched on. The products will be stressed more with a full heating and cooling in each cycle during the test, which means that the products will behave more in the direction of how it is actually used in the real world. The project will test this hypothesis by performing both test methods in parallel on a number of LED products/light sources, with 5 and 10 samples of each to obtain a good statistical basis.

DTU Electro has experience from the ELFORSK project 342-035 "LED Positivliste" [3] in that project in which early IES LM-84 6000 h lifetime tests were carried out, and experience from this project showed that long-term tests is a time- and resource consuming task [4]. There is a large cost associated with the fact that, during the test, light must be measured 7 times in the integrating sphere setup.

The aim is thus to establish a laboratory facility at DTU Electro where both of these tests can be carried out, as automatically as possible and where data is continuously saved. Therefore, the aim is to develop a monitoring system to continuously measure the luminous flux, temperature, and power consumption of the individually tested light sources. This ensures that you do not lose data in the event of catastrophic errors on products and will be able to provide a luminous flux measurement up to the time of the error. Through integrating sphere measurements, it is investigated to what extent the results agree with the sensor measurements. If there is a good correlation, it will be able to reduce the costs in connection with the durability test considerably.

A secondary goal of the project is to develop an automatic setup that the industry will be able to use to do in-house simple durability tests of their products in their own facilities/premises. The idea is that the setup should be cheap and easy to install so many companies will use it. An automatic setup that companies can manage and use themselves will be of great value. It requires automatic data processing and reporting, which must be developed in the project.

The project will use the results from the durability tests to develop a model for different types of LED products in different applications to predict the lifetime based on actual use. The model will have to be able to be combined with the buildings' logging systems to provide an assessment of when the LED products in the building would need to be replaced. The starting point is the partner companies' LED products for this purpose.

3 Project implementation

The progress of the project has been acceptable, even though the project was greatly impacted by the COVID-19 pandemic with restricted access to laboratory facilities as well as issues with the supply chain of light sources and components, especially power supplies, for the measurement setup. The project was furthermore impacted by extended periods of sickness among the experts working in the project. A one year extension was applied for and granted due to these circumstances, so that the finish date was moved from 28/2-2022 to 28/2-2023.

The project work was divided into a series of work packages, outlined below:

- **Work package 1** – Administration, project meetings, coordination between project partners, economy reporting.
- **Work package 2** – Design and development of long-term monitoring systems. A monitoring system based on an RGBW sensor and a microcontroller, including programable power control for on/off cycling and temperature sensors to be used in WP5, 6 and 7 was developed.
- **Work package 3** – Collection of LED products for testing, the industrial project partners came with suggestions for different LED products to be tested in the project, a range of these was chosen for testing.
- **Work package 4** – Configuration of maintenance test facility, with room for all the LED products to be tested.
- **Work package 5** – 3600 h test, EU endurance testing of LED products, calibrated spectral measurements was done initially and after the test was completed. It was determined what LED products passed the test and which didn't. The system developed in WP2 was used to monitor selected LED products during their test period.
- **Work package 6** – 6000 h test, LM-84 maintenance testing of LED products, calibrated spectral measurement was done initially, and every 1000 h until 6000 h. The system developed in WP2 was used to monitor selected LED products during their test period.
- **Work package 7** – Industrial laboratory experiments. The industrial partners have configured the laboratory for EU endurance testing, where the sensors developed in WP2 will be used. The testing of the LED products during the project period was only done at DTU Electro.
- **Work package 8** – Data analysis and modelling, calculations, analysis and comparison on the measured data from the LED products tested in WP5 and 6.
- **Work package 9** – Documentation and reporting of results. The results obtained in WP5 and WP6 was reported to the industrial partners and anonymized to be used in WP10.
- **Work package 10** – Dissemination of project ideas and results.

Despite the delays and problems in the project the overall results and milestones have been achieved. At the end of the first year the test laboratory was established, and the first test started, i.e. milestone M2. At the same time the first long-term monitoring system was ready and was tested in a student project, milestone M1. The measurement system for the industrial partners was delayed and delivered at the end of the project. The research related to milestone FM1, i.e. a scientific paper on endurance test, was written and published as a conference proceedings paper accompanied with a poster presentation, which was online due to COVID-19. It will be considered whether this can be turned into a journal paper including more test results from the project. An important milestone in the dissemination of results for the project was the thematic meeting for industry on LED technology and lighting (Milestone M3). This was held 28. February 2023 and had the title "LED Temadag 2023". It was attended by more than 75 stakeholders from all parts of the Danish lighting industry from vendors to facility owners and researchers.

4 Project results

The expected results of the project have to a large extent been achieved. The project has realized a test laboratory for LED product lifetime testing, the laboratory has been designed around the use of the methods described in IES LM-84 [5] and the EU endurance test [1](see section 4.3.1), these methods have been studied. A number of LED lighting products have been tested throughout the project, the tests consist of long periods of operation under controlled environmental conditions, and photometric and radiometric testing, the results can be seen in section 4.5. To supplement the photometric testing a monitoring system has been designed and developed and used in the test laboratory during the operation of the devices under test. The expected model for lifetime and energy consumption of different types of LED products in different applications was not established, partly due to the fact that the luminous flux maintenance data that was generated in the project did not show steady depreciation could therefore not be extrapolated. This situation is sought mitigated in this report as well as in the work following this project, the mitigation will take the form of recommendations towards a more comprehensive lifetime testing regime that will enable such modeling for contemporary as well as future light sources. Dissemination of the results was achieved though presentations for industry, articles and new items in industry magazines and participation in a scientific conferences as well as participation in standardization and consultancy for regulatory bodies (see section 4.7 and the List of dissemination activities in the annex). In the following sections the background for the work and results of the project will be presented.

4.1 Background

LED lifetime has been one of the key parameters enabling the rapid expansion of LED technology into the lighting market, as the world looks for sustainable and long-term solutions to problems that has previously had short term solutions. LED technology promises not only lower energy usage during operation but also lower cost in natural resources and maintenance work needed for production changes and disposal or recycling. However, LED components and some related components are fragile to mistreatment, such as over-heating, current spikes, and contamination from the environment. Therefore, some claims about lifetime have been seen to not hold up to scrutiny [6], and this is why LED product lifetime testing is a critical aspect of ensuring trust in the reliability and quality of LED lighting products in an international market with many participants.

Lifetime testing involves subjecting the LED product to various environmental conditions and measuring its performance over an extended period of time. The goal of this testing is to simulate the real-world conditions that the LED might encounter during its lifetime and then to determine its expected lifespan in similar usage situations.

LED lifetime testing typically involves subjecting the LED to a range of temperatures, humidity levels, and electrical stress conditions. The LED can be continuously monitored throughout the testing period, and/or its performance may be measured at regular intervals using specialized equipment such as photometers or spectrometers.

One issue with LED lifetime testing is the long timespan needed to determine the lifetime especially of products of high quality and endurance. In normal conditions it is recommended not to extrapolate the lifetime over 6 times the duration of the test. As for instance a 6000 h test from IES LM-84 takes approximately 8 months, the test are very costly. Furthermore, given the fast pace of development in the LED lighting industry, a product may have been altered or replaced in the product assortment before the test is finished.

4.2 Failure types

There are generally two categories of LED product failure: Parametric failure and catastrophic failure. Initial claims of extraordinary long LED lifetime towards 100000 hours, where based on catastrophic failure rates such as mean time to failure (MTTF) and mean time between failures (MTBF), which are not suitable to characterize the slow deprecation of the light output from LED components, and the relative rarity of sudden failures [6]. In this report we focus mainly on parametric failure, of the products tested, only one experienced catastrophic failure.

4.2.1 Parametric failure

Parametric failure is a type of failure that occurs when a product or system no longer performs within its specified parameters. This means that the product or system is no longer able to meet the performance criteria that it was designed to meet, due to a change in one or more of its operating parameters. The most typical parametric failure is the deprecation of luminous flux to a level lower than some specific percentage of its initial output. The lifetime of an LED or LED fixture is typically defined as the point at which its light output has decreased to 70 % of its initial output. This point is known as the L70 lifetime.

Other types of parametric failure are also possible such as:

- Depreciation of the correlated color temperature and color rendering due to the degradation of the phosphor material. This could for instance cause a row of lights to no longer look homogenous.
- Increase in temporal light modulation, for instance flickering, to a level beyond the acceptable limits.

4.2.2 Catastrophic failure

Catastrophic product failure refers to a situation where a product fails in a manner where it is rendered completely or mostly useless. Examples are complete loss of light output, near complete loss of light or strong flickering.

The worst kinds of catastrophic failures are when the failure causes a situation that poses a significant risk of harm or injury to consumers, users, or the environment. Examples are fires caused by electrical short-circuits, or overheating, or complete loss of lighting in places where visual overlook is critical for safety such as stairwells or traffic intersections.

4.3 Method

The general method for lifetime testing is to subject devices under test to long durations of operation and monitor the depreciation of the performance during these periods. The conditions under which the operation is being conducted are important as ideal conditions tend to cause longer lifetimes while extreme conditions tend to lower the lifetime of the device under test. Extreme conditions can be utilized to accelerate the depreciation of light output parameters [7], [8] however these methods run the risk of introducing degrading effect that are not present under normal circumstances, and thus underestimating the lifetime.

The main conditions for LED components are the voltage or current and the temperature, but for special application it might be beneficial to control and monitor other parameters such as contamination, mechanical disturbances etc. according to the environment where the devices are to be operated. In this report we consider only standard parameters.

The performance characteristic that is usually tested is the luminous flux or equivalent, i.e., total or part of the total light output. Secondary is the color characteristics such as correlated color temperature or chromaticity coordinate. Changes in the luminous intensity distribution are quite rare, so testing is usually performed in an integrating sphere (see Figure 1). Each product is labelled with a device ID and the package labelling is recorded.

Initially the devices are subject to photometric tests to determine the baseline then the devices are divided into two groups one for each of the test methods.

4.3.1 Test methods of product endurance

During the project two maintenance test methods were used, in this report named EU endurance test and LM-84 [9]. Towards the end of the project only the EU endurance test was used. Prior to the start of the testing all the samples were measured using a 2 m integrating sphere spectroradiometer setup, see Figure 1.

