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1 Executive Summary

Solid-State Lighting (SSL) has the potential to revolutionize the efficiency, appearance and quality of lighting as we know it. SSL is the most efficient lighting technology available; although the technology is still in development, it is predicted to become twice as energy efficient as fluorescent lamps and more than ten times as efficient as incandescent lamps. As one fifth of global electricity consumption is for lighting, a considerable reduction in energy consumption could be obtained by replacing conventional lighting products by SSL technology.

However, market acceptance of SSL was not immediate. Both professional users and consumers were reluctant to embrace SSL, often due to previous unjustifiable or simply false claims about "low energy" lighting product performance. The need for reliable product information covering all relevant aspects is clear. Such information can only come from measurements. Photometry of incandescent light sources is well established. However, from a measurement perspective, there are significant differences between SSL and incandescent light sources. SSL sources have a different spectral and angular distribution of the light, can be pulsed with high frequency and have complex electrical characteristics. All of these properties make the measurement of SSL sources more difficult than that of incandescent sources.

The challenge to develop a dedicated metrology framework for SSL in Europe was taken up by a consortium of fourteen national metrology institutes (NMIs), three non-NMI partners and three researcher excellence grant (REG) recipients under the coordinatorship of VSL in the project "Metrology for Solid state Lighting". The project was submitted and approved as part of the 2009 Energy call of the European Metrology research Program (EMRP), and started 1 May 2010.

The project has laid the foundations for reliable SSL metrology in Europe, by working on four interconnected objectives: (1) the definition of suitable quality metrics, in which to properly express the performance of SSL lighting systems, both from a general and an application-specific point of view; (2) the investigation of the correlation between proposed physical quality metrics and the human perception of the light; (3) the development of measurement methods, for the reliable measurement of the relevant quality metrics; (4) the establishment traceability for SSL measurements, by developing dedicated facilities, instruments and calibration methods.

Different aspects of SSL were considered. New electrical metrology was developed, taking into account the complex, non-sinusoidal current spectrum of SSLs and the important effect of source impedance on SSL power measurements. A first-ever comparison on luminous efficacy determination of actual SSL products was organised between European NMIs. Special attention was paid to spectral measurements, since the spectrum of SSLs is one of the most important differences with respect to incandescent lighting. Correction methods for array spectroradiometers and integrating sphere photometers were developed. Important first steps were taken in resolving the complex issue of providing traceability for ray files. Likewise, important first results were obtained towards reliable life-time estimation, e.g. on the equivalence of natural and accelerated aging. Since life-time and the spectral composition of the light are both connected to the junction temperature, work was done on the modelling of SSL spectra and the measurement of junction temperatures, by electrical or optical means. The latter resulted in two patents. As illumination under mesopic conditions is an important application area for SSL, e.g. in road or tunnel lighting, traceability in this area was a research topic within the project, resulting in a novel mesopic (mixed photopic-scotopic) luminance meter and a traceable calibration chain for scotopic instruments. This work has enabled the market introduction of commercial scotopic photometry heads. The human perception work has concentrated on the important issues of colour rendering and glare. In the area of colour rendering, a new quality index is currently under debate. The project has contributed to the resolution with an extensive subjective experiment, relating proposed physical measures of colour rendering to test panel evaluation of naturalness, vividness etc.

The research results were supplied as input to standardization activities in e.g. CIE and CEN. Dissemination to stakeholders was a constant activities, with a large number of appearances at SSL events across Europe and a successful final workshop in April 2013.

2 Project context, rationale and objectives

2.1 The need for the project

Solid-State Lighting (SSL) has the potential to revolutionize the efficiency, appearance and quality of lighting as we know it. SSL is the most efficient lighting technology available; although the technology is still in development, it is predicted to become twice as energy efficient as fluorescent lamps and more than ten times as efficient as incandescent lamps. As one fifth of global electricity consumption is for lighting, a considerable reduction in energy consumption could be obtained by replacing conventional lighting products by SSL technology.

However, market acceptance of SSL has not been immediate. Both professional users and consumers have been reluctant to embrace SSL, often due to previous unjustifiable or simply false claims about "low energy" lighting product performance. The distrust of performance claims in the case of SSL was not entirely without reason. In 2009, VSL conducted a study on replacement lamps purchased in regular shops which showed a similar picture, with the real luminous flux being 10-30% of the suggested value and the power consumption up to 150% of the specified value. The products were claimed to be equivalent to 25 to 40 W incandescent lamps, but in reality the equivalence was substantially less than 15 W. Expressing SSL output in equivalent wattage itself can be a source of expectation mismatch, even if the wattage is specified correctly. The statement of "equivalence" suggests a user experience of equal value, which is not necessarily true. Other aspects of the light than luminous flux play an important role in the user experience. For instance, the color of the light from SSL sources can be quite different from incandescent sources and weighs heavily in the user perception.

Past experience has shown that the reputation of new lighting technology can be seriously damaged when accurate and unambiguous performance information is not available at the time of market introduction [1]. This is to be regretted when a new technology offers considerable advantages in energy efficiency. Where the overestimation of performance is widespread, the "good" manufacturers suffer with the "bad", since users do not know which product specifications to trust. Governments wanting to stimulate the use of new products by means of subsidies or tax benefits face a similar dilemma. If such a situation is not addressed in time, not only does the uptake of the technology by users suffer, but also the incentive for manufacturers to invest in the further development.