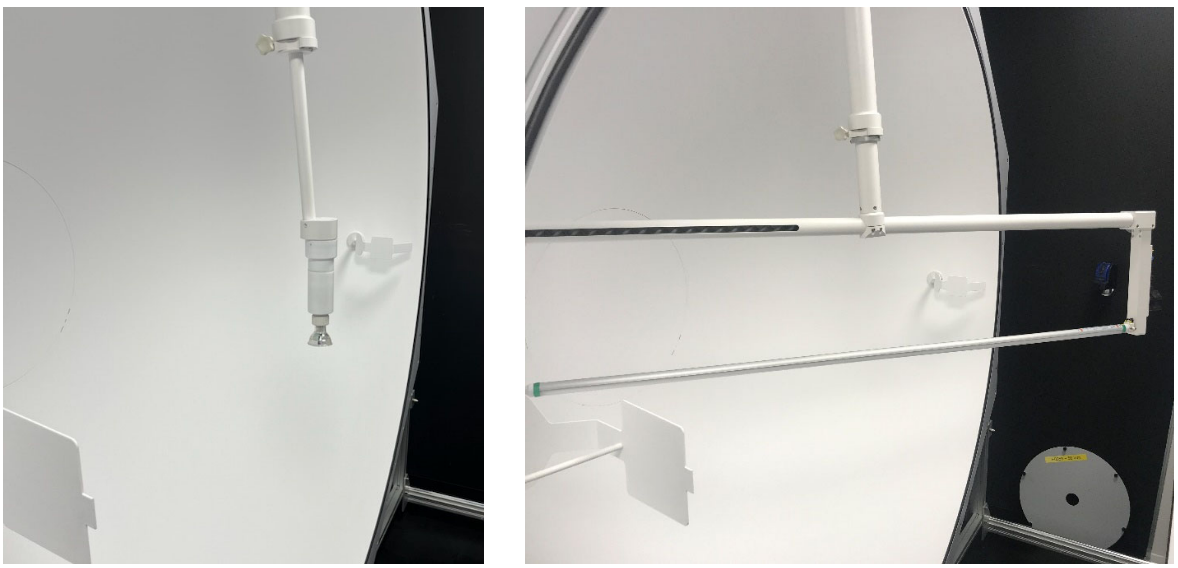

Figure 1 - Integrating sphere (Ø 2 m), with a spotlight facing down (left) and an LED tube (right) mounted for test.

The light sources were measured for power consumption [W], luminous flux [lm], luminous efficacy [lm/W], correlated color temperature [K], color rendering index and other colorimetric properties. The result of these measurements will be shown in chapter “4.5 Measurement results”

4.3.1.1 IES LM-84

IES LM-84 is a standard developed by the Illuminating Engineering Society (IES) that provides guidelines for the testing and measurement of solid-state lighting (SSL) products, such as LED lights. The standard aims to provide a consistent and reliable method for evaluating the performance and characteristics of SSL products, which can help ensure that they meet given quality and safety standards over time.

The first test method for LED components was IES LM-80 [9] published in 2008, the first method for lamps and luminaires was IES LM-84-14 published in 2014 [5], this was updated in 2020 [10]. IES LM-80 was also updated in 2020 [11], supported by DTU Electro. The test scheme prescribed by LM-84, is operation of the products for 6000 h with photometric measurement performed at 1000 h intervals. The test method prescribes the environmental conditions for the test.

The measurement scheme prescribed by LM-84, is to operate the products under test for 6000 h with photometric measurement performed at 1000 h intervals. The measurement method also prescribes the environmental conditions that need to be provided for the duration of the measurement period. It is important to note that LM-84 is a light measurements (LM) method and not a pass/fail test. It does not include performance criteria. The larger number of photometric tests (7) in LM-84 provides data that can be used to predict product lifetime with a much higher accuracy than the EU endurance test, since this only has two measurements.

If predictions of lifetime such as L70B50 based on this data is to be made it requires not only time resolved data to be fitted to an exponential function (IES TM 28-14 [12]) it also requires that the DUT has reached the steady deprecation phase, if not the lifetime projection will not be reliable.

4.3.1.2 EU endurance test

In 2019 the EU published a new regulation EU 2019/2020 for ecodesign requirements of light sources and separate control gears, which came into force 1 September 2021[1]. In this document a new endurance test was introduced to verify claims of lumen maintenance and survival factors. The test is a switching cycle test, where the light source is operated for 1200 on/off cycles. A switching cycle consists of two stages, one where the light source is switched on at full power for 150 minutes, followed by a complete power-off for 30 minutes. Thus, the light sources are on for 3000 hours, and off for 600 hours giving a total test time is 3600 hours.

After the test lasting approx. 5 months, the survival factor is determined by counting the number of samples still operational. It is a requirement that 90 % of the light sources of the test batch must be operational after the 1200 cycles. For the samples still operational the final luminous flux measurements are made in the 2m integrating sphere spectroradiometer. The average lumen maintenance factor X_{LMF} % is determined by averaging the lumen maintenance factor for each of the operational samples. This needs to be compared to the producer's stated lifetime for L70B50. For this LED tube the datasheet states: > 50000 h @L80B10, which corresponds to at least 26 000 hours for L70B50, and for this the average lumen maintenance factor has to be compared with a minimum value of 96% (EU regulation EU 2019/2020) [1].

4.3.1.3 Comparison of the two methods, and DTUs combined method.

Table 1 compares the specifications and requirements for each method and shows the combined method that DTU will be using in this project, that encapsulates both.

Table 1 – The requirements for the two test methods, and the combined test that the DTU test laboratory should fulfil.

Description	unit	EU endurance	LM-84/TM-28	DTU method
Samples				
No of samples		10	5-6	
Mounting direction		Base up	Man. spec.	
Power supply				
Voltage	[V]	230	Man. spec.	230
Max. Voltage variation	[±%]	2	2	2
Max. Voltage variation	[±V]	4.6		4.6
Max. THD	[%]	3	3	3
Frequency	[Hz]	50	50/60	50
Impedance			low	low
Ambient conditions				
Ambient temperature	[°C]	25	25	25
temperature variation	[±°C]	10	5	5
Maximum humidity	[% RH]	-	65	65
Max. Air velocity	[m/s]	0.2	minimized	
Other				
Seasoning	[h]	none	none	none
Marking			Labels on DUT	Labels on DUT
Operating cycle		2.5 h on / 0.5 h off	Continuous	both
Cycles		1200		
Total operation time		3000	6000	both
Minimum temporal resolution	[%]		0.5	

4.3.2 Photometric test standards

The photometric tests were conducted using the international standard CIE S 025/E:2015 Test Method for LED Lamps, LED Luminaires and LED Modules (CIE S 025) [13]. This international standard was developed mainly for photometric and colorimetric characterization of LED based light sources (not for single LED components).

Currently a revision of the standard is underway in CIE, the technical committee TC 2-97 [14] chaired by DTU and supported by ELFORSK, the standard will be updated with new knowledge and techniques by experts from around the world [15].

4.3.3 Photometric tests

LED lamps and luminaires are tested using photometric quantities to measure their performance in terms of light output and quality. For this work the relevant photometric quantity is the luminous flux, for other applications luminous intensity, illuminance, and luminance may be relevant. Photometric quantities are defined by international standards.

Integrating spheres are commonly used in LED lamp and luminaire testing to measure the total light output of the device. The sphere collects light from all directions and diffuses it over a large area, providing an average measurement of the light output. The sphere also allows for measurement of other photometric quantities such as color temperature and color rendering index. The international agreed descriptions of integrating spheres are currently CIE 084 [16] from 1989, this document is currently undergoing a much-needed update by the technical committee CIE TC 2-78, with participation from DTU Electro.

A spectroradiometer is the instrument used here to measure the spectral distribution of light. It can be used to measure the color of light sources by analyzing the different wavelengths of light emitted by the source [12]. The spectroradiometer works by splitting the light into its component wavelengths using a diffraction grating. The instrument then measures the optical power present at each wavelength and generates a spectral power distribution of a given light source[17]. The spectrum can be used to calculate various color parameters such as color temperature, chromaticity coordinates, and color rendering index (CRI). These parameters are important for evaluating the color quality of light sources and ensuring they meet the desired specifications for a given application. The two documents [17], [18] were prepared with participation of DTU Electro (outside this project).

For photometric testing of lamps and luminaires the international standard CIE S 025 specifically regarding the integrating sphere and the spectroradiometer, which coupled together form an integrating sphere-spectroradiometer [17].

As LED sources are driven by electrical power the electrical conditions during operation are key parameters, the requirements used in the tests of this report is described in CIE S 025 [13].

4.3.4 Electrical test

When supplying power and measuring the electrical properties of the products in this report, we follow CIE S 025 [13]. The AC voltage has been set to 230 VAC ± 0.1 %, using an ELGAR CW1251P power supply. The electrical parameters of the measurements have been measured using a Yokogawa – WT3000 by the use of a 4-wire connection ensuring that the voltage is being measured at the product.

Note: 15 products of the products that were tested at time 0, unfortunately consumed too much power for our maintenance test laboratory to run. But their initial parameters have been measured.

4.3.5 Colorimetry

The CIE 1931 diagram is a standardized color space [19] that maps the visible gamut of colors in terms of their chromaticity coordinates, or color coordinates, based on the human eye's response to light of different wavelengths. The diagram is a 2-dimensional plot where the x and y coordinates represent the color's position on the spectrum. For color maintenance in LED long-term testing, the CIE 1931 diagram (seen in Figure 2) can be used to assess the stability of the LED's color over time. LEDs are known to exhibit changes in color over time due to factors such as aging, temperature, and environmental conditions.

By comparing the chromaticity coordinates of an LED's color at different points in time, it is possible to assess its color shift and determine whether it falls within acceptable limits. This information is useful for ensuring that the LED maintains its intended color characteristics over the long term and is particularly important for applications where color accuracy is critical, such as in lighting for color-sensitive environments or in digital displays.

The relevance of the color difference is evaluated using CIE Technical Note TN 001 [20] here noticeable differences are determined using circles in the CIE 1976 uniform chromaticity scale (UCS) diagram (known as CIE (u', v'). Due to the non-uniformity of CIE 1931 the circles defined in CIE (u', v') becomes ellipses when transformed to the older coordinate system, as seen in section 4.5.2.3.