The need for reliable product information covering all relevant aspects (efficiency, appearance and quality of light and optics) is clear. Such information can only come from measurements. Photometry of incandescent light sources is well established. However, from a measurement perspective, there are significant differences between SSL and incandescent light sources. SSL sources have a different spectral and angular distribution of the light, can be pulsed with high frequency and have complex electrical characteristics. All of these properties make the measurement of SSL sources more difficult than that of incandescent sources. If users or manufacturers are unaware of the peculiarities of SSL and apply classical photometric techniques developed for incandescent sources, large errors can easily be made. This explains at least part of the overly optimistic product specifications. For SSL measurements, dedicated metrology is needed, taking into account the special spectral, angular, temporal and electrical properties of SSL sources.

The importance of the timely development of SSL metrology was enhanced by the decision of the European Commission to phase out incandescent lighting. Motivated by the potential of new lighting technology, on March 18th 2009, the Commission adopted two regulations [2,3] 2005/32/EC with the objective to drive improvement in the energy efficiency of household lamps, and of office, street and industrial lighting products. Production of incandescent lighting products was to be effectively discontinued by 2012 and replaced by energy saving alternatives such as SSL. Quantitatively, the EU Commission estimated in their 18 March 2009 press releases IP/09/411 and IP/08/1909 that the ban of the incandescent light [4]:

> "… will save close to 80 TWh by 2020 (roughly the electricity consumption of Belgium, or of 23 million European households, or the equivalent of the yearly output of 20 power stations of 500 megawatts) and will lead to a reduction of about 32 million tons of CO_2 emission per year. Inefficient incandescent light bulbs will be progressively replaced by improved alternatives starting in 2009 and finishing at the end of 2012. As a result of these regulations, 11 billion euros are expected to be saved and re-injected every year into the European economy. ´These groundbreaking measures respond to the request of the 2007 Spring European Council to the Commission (confirmed by the

European Parliament) to address the efficiency of lighting products both in the domestic and tertiary sectors by 2009. They deliver a clear message about the EU's commitment to reach its energy efficiency and climate protection targets. By replacing last century lighting products by more performant technologies, European homes, buildings and streets will keep the same quality of lighting, while saving energy, CO_2 and money´, said Energy Commissioner Andris Piebalgs."

The challenge to develop a dedicated metrology framework for SSL in Europe was taken up by a consortium of fourteen national metrology institutes (NMIs), three non-NMI partners and three researcher excellence grant (REG) recipients under the coordinatorship of VSL in the project "Metrology for Solid state Lighting". The project was submitted and approved as part of the 2009 Energy call of the European Metrology research Program (EMRP), and started 1 May 2010.

2.2 Project objectives

Starting from the need for reliable and useful information for SSL performance, the measurement issues to be solved were:

- First, the start of any reliable measurement should be a clear link to the definition of the SI units in which the measurement result is to be expressed. This link is called **traceability** and is the core business of the project partners as national metrology institutes. Dedicated facilities and calibration techniques are needed to establish the connection between the SSL products being measured and the primary realizations of the relevant SI units. This includes of course the candela as the base unit for photometry, but since the electrical power consumption is an important factor in the energy savings to be gained with SSL, a solid link to the electrical units volt and ampère is crucial as well.
- Secondly, there should be **measurement methods** to assign in a reliable way values to the defined quality metrics. As stated above, large discrepancies between specification and actual value were not uncommon at the start of the project. The deviations for an individual lamp can be explained in several ways, not all related to erroneous measurements. But the fact is, that at the start of the project, proper measurement methods for the full set of quality metrics for SSL products were not established. The measurement of lighting products had evolved based on incandescent lamps. However, the straightforward application of the techniques and instruments of incandescent photometry to SSL generates a huge potential for errors. With not all users aware of the peculiarities and pitfalls of SSL measurements, and with insufficient SSL-specific methods established, it is not surprising that many honest attempts at product measurement nevertheless resulted in erroneous values.
- Thirdly, there should be a link to the **human perception** of the light. Several quality metrics can be defined to express the color rendition properties of an SSL source, all of which can be calculated from the physical spectrum of the SSL source. However, some of these metrics have a significantly better correlation with the human perception of the colors they produce, being more natural or more pleasing to the eye. Since most SSL is used in lighting applications, the human perception is an important factor to take into account for the deciding the set of quality metrics to be specified and measured.
- Fourthly, there is a clear need for suitable parameters to express the performance of the new, SSL-based lighting products appearing on the market. **Quality metrics** need to be defined, which capture all the essential parameters needed to determine the suitability of a given SSL lighting product for a particular application. These metrics need to be quantitative, objective and measurable. The set of quality metrics associated with an application needs to be complete, to enable an assessment of suitability on all relevant aspects. A single parameter expressing "equivalence" to an existing solution will not suffice.
- Finally, to achieve **impact**, the project results need to be disseminated to the larger community and incorporated in quality control systems, standards for product testing and regulations.

These core needs were distilled into the project's four scientific and technological objectives which were:

1. The development and validation of **traceable measurement facilities** and traceability routes aimed specifically at SSL.
2. The development and validation of basic **measurement methods** for the characterisation of SSL products, including optical, electrical and thermal properties. Both single devices and complete systems will be considered.
3. The implementation of metrics for the **human perception** of SSL.
4. The development and validation of traceable **application specific quality metrics** for the specification of SSL products in a number of target applications.

These objectives represented a significant R&D effort to advance SSL metrology well beyond the state of the art.