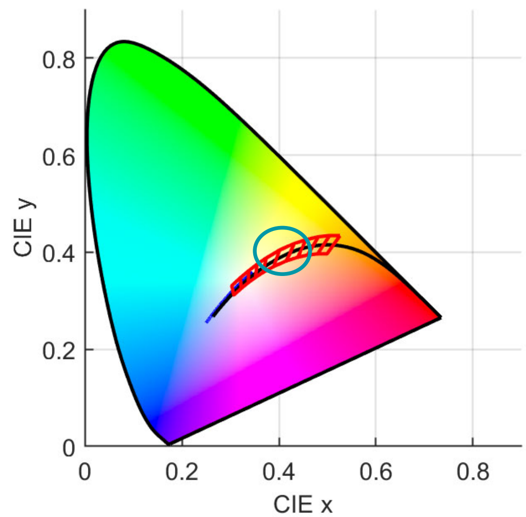

Figure 2 - CIE1931 color diagram, with ANSI quadrangles (red grid) and the Planckian locus (solid black line). The blue circle shows the part of the diagram particularly relevant to this investigation.

4.4 Maintenance test facility

The light sources tested in the two test methods were being run in a maintenance facility established for the purpose of this project. Here the light sources are run according to the method they are being tested under. Either continuously or with an on/off cycle described previously. The light sources are installed in moveable racks, with a distance in between each light source ensuring that they won't be influenced by neighboring light sources heat generation, see Figure 4.

Temperature probes are attached to the monitoring system, these can be used to measure the temperature of the maintenance test laboratory and the light source they are monitoring. An example of such a temperature monitoring can be seen on Figure 3, here it is seen that the temperature in the lab varies from around 20.5 to 28.5 degrees in the laboratory, just within the limitations stated in the DTU method. Other laboratories have made similar setups where they can control the ambient temperature around the light source, and thus changing the light source temperature [21].

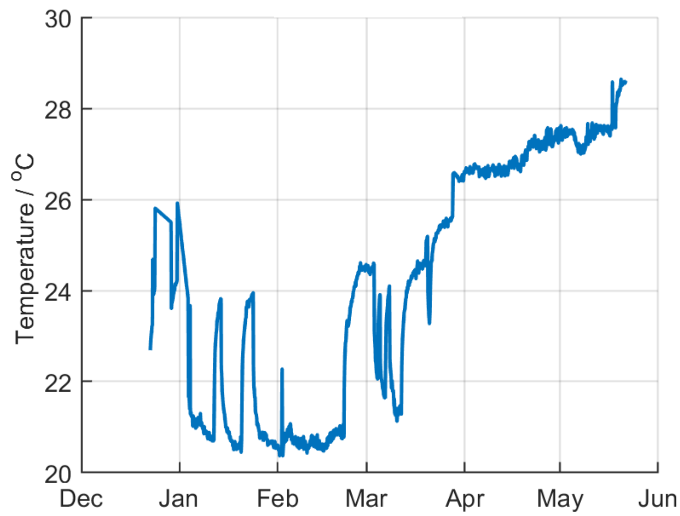

Figure 3 – Ambient temperature in the maintenance test facility from January to June 2021.

Figure 4 – Showing light sources installed in the maintenance test facility laboratory.

4.4.1 Power on/off control

To control the power of the products being tested under the EU endurance test, several energenie programable power strip were used. By programming these it enabled the possibility to have the products turned on for 2.5 h and turned off for 0.5 h periodically, making it possible to cycle them 1200 times. Figure 5 shows the power strip together with a screen shot of the software used to program it.

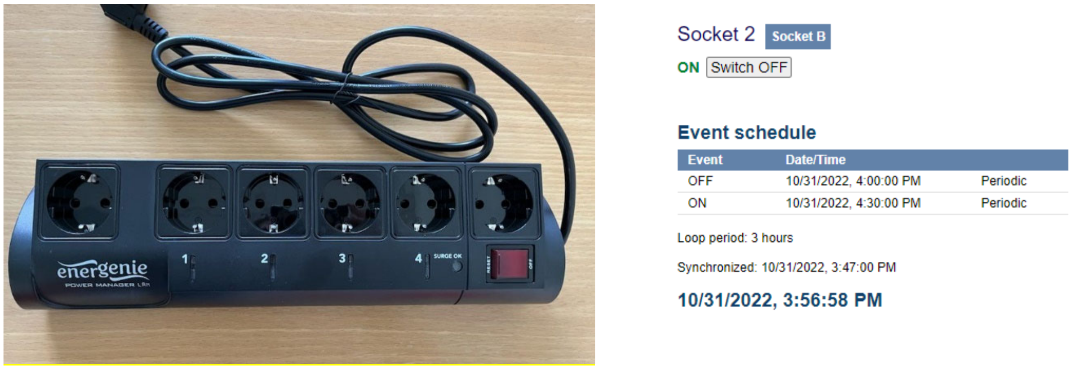

Figure 5 – (left) Photo of energenie programable power strip (right) control software.

4.4.2 Monitoring system

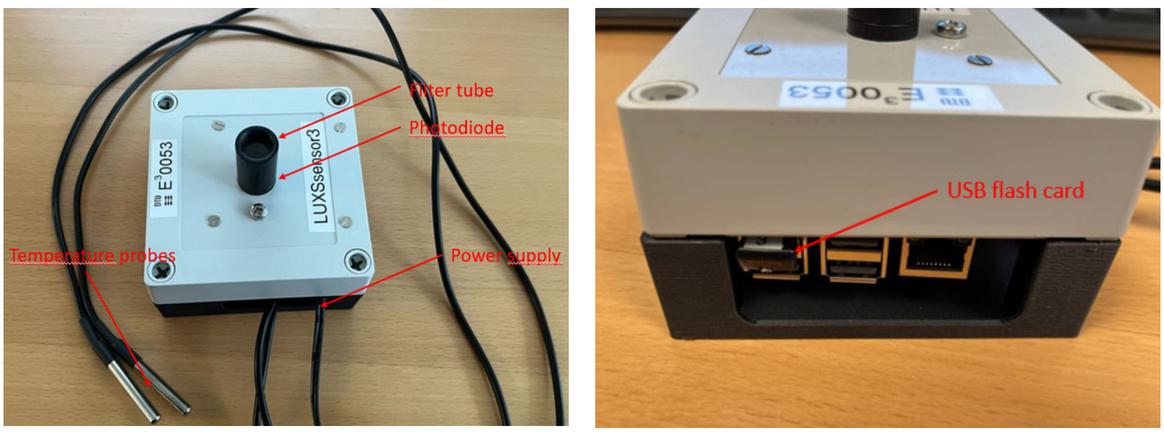

Figure 6 - monitoring system with temperature probes and neutral density filter tube.

In order to monitor the light sources under test (device under test / DUT) a monitoring system have been designed and build, see Figure 6. A total of six sensors have been created in the project, one for each of the project partners and four for DTU. A RGBW photodiode installed in the sensor measures the emitted light from the light source, one measurement per minute, it saves the data locally on a flash card, in .csv-data format. It is possible to reach this data either by communication via Wi-Fi or directly from the flash card installed in the sensor. A Raspberry pi microcontroller is programed using python, in order to be as stable as possible, the program does a measurement, saves the data and reboots each minute, giving very accurate timestamps for each measurement and long-term stable operation. In order to guarantee that the monitoring system only measures the light coming from the light source it is attached to, and not neighboring light sources, a filter tube is applied, narrowing its field of view. Furthermore, to ensure that the sensor is not saturated, neutral density filters can be applied, adjusted to fit to the luminance level from each individual light source. Temperature probes are attached to the raspberry pi, these can be used to monitor the ambient and light source temperature, in the final system three probes are installed.

4.4.2.1 Calibration of the sensor

One of the goals in this project was to examine whether or not it was possible to design a sensor that could be calibrated and give absolute values, compared to a reference measurement from an integrating sphere. The sensor measures data relatively, but by comparing this relative measurement with an absolute measurement from an integrating sphere, the idea was that it could be possible to relate these two measurements with each other and thus calibrate the sensor, and if the light from the sensor decreased during the monitorization this could then be used to estimate an absolute luminous flux from the light source, using a simple equation *(1)*.

$$\Phi_{sensor} = \frac{S_{test}}{S_{ref}} * \Phi_{IS} \tag{1}$$

where:

Φ_{sensor}	is the estimated luminous flux value from the sensor value,
S_{test}	is the relative measurement from the sensor, installed at the light source,
S_{ref}	is the relative measurement from the sensor, installed at the light source just after the measurement in the integrating sphere,
Φ_{IS}	is the measured luminous flux of the light source measured the integrating sphere.

4.5 Measurement results

This section will contain the results of the project. It will contain a list of the different light sources, what the packages states in regard to the power consumption, luminous flux and lifetime. For each light source their spectral power distribution and power consumption have been measured at different operation times according to the two methods, using an integrating sphere (Instruments Systems, DE) fiber coupled to a CAS140CT spectroradiometer (Instruments Systems, DE), see Figure 1. From these measurements the luminous flux and efficacy, correlated color temperature, (x, y)-chromatic coordinates and color rendering index will be calculated as a function of time. Finally, the results from the developed sensor will be presented.

For the two methods a total of 90 samples have been tested. These have been divided into series (devices that are supposed to be similar according to their packaging) and into the two groups, one for each of the test methods.

A total of 70 samples have been tested in accordance with the EU endurance test, and 20 in accordance with LM-84. In this report results for 40 samples from the EU endurance test will be presented, the measurements from the last 30 will be finalized in May 2023, and thus not possible to present in this report. For the LM-84 test all tests have been completed. The results of 220 measurements will be presented in this report.

4.5.1 Tested products

This section contains a list of the different products tested, presented in two tables, and what information was stated on the packaging. The LED products that have been tested in this project consists of 16 LED tubes with a length of 120 cm, 25 omnidirectional LED lamps, 20 LED spots and 29 retrofit LED lighting products to be built into existing luminaires.

The Device ID is an internal DTU ID system, where a number is given for each new light source tested, to keep track of the results. The Batch ID is a collection of samples from identical products, example L31855 – L31865 are all identical LED tubes being tested under the EU endurance test and given the batch ID A, L31866 – L31869 + L31982 are the same LED tubes, but these are tested using the LM84 test method and given batch ID J.

Table 2 The different products tested in the EU endurance test and what was stated on the packaging.

Device ID	Batch ID	Socket	Rated power [W]	Rated luminous flux [lm]	Rated lifetime [h]
L31855 – L31865	A	G13	25	3750	50000
L32121 – L32130	B	-	14	x	x
L31901 – L31910	C	E27	7.5	806	15000
L31886 – L31895	D	GU10	5	380	15000
L32036 – L32045	E	-	75	14000	x
L32241 – L32245	F	E27	24	x	x
L32246 – L32250	G	E27	13	1521	15000
L32291 – L32295	H	GU10	4.8	355	15000
L32297 – L32300	I	-	18	1380	18000

Table 3 The different products test in the LM-84 test and what was stated on the packaging.

ID	Batch ID	Socket	Rated power [W]	Rated luminous flux [lm]	Rated lifetime [h]
L31866 – L31869 + L31982	J	G13	25	3750	50000
L32131 – L32135	K	-	14	x	x
L31911 – L31915	L	E27	7.5	806	15000
L31896 – L31899	M	GU10	5	380	15000

4.5.2 Test results

This chapter will present the results of the measurements done in the project and discuss these. The focus will be on the luminous flux, luminous efficacy and color maintenance of the tested products. Furthermore, the results of the EU endurance test will be presented and the data from the monitoring system will be analyzed.

4.5.2.1 Luminous flux maintenance

In this section the luminous flux as a function of time for the different products is presented for the two test methods. The dashed lines correspond to the LM-84 test results, and the solid line corresponds to the EU endurance test results, the purple lines represent the mean values for the product series in each test, where the error bars correspond to the standard deviation of the product series.

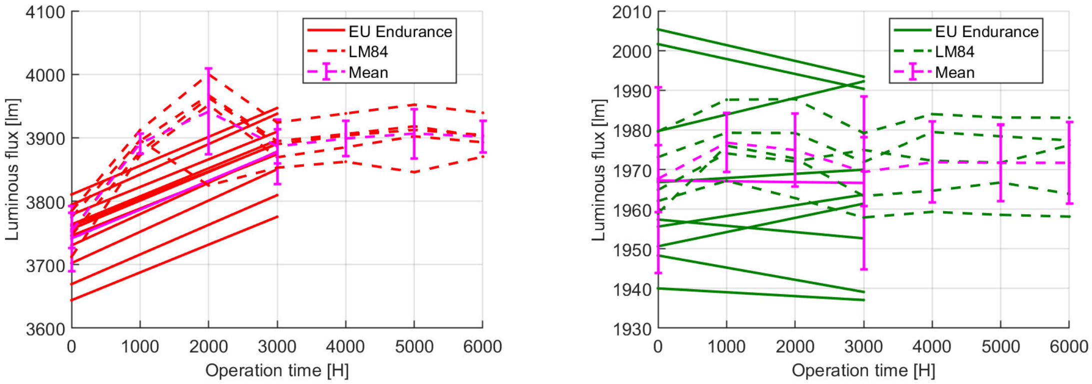

Figure 7 – (left) Luminous flux as a function of operation time for batch A and J in the EU endurance test (solid line) and LM-84 (dashed line) respectively. With the purple line being the mean value of the tests. (right) Luminous flux as a function of operation time for batch B and K in the EU endurance test (solid line) and LM-84 (dashed line) respectively.

Figure 7 (left) shows the luminous flux as a function of operation time for batch J in the two test methods. It is seen that, for this product series, the luminous flux for each product is generally increasing as a function of time, and that around an operation time of 2000 h to 3000 h the flux stabilizes. When looking at the mean values, it is seen that there is a good correlation between the two test methods after an operation time of 3000 h, and that no further information is obtained by running the product for another 3000 h until 6000 h.

When looking at Figure 7 (right), for batch B and K, a similar relationship is seen, that the two methods aligns well at an operation time of 3000 h, also it is seen that this product series is even more stable and the variation within the series is very small.

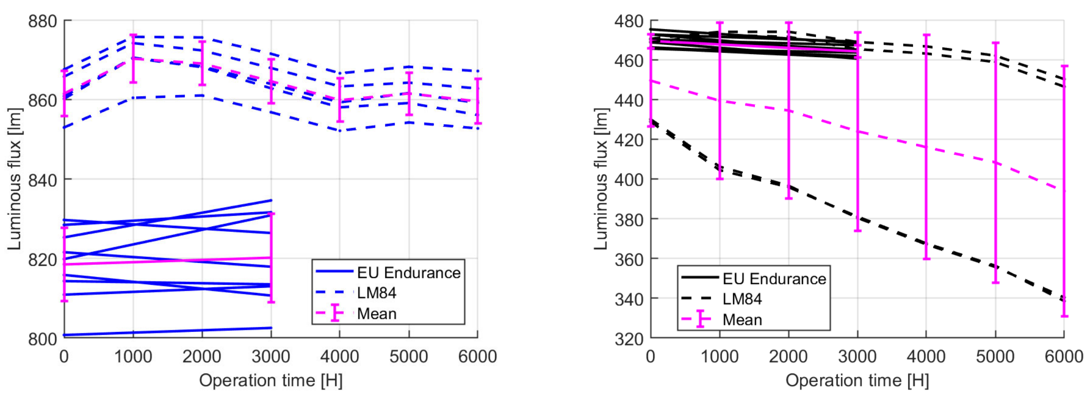

Figure 8 - (left) Luminous flux as a function of operation time for batch C and L in the EU endurance test (solid line) and LM-84 (dashed line) respectively. With the purple line being the mean value of the tests. (right) Luminous flux as a function of operation time for batch D and M in the EU endurance test (solid line) and LM-84 (dashed line) respectively.

Figure 8 (left), for batch C and L, shows an interesting result. Here it is seen that within the two test methods the variation between the product series is very low, but when comparing the products in both test methods it is seen that there is a difference of almost 5 %. The products have been picked from a product series, delivered in a box with 15 samples, with identical packaging, the first 5 samples of the box has been picked for the LM-

84 test and the next 10 for EU Endurance test, it's a coincidence that the devices with very similar attributes are being tested using the same test method. A cautious conclusion is that they are from different production batches from the factory. That being said a variation of 5 % in the luminous flux within similar batches is not a lot.

Figure 8 (right) shows the results for batch D and M, here it is seen that two of the devices in the LM-84 test behaves in a similar manner as the ones in the EU endurance test. The remaining two behaves in a significantly different manner decreasing to almost 70 % of their initial luminous flux after 6000 h of operation, this is also shown in the standard deviation for the mean values of the products running the LM-84 test, being almost 15 % after 6000 h of operation. If these two devices were in the EU endurance test, the product series would have failed the test. Because of the increased stress the EU endurance test inflicts on the products compared with the LM-84 test method it is even possible that they would have failed before the 3000 h of operation was done.

When looking at both Figure 7 and Figure 8 and looking past the two failed products on Figure 8 (right), it is seen that there is a good correlation at 3000 h of operation for the two, as such the EU endurance test could supplant the LM-84 test method for maintenance / endurance testing, saving approximately 3 month of test duration.

4.5.2.2 Luminous efficacy maintenance

At first glance Figure 9 and Figure 10 for the luminous efficacy as a function of operation time looks very similar to the figures showing the luminous flux maintenance. This means that the power consumption of the products does not change significantly as a function of time. It is also seen in Figure 10 (left) that the luminous efficacy follows the same trend as in the luminous flux maintenance, with a 5 lm/W difference between the two methods. This shows that the devices consume approximately the same power. Giving strength to the cautious conclusion that they are from two different production batches from the factory.

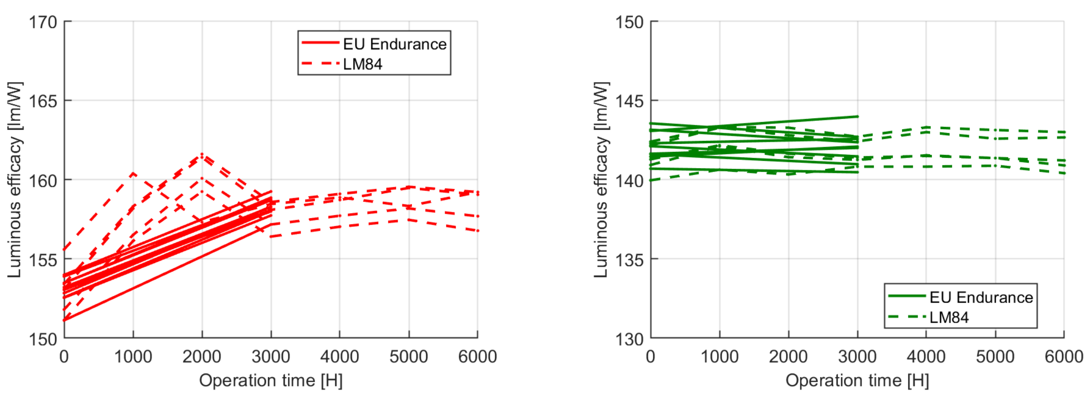

Figure 9 – (left) Luminous efficacy as a function of operation time for batch A and J in the EU endurance test (solid line) and LM-84 (dashed line) respectively. (right) and Luminous efficacy as a function of operation time for batch B and batch K.

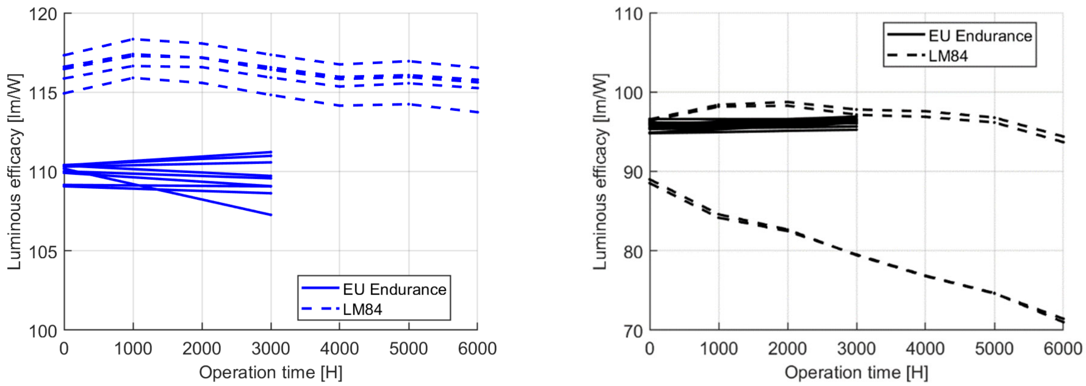

Figure 10 - (left) Luminous efficacy as a function of operation time for C and L in the EU endurance test (solid line) and LM-84 (dashed line) respectively. (right) and Luminous efficacy as a function of operation time for batch D and M.

4.5.2.3 Color maintenance

In this section the color maintenance of the tested products will be examined, with the basis in the CIE standard colorimetric system, (CIE 1931 color space). The results are shown on graphs that are zoomed in on the area as indicated in Figure 2. The CIE1931 diagrams in this section shows the chromatic coordinates for the products in the two tests methods EU endurance and LM-84, following the same line scheme used in this report where the dashed line is the LM-84 test and the solid line is the EU endurance test.