The diagram below shows how the scientific and technical objectives are linked to the issues listed above

Traceable measurement facilities	**Measurement methods**	**Human perception**	**Application specific quality metrics**
- Electrical measurement systems - Time-resolved measurements - Mesopic photometers - Spectral effects in measurement systems - Near-field goniometry - Environmental influences	- Electrical characterisation - Efficacy - Goniometric measurements - Lifetime	- Colour quality - Visual comfort - Mesopic and scotopic vision	- Measurement equipment - Indoor lighting - Road lighting - Greenhouses - Art

3 Scientific and technological results and foreground

3.1 Traceable Measurement Facilities and Measurement Methods

Electrical Measurement

SSL light sources are not only different optically from conventional, incandescent sources, they are also different electrically. Whereas incandescent sources are resistive in behaviour, SSL sources feature complex driver electronics and are nonlinear. The electronic signature of SSL products has a complex repetitive non-sinusoidal shape.

Fig. 3.1 shows the current waveforms rich in harmonic and non-sinusoidal shape measured on the same SSL product in the three laboratories. The discrepancies are caused by the source impedance; this really challenges making traceable and accurate electrical measurements for SSL products.

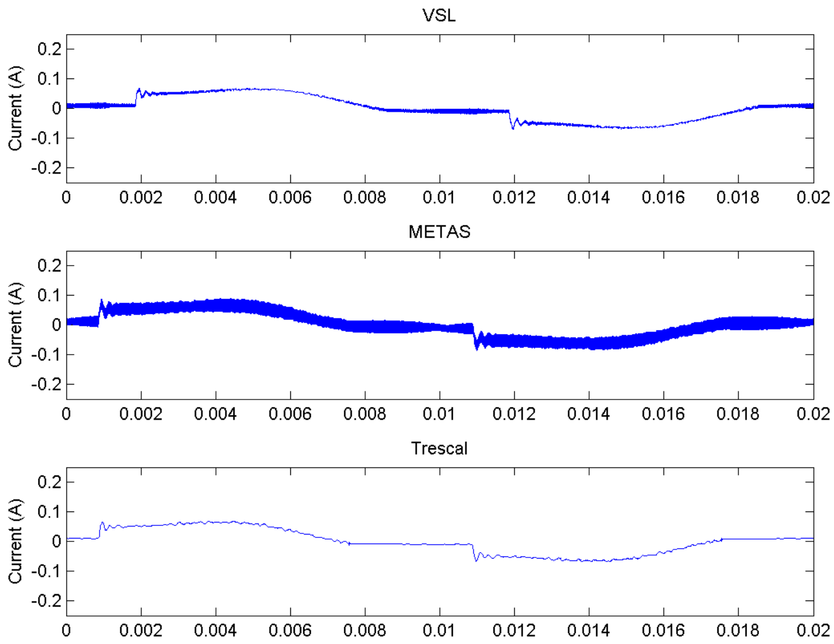

Fig. 3.1: The current waveform of the one SSL product measured by three labs

Highly distorted current drawn by the luminaire leads to a current flow with frequencies other than 50 Hz or 60 Hz. In addition, higher harmonics up to 100 kHz are also introduced when dimmable SSL luminaires are introduced based on pulse width modulation. Fig. 3.2 shows clearly the rich current harmonics and inter-harmonics of a typical SSL product, with several peaks appearing beyond 40 kHz.

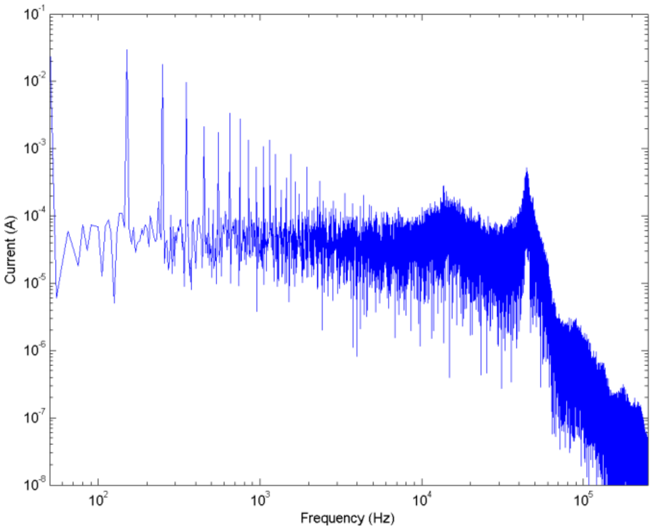

Fig. 3.2: The current spectrum of an SSL product

Since the electrical power consumption of the SSL luminaire determines the energy efficiency (together with the light output), it needs to be measured with sufficient accuracy. Also the power factor is an important parameter, since large-scale implementation of SSL devices with low power factors can deteriorate the power quality and increase losses in the power grid.

In order to perform traceable measurements of electrical parameters of SSL devices, it is necessary to define technically adequate procedures. To gain this kind of knowledge, within the project we have created three different test setups located in three different countries: METAS (EJPD) in Switzerland, Trescal in Denmark and VSL in the Netherlands. The measurement setup from METAS is shown in Fig 3.3.

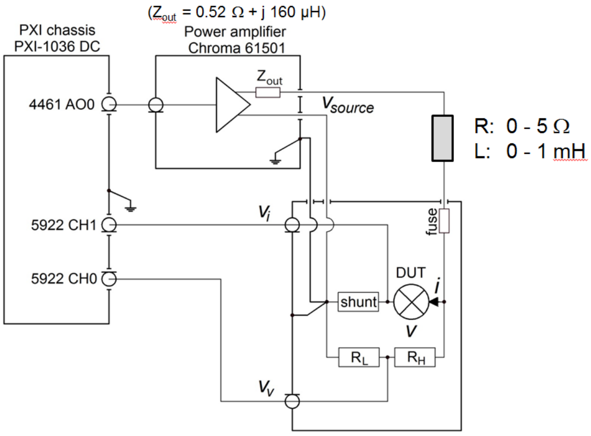

Fig. 3.3: Measurement setup from METAS

These three test setups include hardware and software built independently for the purpose of an intercomparison. The main differences are in the power supplies, voltage dividers and current shunts. The digitizers are from the same manufacturer. Thanks to these different implementations, the source impedance, especially the reactive impedance, was found to be one of the main sources of measurement discrepancies. This finding would not have been made with a single or identical measurement system.