When looking at Figure 11 it is seen that there is no significant color variation within these two product batches (A | J and B | K), the (x, y)-chromatic coordinates are well within a one-step ellipse meaning that it is not possible to see any difference in color with the human eye.

At Figure 12 (left) it is seen that the (x, y)-chromatic coordinates is well within a one-step ellipse for each of the test methods, but also that they are far apart but close to the 4000 K isothermal line. If an ellipse should be big enough to encapsulate both batches (C and L) it would have to be 3-4 steps. This means that within these batches (C and L) it would be possible to notice a color difference if the products were situated close together. This further strengthens the theory that the products within these batches come from two different production series from the factory.

Finally, when looking at Figure 12 (right) it can be seen that the two products that failed the luminous flux maintenance also changes significant in color, their (x, y)-chromatic coordinates moves several step ellipses and are outside what can be seen with the human eye. For the remaining devices these stay within a two-step ellipse.

When looking at the color rendering index a small change in the index is observed, it is in the range of 0.2-0.4, this small change is not significant and does not have huge influence on how colors will be perceived under illumination from these products. Furthermore, the CRI are still above 80 for all devices.

In conclusion the wide majority of the LED products tested, that are within the same batch do not present any significant color change as a function of operation time.

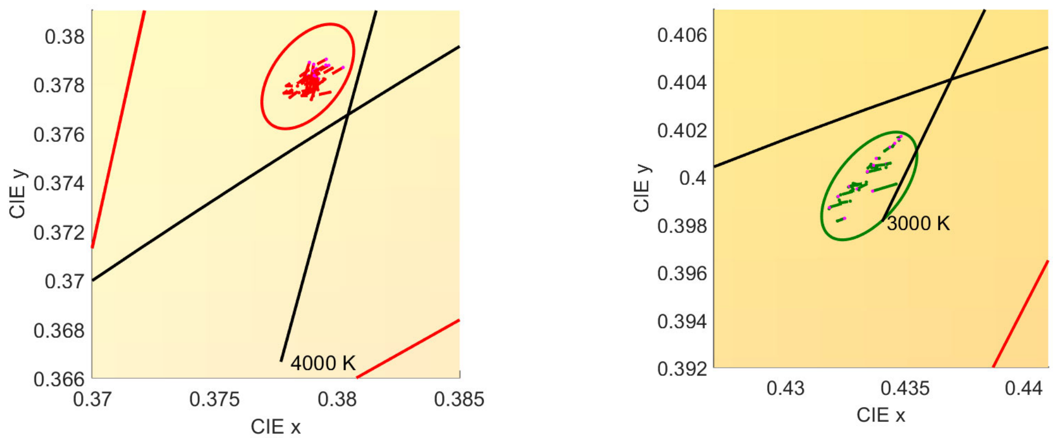

Figure 11 – (left) the CIE1931 (x, y) chromatic coordinates for batch A and J in from the EU endurance and LM-84 test respectively, with a one-step ellipse around the center point of the measurements (right) and for batch B and K from the EU endurance and LM-84 test respectively, with a one-step ellipse around the center point of the measurements..

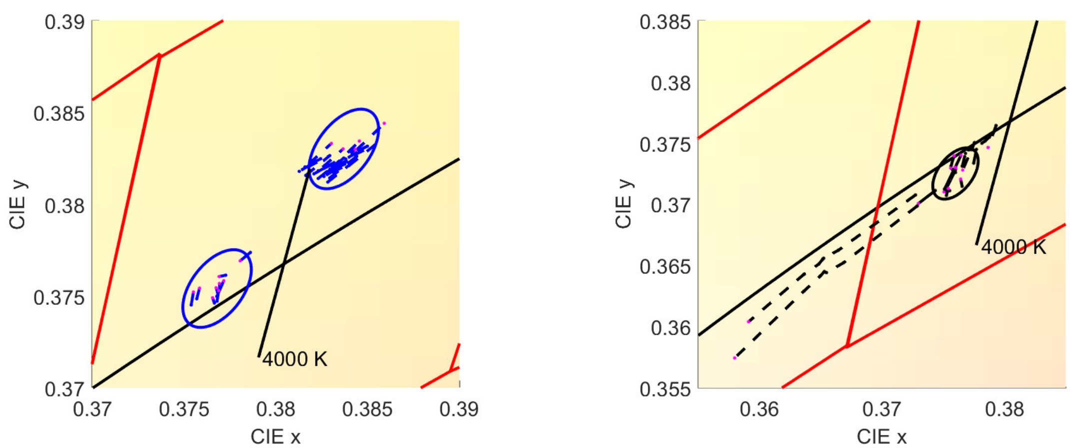

Figure 12 – (left) the CIE1931 (x, y) chromatic coordinates for batch C and L in from the EU endurance and LM-84 test respectively, with a one-step ellipse around the center point of the measurements (right) and for batch D and M in from the EU endurance and LM-84 test respectively, with a one-step ellipse around the center point of the measurements.

4.5.3 Functionality after the EU endurance test

In order to determine whether a product lives up to the EU endurance test, two criteria must be met.

- It must not suffer parametric failure.
- A maximum of one out of ten samples in a batch can suffer catastrophic failure.

To test for whether or not a batch suffers from parametric failure, first the luminous flux maintenance factor for each product in the batch must be found, using equation (*2*)

$$X_{LMF}\% = \frac{\Phi_{3000h}}{\Phi_{initial}} * 100 \qquad (2)$$

where:

$X_{LMF}\%$ is the luminous flux maintenance factor after the EU endurance test is completed,

Φ_{3000h} is the luminous flux of the DUT after 3000 h of operation,

$\Phi_{initial}$ is the luminous flux of the DUT before the EU endurance test was started,

From this the mean $X_{LMF}\%$ value from the batch is found. This is compared with the minimum allowed luminous flux maintenance factor for a batch, this value is determined using equation (3), and is depending on the declared lifetime of the products in the batch.

$$X_{LMF,MIN}\% = 100 * e^{\frac{3000 * ln\,(0.7)}{L_{70}B_{50}}} \qquad (3)$$

where:

$L_{70}B_{50}$ is the declared lifetime on the packages or datasheets of the products.

The criteria to fulfil is stated in equation (4)

$$\overline{X_{LMF}\%} > X_{LMF,MIN}\% \qquad (4)$$

where:

$\overline{X_{LMF}\%}$ is the mean value of the luminous flux maintenance factor of the batch.

If the batch lives up to both criteria it is said to have passed the EU endurance test. To give an easy overview of required $X_{LMF,min}\%$ values for some commonly declared lifetimes Table 4 have been created.

Table 4 - XLMF,min% values for commonly used determined lifetime

$X_{LMF,min}\%$ / declared lifetime	10000 h	15000 h	18000 h	25000 h
$X_{LMF,min}\%$	90 %	93 %	94 %	96 %

The results for the batches, that have completed the EU endurance test, is shown in Table 5 for batch A. The results for the other batches are shown in A.3. These tables show the initial luminous flux and the luminous flux after 3000 h of operation for each individual device within the batches. There is a column showing whether or not a product experienced catastrophic failure, what the degradation for the product during the test is, where a negative number means that the luminous flux increased, and finally what the luminous flux maintenance factor is. The mean values with their standard deviations, their maintenance factor, and the number of catastrophic failures, have been summed up in Table 6.

When looking at the declared lifetimes of batch A – D from Table 2 it is seen that the minimum lifetime is 15 000 h, this corresponds to a $X_{LMF,min}\%$ value of 93 %, the mean LMF% for the batch must be larger than this value. When looking in the tables it is seen that they all fulfil this requirement. Thus, batch A – D lives up to both criteria and passes the EU endurance test.

Table 5 - Luminous flux maintenance table for batch A

Device ID	Initial luminous flux [lm]	Luminous flux 3000 h [lm]	Catastrophic failure [Yes / no]	Degradation [%]	X_{LMF}% [%]
L31855	3669	3810	no	-3.8	103.8
L31856	3730	3878	no	-4.0	104.0
L31857	3761	3890	no	-3.4	103.4
L31858	3794	3938	no	-3.8	103.8
L31859	3779	3910	no	-3.5	103.5
L31860	3746	3874	no	-3.4	103.4
L31861	3763	3896	no	-3.5	103.5
L31862	3811	3947	no	-3.6	103.6
L31863	3644	3775	no	-3.6	103.6
L31864	3756	3891	no	-3.6	103.6
L31865	3702	3850	no	-4.0	104.0
Mean	3741.5	3878.2	X	-3.7	103.7
Standard dev.	49.0	48.6	X	0.2	0.2
Minimum	3644	3775.5	X	-4.0	103.4

Table 6 - Luminous flux maintenance table for batch A – D – mean values

Batch ID	Initial luminous flux [lm]	Luminous flux 3000 h [lm]	Catastrophic Failure [# / tot #]	Degradation [%]	Maintenance [%]
A	3741.5 ± 49	3878.2 ± 48.6	0 / 11	-3.7	103.7 ± 0.2
B	1967.3 ± 22	1966.6 ± 21	0 / 9	0.0	100.0 ± 0.5
C	818.5 ± 8.7	820.1 ± 10.5	1 / 10	-0.2	102 ± 0.6
D	469.3 ± 3.3	464.1 ± 3.0	0 / 10	1.1	98.9 ± 0.5

4.5.4 Data from the monitoring system

This section contains some examples of the measurements done by the sensor in the monitoring system. The developed sensors were used to monitor the relative light output from both test methods for some of the products in the different batches.

To the left in Figure 13 is shown an example of 11 on/off cycles in the endurance test from batch A and on the right all the cycles can be seen, with a duration of 150 minutes.

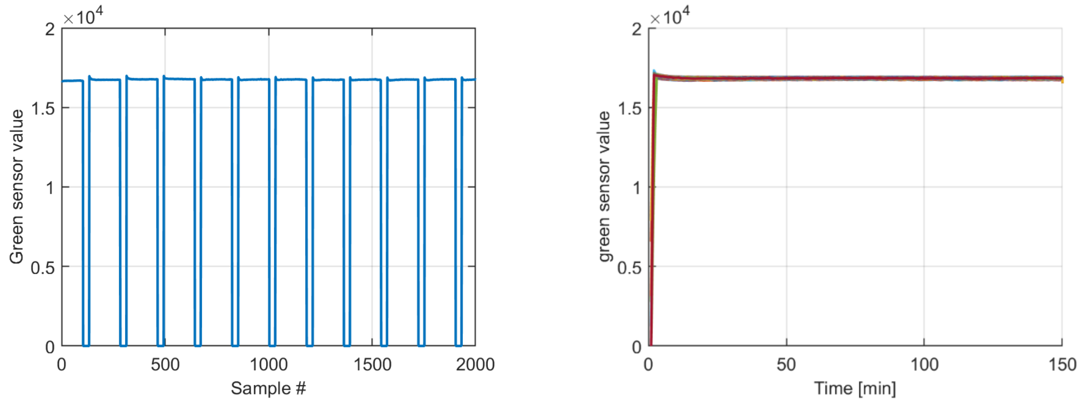

Figure 13 – (left) Measured sensor values as a function of measurement point number, Device L31859 showing a zoom of the first 11 on/off cycles out of 1200. The on part of all cycles shown in the same graph (right).