With a thorough investigation, the key uncertainty sources have been identified and a full uncertainty analysis has been carried out. One of the major findings during this EMRP project is that the source impedance has a huge effect on the results. Besides the source impedance, other important uncertainty sources were identified and analyzed. One example of the uncertainty analysis for SSL product is compiled in the guideline produced by the project [5]. In Table 3.1, an example of uncertainty analysis is included.

Uncertainty budget, Voltage

Source	Type	Value (µV/V)	Distribution	k-factor	Sen.-Coef.	Std. Unc. (µV/V)
Calibration voltage channel	B	435	Gaussian	1	1	434.8
Stability after varm-up	B	435	Uniform	1.732	1	251.0
Repeatability	A	210	Gaussian	1	1	210.0
				Combined uncertainty:	544	

Uncertainty budget, Power

Source	Type	Value (µW/VA)	Distribution	k-factor	Sen.-Coef.	Std. Unc. (µW/VA)
Calibration current channel	B	100	normal	1	1	100.0
Calibration voltage channel	B	435	normal	1	1	434.8
Temperature dependence	B	800	Gaussian	1	1	800.0
Influence of power supply THD	B	1800	Uniform	1	1	1800.0
Wiring error	B	32	normal	1	1	32.0
Stablization of EUT	B	2000	normal	1	1	2000.0
Repeatability	A	100	normal	1	1	100.0
				Combined uncertainty:	2844	

Uncertainty budget, Current

Source	Type	Value (µA/A)	Distribution	k-factor	Sen.-Coef.	Std. Unc. (µA/A)
Calibration current channel	B	100	normal	1	1	100.0
Bandwidth error	B	22	normal	1	1	22.0
Ac flatness of current channel	B	1500	normal	1	1	1500.0
Wiring error	B	32	normal	1	1	32.0
Influce of shunt resistor	B	8241	normal	1	1	8241.0
Stablization of EUT	B	2000	normal	1	1	2000.0
Repeatability	A	200	normal	1	1	200.0
				Combined uncertainty:	8615	

Table 3.1: Example of uncertainty analysis

During the EMRP project VSL, METAS and Trescal have aimed for the best measurement capability when measuring electrical parameters of SSL lamps. To evaluate measurement capability stated by the three partners earlier in the project a comparison has been carried out. Three sets of commercial available LED lamps were purchased, one set for each lab. In each set, there are five lamps of different models, noted as L1-L5. The lamps were circulated between the labs and electrical parameters such as RMS voltage, RMS current, active power, apparent power, power factor and total harmonic distortion were measured.

In Fig. 3.4, the comparison shows relative deviation from the mean (one mean of 3 lamp samples for each lamp model). The y-axis is the relative deviation and the x-axis is the lamp model. The RMS current measurement results are compared. Full details can be found in the comparison report [6].

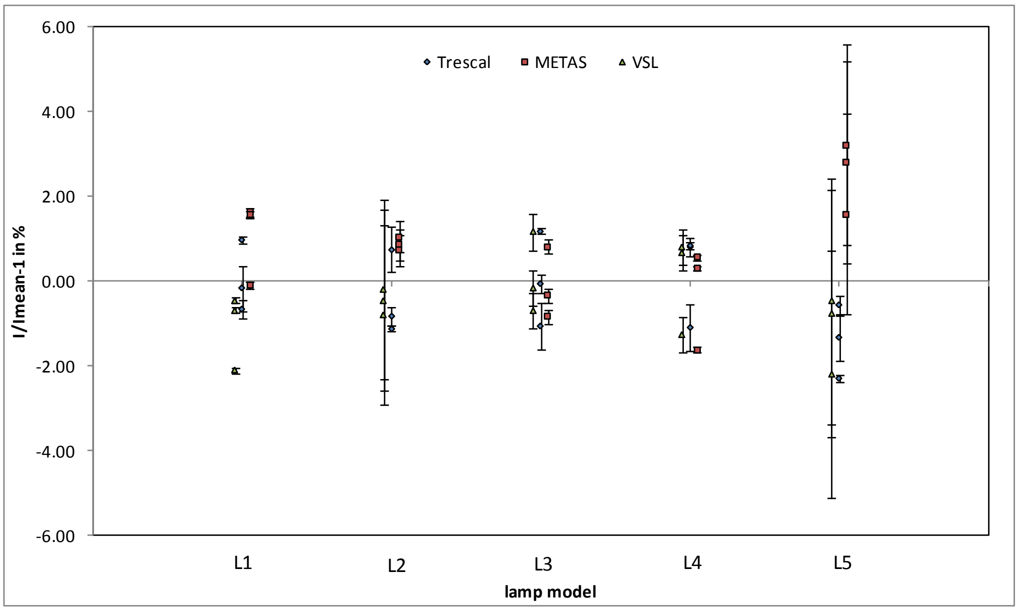

Fig. 3.4: The comparison of relative deviations of the measured Irms

At the end of a four month measuring period the following conclusions were made:

- Generally, the uncertainty of power measurement can be estimated at NMI's to be within 0.3-0.6% for SSL products. The uncertainty depends strongly on SSL products themselves.
- For RMS current measurement, the uncertainties for some special lamps were as high as 3%. The large uncertainty of RMS current measurement has three reasons. The first reason is that the measurement has larger uncertainty at higher frequencies. This is due to the characteristic of the digitizer and the transducers used for the measurements. If the lamps have rich harmonics in the high frequency range, the total uncertainty increases. The second reason is that the setup includes not only the lamps, but also the cable, of the power supply, the connections is parts of setup, which varies for different measurements. The third reason is that the transducers (mainly the current shunt) can change the current waveform of the total setup including the lamp. This is a significant uncertainty source for some lamps with large peaks in current waveform.
- Uncertainty analysis for electrical measurement of SSL products never appears in literature. In this project, the participating laboratories did the initial investigations. It is concluded that for SSL products, with rich high frequency harmonics, the uncertainty calculations of electrical parameters should follow a new approach. The approach is included in the guideline produced by the project.
- The electrical assessment of SSL products depends heavily on the source impedance. To achieve adequate reproducibility in these measurements, a method using a source impedance stabilization network is proposed and published in a CPEM paper [7]. This method will be further developed in the future.
- The power factor is highly sensitive to the bandwidth of measurement system. Fig 3.5 below shows that when the measurement bandwidth increases, the PF measurement results decreases. This is caused by the inclusion of higher frequency harmonics and inter-harmoncis in the Irms measurement result directly increases the apparent power. The active power is not affected by the bandwidth due to the fact that the active power is concentrated at 50 Hz, with no harmonic active power flows.

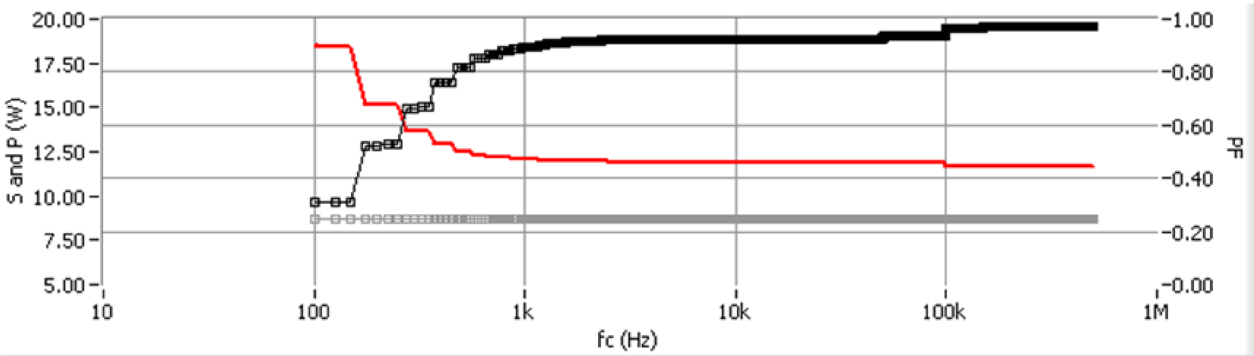

Fig 3.5: The PF (red) and apparent power (black) dependences of bandwidth of measurement system. The active power (gray) is not affected by the bandwidth.

Efficacy determination

The efficacy of SSL, defined as the ratio between the total luminous flux and the electrical power consumption and expressed in lumen per watt (lm/W), is the key parameter for evaluating the potential for energy saving. It is therefore important to establish the state of the art in efficacy determination, and for this reason, a comparison featuring different types of SSL products was organized between the various European NMIs participating in the project.

This comparison is the first of its kind within Europe. In total, ten NMIs participated, of which three used goniophotometers and seven integrating sphere goniometers. The artefacts chosen for the comparison were an omnidirectional E27 replacement bulb (Philips Master LED), a directed spot light (Osram PAR 16 20 CW 20º), a retrofit tube light (RetroFix SMD Clear Tube 120 cm) and for control purposes a conventional 100W incandescent lamp. In all, nine sets of artefacts were used, used by the pilot laboratory (VSL) to the other participants in a star-shaped scheme, as illustrated in Fig 3.6. This particular organisation form was chosen to avoid problems resulting from the stability of the lamps and to minimize the overall duration of the comparison.

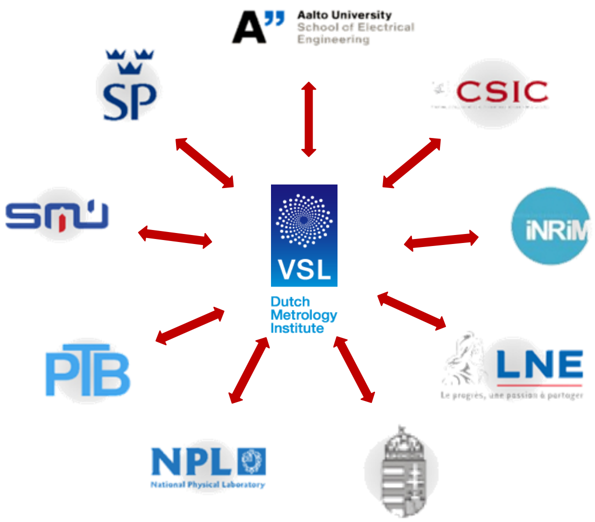

Fig 3.6: Comparison scheme

The prescribed measurement procedure was deliberately kept to a minimum, in order to have the measurements carried out as much as possible according to the own normal calibration practices of the participating laboratories. For the electrical input, the voltage was specified as 230 V 50 Hz. The ambient temperature was specified as (25 ± 1) ºC, to be measured at the same height and within 1 m oft he lamp. All artefacts were seasoned by the pilot for 100 h and a stabilization criterium of 0.5% within 30 min was prescribed for both the light output and the electrical power.