Looking at Figure 13 (right) it is seen that the light sources reach stability quickly, but it is also seen that it is very difficult to see what happens to the light emitted from the device as a function of time. Because the product reaches stability quickly, it is possible to use the median value as a representative point for each cycle, and by normalizing this to the first cycle, it is possible to calculate the difference in % from the first cycle to the last, an example of this is seen in Figure 14, for batch A. Here it is seen that the sensor measures a difference of 1.5 % from the start to the end cycle, when comparing this to the luminous maintenance factor from batch A, it is seen that the flux is increasing in both methods.

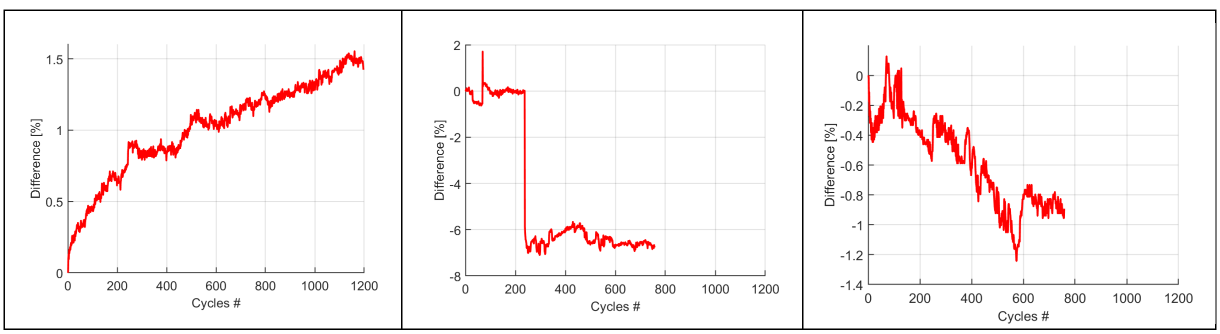

Figure 14 - the difference in light output measured by the monitoring system from device L31856 (left), L32244 (center) and L32250 (right).

An interesting results can be seen in Figure 14 (center), here it is seen that the light source was very stable for the ~230 first cycles, but then dropped ~6 %, it will be interesting to see if the luminous flux maintenance factor of the light source also drop significantly after the EU endurance test is completed on the device, the test will be completed in May 2023. This shows the strength of having such a monitoring system observing the products under test, it is possible to see when the changes happen, and see at what time they experience parametric or catastrophic failures, there is for instance no reason to continue the EU endurance test of the product fails before the test period is complete.

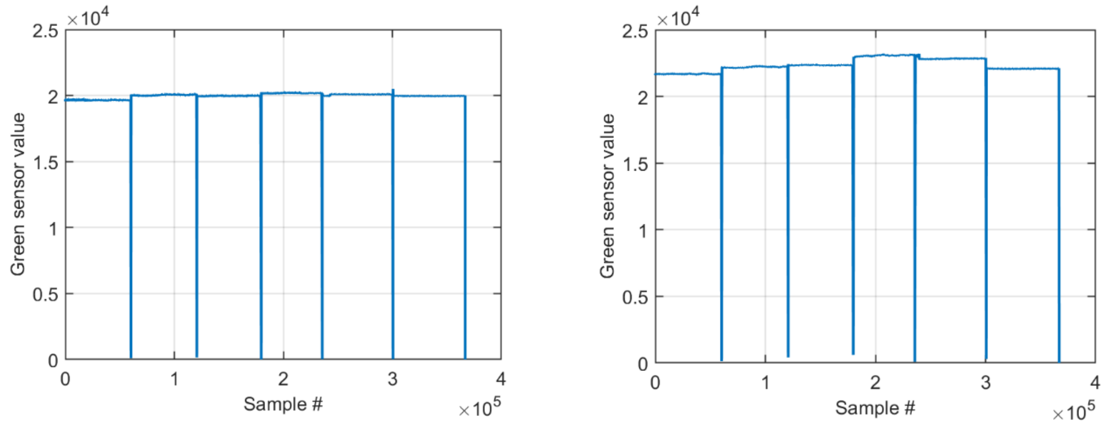

Figure 15 – The sensor value for two devices L31867 (left) L31869 (right) under the LM84 test.

Figure 15 shows the raw sensor value from two devices in batch J that was tested using the LM84 test method, the sudden drop that happens 6 times for each product is when the product is being taken out for testing. The reason that there is a change in detected sensor value after each drop is due to the fact that the sensor did not look at exactly the same position on the product after they were put back in the maintenance test rack. It is possible to correct the curves by normalizing to the measured luminous flux after each measurement.

We have shown that the monitoring system can give some valuable information during the tests that the test methods themselves does not give by default. They give possibilities to see when the changes happen in the test and if / when the products fail within the test period, giving the possibility to end the test before the 3600 h is up.

4.6 Data handling and calculations

An algorithm, developed in MATLAB, used to analyze and monitor light sources tested in the two maintenance test methods has been developed. Among other things it keeps track of the operation time, the on/off cycle, the temperature, the relative luminous flux, ensuring that the LED products are being tested according to the methods. Calculations are done for each measurement completed on the LED products, the results are being stored in a data structure, an example of one can be seen in Figure 16. The algorithm has accumulated data for each test, taking different parameters into account and added the information to the data structure. It is possible to use this structure to analyze the data, the figures presented in this report have been created using the algorithm. The data accumulated includes but not limited to, power consumption, luminous flux, efficacy, color rendering index, correlated color temperature and color coordinates. Furthermore, it is also used to analyze the data measured using the monitoring system, examples of this can be seen in Figure 13 and Figure 14.

DoLEDLast_3600h{2, 1}

Field	Value
L3	'L31856'
Hour	[0 3600]
TestDate	1x2 cell
ElectricalStruct	1x2 cell
meanPower	[24.4502;24.5438]
ISDfiles	1x2 cell
SPDMetaData	1x2 cell
meanSPD	1x2 cell
LF	[3.7304e+03;3.8784e+03]
x	[0.3791;0.3792]
y	[0.3779;0.3786]
u1960	[0.2238;0.2236]
v1960	[0.3346;0.3348]
u1976	[0.2238;0.2236]
v1976	[0.5019;0.5022]
CCT	[4046;4047]
CRI	[83.3380;83.0369]
M3	1x2 cell

Figure 16 - showing the data structure given by the algorithm.

4.6.1 Lifetime estimation

The lumen maintenance results have been compared between the two methods. For these products comparable results are seen at 3000 h operation time and thus they are in good agreement. The majority of the products tested within the project period have a luminous flux maintenance factor above 100 %. This means that a high lifetime can be anticipated but that the test procedure is insufficient to estimate the actual lifetime of the product. We see that for the products the light output generally increases or is stable, this means that during the test duration the devices were still in a phase of stabilization, which is typically seen before the phase of more steady decline. Without entering the phase of steady decline, it is not possible to project lifetime beyond applying a simple constant factor to test duration. If actual lifetime projections are to be done, then either the test duration must be extended or accelerated ageing techniques must be employed. Both options have negative consequences as longer test times are expensive and disadvantageous for innovation while accelerated testing might produce erroneous results due to the introduction or exacerbation of irrelevant deprecation phenomenon. What can be stated though is that according to the EU endurance test, the tested products be likely to will live up to their stated lifetime according to their packaging.

4.7 Target group and dissemination

Lifetime testing is important to many in the lighting community as it can have a radical impact on market access for manufacturers, return on investment (ROI) for facility owners, reliability of safety features and aesthetics of lighting solutions for users among other effects. For this reason, this project has had emphasis on dissemination to a wide audience from scientific peers at conferences to trade magazines to a wider audience. For stakeholders to have access to the results they are presented on the website of DTU [22]. This webpage features publications, related projects, and related activities, as well as the related UN sustainable development goals. The project is also featured on the webpage of ELFORSK [23]. Results were presented in the Danish industry magazine LYS, concerned with lighting, at the beginning [24] and at the end of the project [25]. In 2021 preliminary results were presented in a poster and conference proceeding paper [26].

The results from the project were disseminated through the participation of Anders Thorseth as expert in the IES Testing Procedure Committee on the revision of IES LM-80 from the 2008 version [9] to the 2020 version [11]. Carsten Dam-Hansen has as an expert member of the IEA 4E SSL Annex, https://www.iea-4e.org/ssl/, discussed ideas and results of the project within the expert group at biannual meetings throughout the project period.

Lifetime and endurance are very important topics in presentations on LED technology and LED lighting in general and have hence been included in more general talks, a list of these are included in A.1 List of dissemination activities.

A thematic day on LED technology, called “LED Temadag 2023”, was arranged, and held on 28 February 2023 at Niels Bohr Auditoriet on DTU Risø campus. It was announced on LinkedIn, newsletter from Dansk Center for Lys, homepage at Elforsk ([ELFORSK news about the thematic day)](ELFORSK news about the thematic day), and by direct mails to project stakeholders.
A website with information and the program can be found on https://dtu.events/ledtemadag2023/program. Links are provided to all the presentations that were given on the day. The event gathered about 75 participants from the lighting industry, designers, students and researchers.

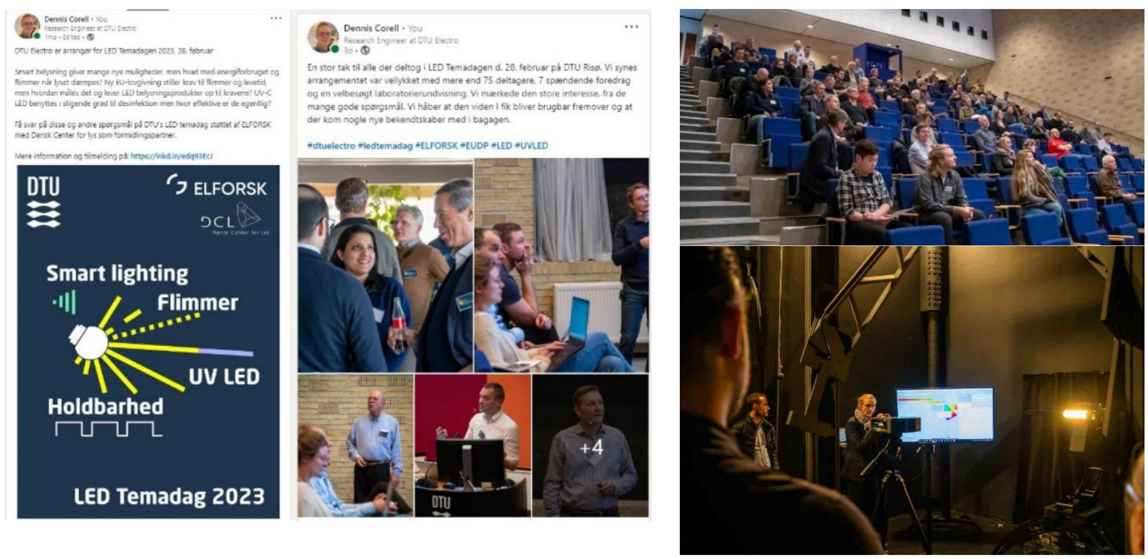

Figure 17 Copy of LinkedIn posts and photos from the Niels Bohr Auditorium and DTU Electro’s photometric laboratory at LED Temadag 2023, Photo: Carsten Dam-Hansen.

The first talk of the day ”Velkomst” given by Carsten Dam-Hansen in which he presented the research group and project and two talks on the day were on lifetime testing. The project had invited Steve Coyne from the company Light Naturally in Brisbane Australia to give a talk on “Lifetime testing, standards and methods”. He was invited in his capacity of being the Australian expert member of the IEA SSL Annex, where he has worked on an overview of standards on lifetime testing. His talk was followed by a talk on the results of the project, “DoLEDlast resultater” presented by Dennis Corell, DTU Electro. The day was completed with a laboratory tour and demonstrations, in which around 40 people participated.

5 Application of project results

The obtained project results will be applied in different ways by the partners and stakeholders. The industrial partners will apply the developed long-term monitoring and sensor system in their own laboratories, so that they have their own simple facility to perform long term testing under on/off power cycling on single LED lamps. They will be able to screen their own products using this and DTU Electro will initially provide assistance for them in analyzing the data.

The developed maintenance test facility that complies to LM-84 and EU endurance testing will be used at DTU Electro in further research and international collaboration on LED lighting product lifetime testing. It will be provided as an impartial third-party test for industry or other stakeholders. The competencies and knowledge gained in the project will be used in teaching bachelor and master student at DTU and continued education in LED technology and lighting. It will also be used in consultancy work for the lighting industry and the Danish Energy Agency e.g. through the work in the IEA 4E SSL Annex.

DTU Electro will use the test results on specific batches of LED products, to provide input to ongoing research on lifetime testing, by doing further testing. New test methods have to be compared to the established test methods, and through this project we have very valuable data for LM-84 and EU endurance testing on batches of different LED lamps. Further test on these according to a new test procedure at elevated ambient temperatures will be carried out in collaboration with the Swedish Energy Agency and Steve Coyne, Light Naturally, through the IEA 4E SSL Annex task 5. This will include LED lifetime testing through the measurement of luminous flux depreciation while a lamp is operated within an elevated ambient temperature (e.g. 60 °C) for 1 500 hours and linking these results with the determined luminous flux relationship between ambient and junction temperatures, through a pulse and soak test [27].

The project partners will use the automatic test system to be able to run the EU endurance test on single LED lamps in their own facilities. The stable and high resolution platform with both light and temperature sensors in the developed long-term monitoring system has many other potential applications in research, development and demonstration projects within lighting and will e.g. be used for environmental monitoring over long terms.

This project has put lifetime of LED products in focus, and the tests that have been investigated in the project has different test durations and methods. The shorter test duration the higher probability that tests will actually be done on LED lighting products. The EU endurance including stressing of the products through on/off cycling will ensure that LED lighting products that fail prematurely are caught in testing, and that they comply to the lifetime stated on the packaging. This will remove low quality products from the European market, increasing trust of consumers/installers making them more inclined towards transition to LED products, and thus save energy. Environmentally, the removal of low quality, short lifetime LED lighting products will ensure products installed have longer life of and fewer replacements of underperforming products.

Table 7 UN sustainable development goals supported by the project.

The project will help deliver on the UN sustainable development goals under headings 7 [28], 9 [29] and 12 [30], see Table 7, which are:

- 7.3 By 2030, double the global rate of improvement in energy efficiency

- 9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities
- 12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

The EU endurance test seems to be a reasonable method within its scope, it is faster than the LM-84 method and gives comparable results after 3000 h of operation time. One improvement could be to perform the measurements at other ambient temperatures to see how the LED products would perform at for instance 25, 40 or even 60 degrees. This would put some challenges towards the monitoring system and the maintenance test facility but would ensure that the products are tested at ambient temperatures closer to real life conditions for LED products mounted inside luminaires, as well as providing opportunities to extrapolate towards longer projected lifetimes.

6 Conclusion and perspectives

The project has investigated endurance testing of LED lamps and luminaires based on two different lifetime test methods, IES LM-84 [5] and the EU endurance test [1] in order to compare the results. A long-term test laboratory and measurement procedures have been established that complies with the requirements for both test methods. This includes total spectral flux measurements in an integrating sphere spectroradiometer. Measurements have been done initially, intermediately every 1000 h and at the end of the tests, providing lumen maintenance and color maintenance data. Tests have been carried out on different types of LED lighting products, including LED linear lamps/tubes, LED omnidirectional lamps, LED spot lamps and LED retrofit modules. 15 samples of each product were divided into 10 samples running according to the EU endurance test and 5 samples according to the LM-84 test.

A stable, low-cost long-term monitoring system with high temporal resolution has been designed and developed in the project. Several of these systems have been produced and tested during the lifetime testing of LED lighting products. The system includes programable power control for on/off cycling, a sensor system for light measurement and temperature probes for measurement of ambient and device surface temperature. It is shown that this system can be used in both test methods and gives valuable information, it can for instance be used to clarify when catastrophic failures have occurred. Without such a system there is no way of knowing if a catastrophic failure happened at 100 h or after 2000 h. A monitoring and power control system will be installed at the industrial partners for them to be able to run long-term tests on single LED lighting products.

The luminous flux maintenance results have been compared between the two methods where data at 3000 h of operation coincide with continuous operation for LM-84 and on/off cycling for the EU endurance test. For the product tested comparable results are seen at 3000 h operation time and thus they are in good agreement, and the stress factor in on/off cycling has not affected the luminous flux maintenance at 3000 h of operation. The majority of the products tested within the test period have a maintenance factor above 100 %. This means that a high lifetime can be anticipated, i.e., at least 6-7 times the test duration. However, the test procedure is insufficient to enable estimate the actual lifetime of these products. We see that for the products the light output generally increases or is stable, this means that during the test duration the devices were still in a phase of stabilization, which is typically seen before the phase of more steady decline. Without entering the phase of steady decline, it is not possible to make a projection of lifetime beyond applying a simple constant factor to test duration. Lifetime projections will require either that the test duration must be extended or accelerated ageing techniques must be employed, the likely solution is to employ acceleration testing, however besides shorter test time the procedure is likely to be more complicated than the existing methods.

The products tested in the EU endurance test, within the test period, all passed the test requirements. Two samples in batch M, that was tested according to the LM-84 method, showed a very low luminous flux maintenance of 79 % at 6000 h and 89 % at 3000 h. This would have meant that they would not have passed the EU endurance test, where the requirement for luminous flux maintenance was 93 %. It is further possible that the on/off cycling could have increased the possibility of catastrophic failure for these two samples.

The majority of LED products tested do not show any significant color changes during the operation time. This is a testament to the development of LED phosphor technology which is generally the most fragile of the materials with the potential to induce color changes with time. Previous generations of LED products have had more issues with color changes as seen in the following references from 2007, 2013 and 2018 [31]–[33]. This has given the industrial partners in the project reassurance that the LED lighting products they are using are performing well when subjected to the luminous flux and endurance tests.

With the experience gained in the project DTU Electro participated in the development of the updating of IES standard LM-80 [11], on Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays, and Modules.

The products tested in this project were of such quality that the EU endurance test applied did not show any catastrophic failures. The Swedish Energy Agency has tested a number of other LED lighting products where the catastrophic failure rate was up to 25 %, so the EU endurance test has proven to be able to reveal low quality products.

One of the weaknesses of the EU endurance test, is that it only allows for evaluation of claimed lifetimes up to 25 000 h. Therefore, it is still an important task to establish a test method for lifetime testing of LED lighting products that accelerates the parametric failure effects and allows for shorter test duration. Further testing on the samples of LED lighting products investigated in this project will be carried out in order to compare results with a new method limiting the maintenance test to 1500 h but raising the ambient temperature to 60 °C and relating the luminous flux between ambient and junction temperatures, through a pulse and soak test [27]. This will allow for estimation of the lifetime also based on the actual operating temperature of the LEDs in a specific LED lamp or luminaire, and thus be more applicable to real installations where the ambient temperature is higher or lower than the standard 25 °C, which is the temperature used for normal photometric testing of LED lighting products. Being able to do these new tests on LED lighting products for which EU endurance, and LM-84 test already have been done is very important for the comparison of the new method results, since the new test is much faster and the testing of up to 8 months have been done.

The project result indicates that there are products with a lifetime comparable to the 50 000 h that were claimed during the market entry of LED. If the full lifetime of such products is utilized then it will have a positive impact on general energy savings and sustainability, as light sources with low energy usage can be installed for usage over long periods of time.

From the results of this project, we can conclude that the full potential for energy and environmental sustainability cannot be gauged with the currently available lifetime estimation methods. The relatively short maximum for evidence-based lifetime estimation sets a short time horizon for these products. In an institution which uses lighting for 8 hours a day all year round, 25 000 h of lifetime only covers 8.5 years. This is potentially much shorter than for instance the lifetime of the building housing the lighting system.