Fig. 3.7 shows the comparison results for the luminous efficacy of the four lamps. The reference value is the weighted mean of all participants with an upper limit on the weights of laboratories claiming very low uncertainties (in accordance with standard practice).

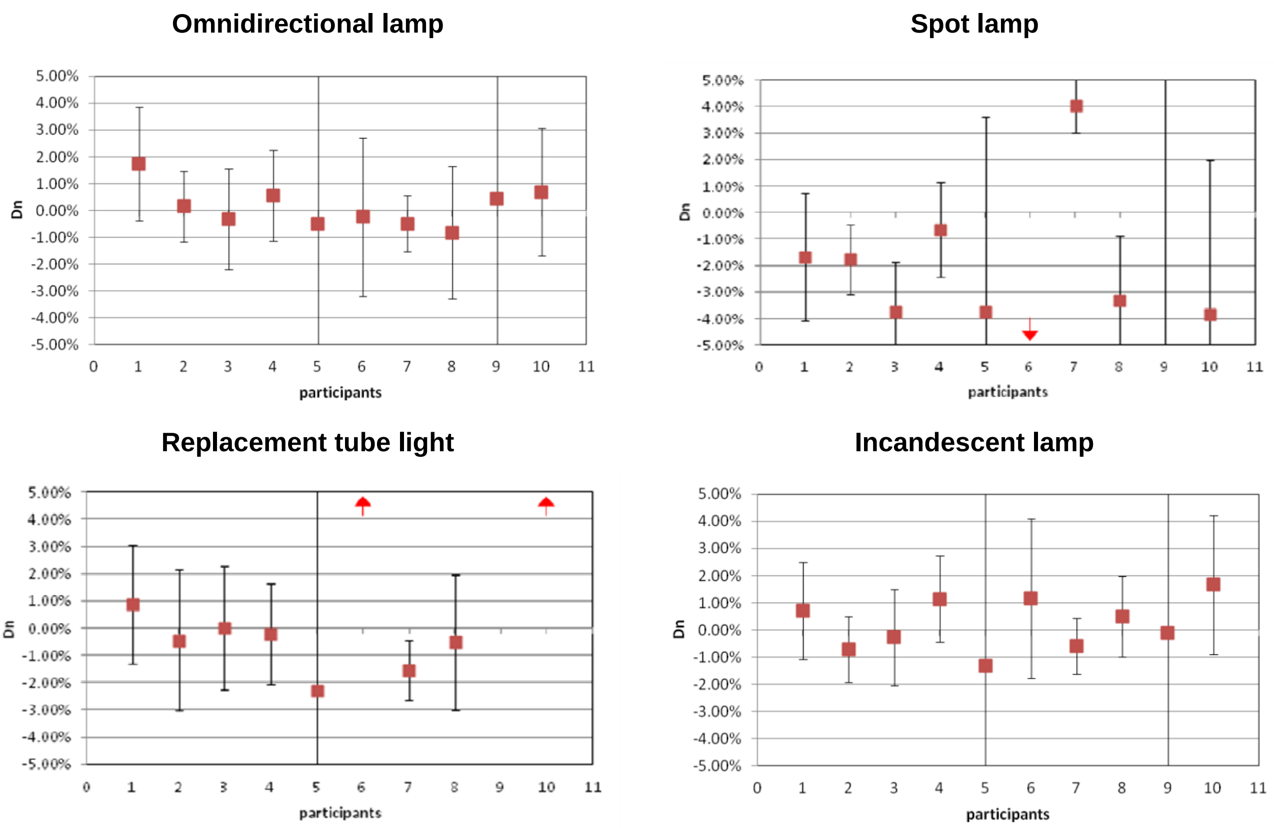

Fig 3.7: Comparison results for the luminous efficacy determination of the four different lamps. The parameter Dn on the vertical axis is the unilateral degree of equivalence, i.e. the relative difference of the participant result with respect to the reference value. The bars denote the 95% uncertainty interval.

Among the various LED-based lamp types tested, the participants data for the spot lamp (lamp 2) showed, relatively, the largest deviations, from the reference values for the photometric and colorimetric quantities. There were two extreme outliers in the data from the participants for the TL lamp (lamp 3) particularly on luminous flux and luminous efficacy measurements. For this particular lamp, several participants mentioned some difficulties in conducting the measurement. However, if the outliers are excluded then there is a relatively good agreement between the values from the rest of the participants and the reference values for the TL lamp. For the control lamp (lamp 4), the participants' values for the various photometric, electrical and colorimetric quantities, in general, have less deviation from the reference values compared with the other three SSL lamp types. The CCT values from the participants showed the most deviations from the reference values, for all lamp types, compared with other photometric, electrical and colorimetric quantities. These large deviations of the colorimetric quantities demand some further attention, and perhaps a good subject for a new stricter comparison activity in the future.

Spectral measurements

Due to the variability of the spectral composition of lighting installations using SSL devices, classical broadband measurements using photometers and colour-measuring tristimulus heads are insufficient to describe the light. Spectral measurements using rapid, often hand-held array spectroradiometers are more and more in use, where the spectral integration and weighting of the measured result is accomplished by a simple mathematic procedure taking all characteristics of the instruments as ideal. However, to produce reliable and traceable measurement results with comparable uncertainties with respect to properly characterised photometers, a couple of influencing variables have to be considered. The work done by partners PTB, NPL and VSL showed how to perform the measurement and the data analysis in such a way that traceable results are obtained. The three partners focused on different aspects of spectral measurements.