The results of this project indicate that the two test schemes investigated lack the ability to predict long term behavior of LED products outside a window of a few years of heavy use. So, from a scientific and environmental standpoint it would be beneficial to have a more rigorously scientific and internationally agreed upon method, that would be able to predict long term behavior within a reasonable time and budget. This method could benefit from including the following methodological changes:

- Include acceleration of parametrical failure effects, by exacerbating the effects of the ambient environment during testing,
- Ability to make adjustment of the measurement intervals based on past behavior, so that highly stable devices are not measured very frequently, while unstable devices are measured more frequently but fewer times, until the steady depreciation behavior is observed,
- Mathematical optimization of the intervals between photometric testing to create more reliable fits to the exponential function to decrease uncertainty of results and avoid unnecessary measurements,
- An agreed model for assignment of measurement uncertainty to lifetime estimates

The current methods are suited for testing products with short lifetime or to ensure a minimally acceptable lifetime for consumer products. This scope does not include the possibility to make studies of the long-term environmental impact of lighting locally or globally. In this way they still support a somewhat narrow definition of sustainability where products are required to be efficient to a point and to last a specific time but still considered part of a throwaway culture and not seen as long-term investments.

The changes proposed could result in the following benefits:

- A reduction in time, cost and time to market for products with relevant endurance testing data
- A reduction in the number of costly photometric measurements
- Comparable data across international markets

This report marks the end of the official part of the project, but the activities continue. In the short term the remaining products from Table 2 that are being tested in the EU endurance test at the time of writing. More EU endurance tests will be completed in May 2023, and data will be analyzed. One idea to further the results of the project is to propose to the CIE to consider publishing a technical report on a scientific test for determination of long-term performance of LED products.

The project has resulted in valuable results on lifetime testing of LED lighting products that will be used in the pursuit of faster and better lifetime test methods, which is necessary in order to obtain sustainable enduring products and energy efficient lighting for the future.

7 References

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Appendix

A.1 List of dissemination activities

Project websites:

DoLEDLast - Holder LED produkter til at give de lovede energibesparelser?, https://elforsk.dk/projektdatabase/doledlast-holder-led-produkter-til-give-lovede-energibesparelser on Elforsk projectdatabase

DoLEDLast - Does LED products last to give the promised energy savings?, https://orbit.dtu.dk/en/projects/doledlast-does-led-products-last-to-give-the-promised-energy-savi , on DTU Orbit

Industry articles:

Carsten Dam-Hansen, Dennis Dan Corell, and Anders Thorseth, "Holder LED produkter? | Elforsk." https://elforsk.dk/nyheder/projektresultat/holder-led-produkter (accessed Apr. 27, 2023).

C. Dam-Hansen, D. D. Corell, and A. Thorseth, "DoLEDLast?," *LYS*, p. 25, 2020. Accessed: Apr. 27, 2023. [Online]. Available: https://orbit.dtu.dk/en/publications/doledlast

C. Dam-Hansen and D. D. Corell, "Testmetoder for levetid af LED-belysningsprodukter," *LYS*, pp. 10–11, 2021, Accessed: Apr. 27, 2023. [Online]. Available: https://orbit.dtu.dk/en/publications/testmetoder-for-levetid-af-led-belysningsprodukter [25]

Scientific Article:

D. D. Corell, C. Dam-Hansen, and A. Thorseth, "Comparison of Luminous Flux Maintenance, Continous vs. ON/OFF Cycles," CIE 2021 Midterm Meeting; Conference, 2021. Accessed: Apr. 27, 2023. [Online]. Abstract available: https://orbit.dtu.dk/en/publications/comparison-of-luminous-flux-maintenance-continous-vs-onoff-cycles [26]

Conference poster presentation:

CIE midterm meeting 2021 Malaysia: D. D. Corell, C. Dam-Hansen, and A. Thorseth, *"COMPARISON OF LUMINOUS FLUX MAINTENANCE METHODS, CONTINOUS VS. ON/OFF CYCLES", https://orbit.dtu.dk/files/320728088/ID_27_poster_slide.pdf*

Presentations:

C. Dam-Hansen, and Kenneth Munch "Status for LED og nye lyskilder", invited talk at Lysets dag 2020: Lys og de 17 verdensmål, https://orbit.dtu.dk/files/238422635/Pr_sentation_Lysetsdag_2020.pdf

C. Dam-Hansen, "Kvalitet i tilbud og på det udførte anlæg" invited talk at Vejbelysningsdagen 2021, Odense, https://orbit.dtu.dk/files/258183769/Vejbelysningsdagen_2021_CADH_DTU.pdf

C. Dam-Hansen *"Belysning og test"*, Talk at seminar for Egedal kommune, 9-11-2022

Carsten Dam-Hansen, "Velkomst", talk at LED Temadag 2023, Risø DTU, 28-2-2023, https://orbit.dtu.dk/files/311768588/LED_temadag_Velkomst.pdf

D. D. Corell, "DoLEDLast – resultater", talk at LED Temadag 2023, Risø DTU, 28-2-2023, https://medialib.cmcdn.dk/medialibrary/8CDB9508-95AD-4963-B9C8-AA407DD15392/454CE051-2CBF-ED11-84C1-00155D0B0940.pdf

Standardization:

Participation in IES Testing Procedure Committee on the revision of IES LM-80 from the 2008 version [9] to the 2020 version [11].

International collaboration:

Carsten Dam-Hansen has as an expert member of the IEA 4E SSL Annex, https://www.iea-4e.org/ssl/, discussed ideas and results of the project within the expert group at biannual meetings in the whole project period.

A.2 Photo for dissemination

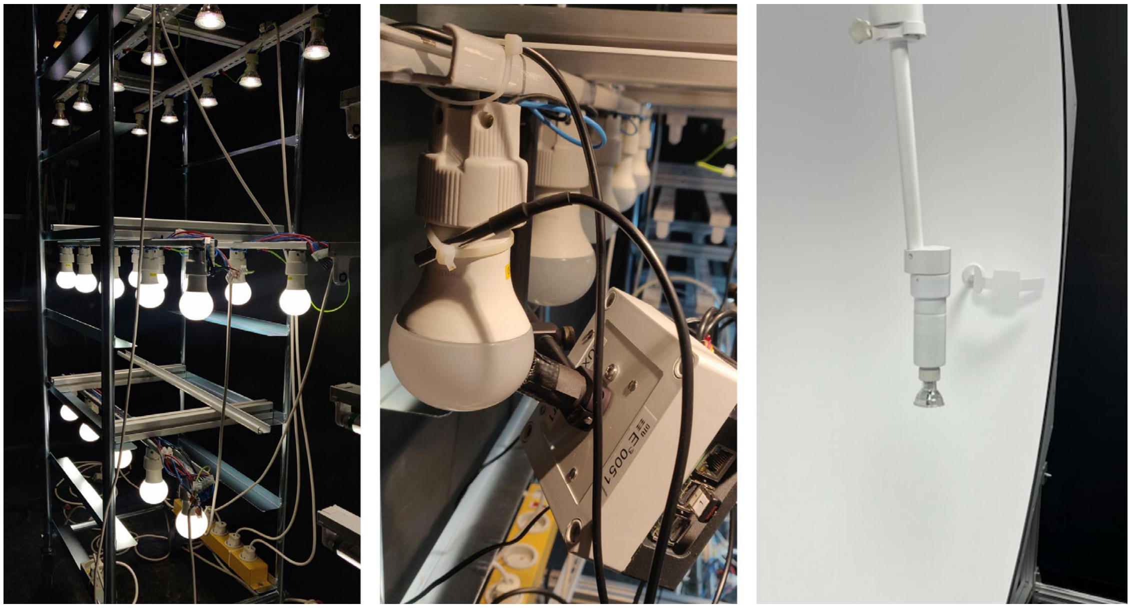

Figure 18 – Endurance testing of LED lamps and modules. The devices are operated in standardized conditions for several thousands of hours. A monitor system logs the intensity and temperature over 5-8 months. At regular intervals, the light output is measured in the integrating sphere. The project has compared the new EU on/off cycling endurance test with continuous on lifetime test. Photos: DTU Electro.

A.3 Luminous flux maintenance tables for EU endurance test

Table 8 - Luminous flux maintenance table for batch B

Device ID	Initial luminous flux [lm]	Luminous flux 3000 h [lm]	Catastrophic failure [Yes / no]	Degradation [%]	X_{LMF}% [%]
L32121	1951	1961	no	-0.6	100.6
L32122	1980	1992	no	-0.6	100.6
L32123	1967	1970	no	-0.2	100.2
L32124	1956	1964	no	-0.4	100.4
L32126	2002	1990	no	0.6	99.4
L32127	2005	1993	no	0.6	99.4
L32128	1957	1953	no	0.2	99.8
L32129	1940	1937	no	0.2	99.8
L32130	1948	1939	no	0.5	99.5
mean	1967.3	1966.6	X	0.0	100.0
Standard dev.	22.1	20.6	X	0.5	0.5
Minimum	1940.0	1937.1	X	-0.6	99.4

Table 9 - Luminous flux maintenance table for batch C

Device ID	Initial luminous flux [lm]	Luminous flux 3000 h [lm]	Catastrophic failure [Yes / no]	Degrada-tion [%]	X_{LMF}% [%]
L31901	820	831	no	-1.3	101.3
L31902	816	811	no	0.6	99.4
L31903	816	x	yes	x	x
L31904	825	835	no	-1.1	101.1
L31905	830	826	no	0.4	99.6
L31906	801	803	no	-0.2	100.2
L31907	814	813	no	0.1	99.9
L31908	828	832	no	-0.4	100.4
L31909	822	818	no	0.4	99.6
L31910	811	813	no	-0.3	100.3
mean	818.5	820.1	X	-0.2	100.2
Standard dev.	8.7	10.5	X	0.6	0.6
Minimum	800.8	802.5	X	-1.1	99.4

Table 10 - Luminous flux maintenance table for batch D

Device ID	Initial luminous flux [lm]	Luminous flux 3000 h [lm]	Catastrophic failure [Yes / no]	Degradation [%]	X_{LMF}% [%]
L31886	465.6	461.8	no	0.8	99.2
L31887	466.2	461.1	no	1.1	98.9
L31888	472.7	463.7	no	1.9	98.1
L31889	470.2	467.2	no	0.6	99.4
L31890	468.7	460.5	no	1.8	98.2
L31891	470.4	465.1	no	1.1	98.9
L31892	475.2	468.3	no	1.5	98.5
L31893	472.7	469.1	no	0.8	99.2
L31894	465.8	460.9	no	1.0	99.0
L31895	465.6	463.6	no	0.4	99.6
mean	469.3	464.1	X	1.1	98.9
Standard dev.	3.3	3.0	X	0.5	0.5
Minimum	465.6	460.5	X	0.4	98.1