Investigations on spectroradiometers were mainly carried out by PTB. The typical behaviour of various types of instruments with respect to stability and linearity was examined. Procedures were developed by PTB, how to measure and correct for spectrally dependent instrumental stray-light and how to determine concurrently the real spectrally dependent band-path, i.e. the distortion from the ideal slit function of the spectroradiometer system. The result of these procedures, based on laser assisted measurements of the spectral line spread functions at various wavelengths, is a stray-light and band-path correction matrix which can be used to correct the distorted, erroneous measured spectrum. A typical result of this correction is shown in Fig. 3.8. It was found that such a correction is important for all applications where the chromaticity coordinates of LEDs (e.g. for binning) are of interest.

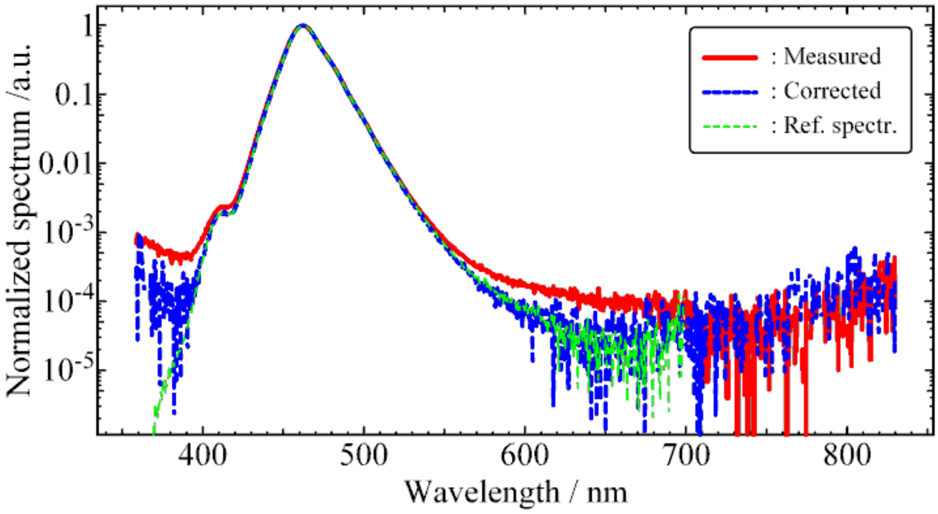

Fig 3.8: Spectral correction result

Once the corrected spectral measurement data points are available, the question about the correct determination of the integrals of the measured spectral quantities appears. This question was comprehensively discussed by NPL and published in the report “Determining the uncertainty associated with integrals of spectral quantities” [8]. This report

- describes how integrated quantities are calculated numerically from measured data
- shows how uncertainty analysis relates to spectrally measured quantities
- gives an introduction to correlation
- applies those concepts to spectral integrals using error models and covariance matrices
- and deals with the problem of chromaticity calculations

Finally, in industry, spectroradiometers are very often used in integrating sphere applications to determine the total luminous flux of SSL devices. Performing measurements with integrating spheres, it has to be taken into account that fluorescence caused by irradiation in the short wavelength range may distort the measurement result in two cases:

1. the dominant UV-peak of a phosphor LED is reflected by the sphere wall causing a secondary conversion effect at the LED-phosphor. This effect may be increased with remote phosphor LEDs
2. the dominant UV-peak of a phosphor LED or the UV-content of the reference source used for calibration of the sphere spectrometer produces fluorescence in the PTFE or BaS04 coating of the sphere wall.

In both cases, the measured total luminous flux measured in a sphere will be different from that measured in e.g. a goniophotometer. VSL investigated both aspects and provided the evaluation of possible errors.

In summary, due to the narrow peaks in the SSL spectrum, accurate spectral measurements are very important. A common measurement setup for SSL consists of an integrating sphere in combination with an array spectroradiometer. Development of guidelines on the calibration and use of such setups including uncertainty estimation have been developed in the project. An important aspect of array spectroradiometers is the correction for band-pass and stray light. A correction method based on a calibration with tunable lasers and the calculation of a correction matrix was developed, using a new approach to ensure numerical stability.

Goniometric measurements

High Power LEDs are high efficient point sources providing extremely high luminance levels. To make them usable for general lighting and to avoid glare, external optical components in front of the LEDs are used to direct or diffuse the light output. In order to determine the effect of these optical components ("light engine"), knowledge of the precise spatial and angular luminous distribution (ray files) of LEDs is essential. At present, industry is only able to deliver example ray files with limited spectral information and without any given uncertainties or tolerances. The situation is even worse if luminaries have to be developed using LED assemblies. Lighting designers suffer from this information deficiency, which results in inefficient, and poor light designs.

CSIC determined the angular and spectral illuminance distributions, as well as illuminance dependence with distance, from different LEDs. High brightness as well as high power LEDs with different angular and spectral distribution were selected. The setup used for the measurements is shown in Fig. 3.9.

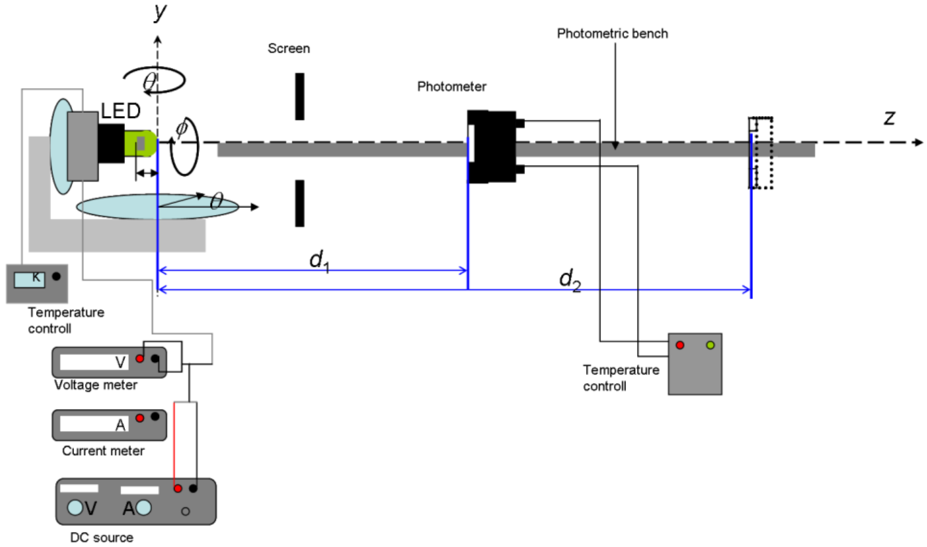

Fig. 3.9: Setup for the illuminance measurements as a function of distance

As a result, a general modified inverse-square model has been obtained. The general model, which can be simplified depending on the type of LED, includes effects of effective radii of virtual source, photometer aperture of detector used and the offset (∆d) of the LED virtual source with respect to the front tip of the LED. The best results for high power white LEDs were obtained when considering the complete model. A simplified model considering only the effects of ∆d can be used for high power colour and high brightness LEDs. Results are shown in Fig. 3.10.

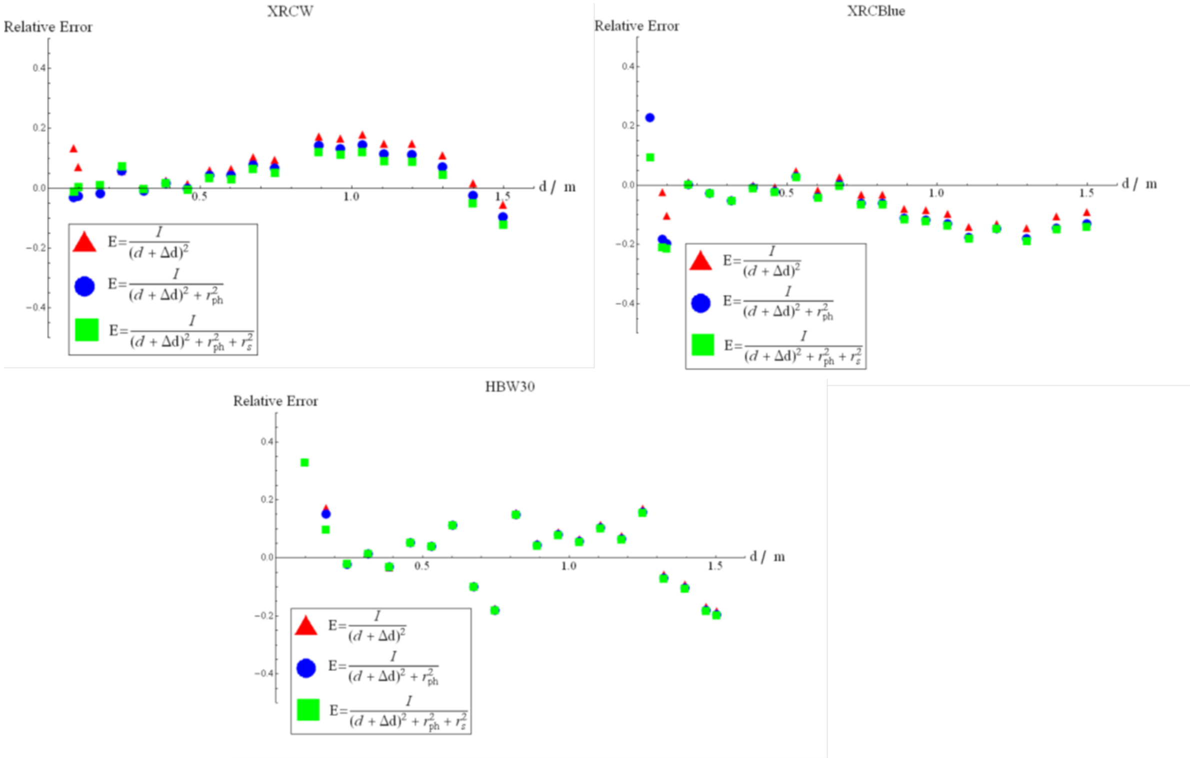

Fig. 3.10: Relative differences (in %) of the experimental illuminance and the calculated illuminance for a high power white LED, a high-power blue LED, and a high brightness white LED.

For a set of single high power LEDs the thermal and temporal dependencies was comprehensively investigated by PTB using various methods for traceable measurements. It has been shown that the luminous output as well as the chromaticity coordinates of LEDs is pretty stable after an initial burn-in period. Typical changes of the luminous intensity of white and coloured LEDs during 1200 hours of operating time are in the range of some 10^{-6} per hour. Roughly same changes were measured for the chromaticity coordinates of the radiation. Hence, high power LEDs are very well suited as reference standards, provided that they are properly seasoned, which may take up to 200 hours of operating time (in some cases even more).

In addition to the axial measurements, selected points on the surface of the same LEDs (i.e. selected rays) were also characterised using camera based near field measurements. The angular luminance distributions of the warm-white LEDs observed were nearly perfect Lambertian and this did not vary with the selection of the “blue” and “yellow” components. Despite of this, there was the typical shift in correlated colour temperature for flat angles clearly visible. However, the cool-white LEDs investigated show a significant change in the angular luminance distribution for the “blue” region. Moreover, the measurement results of the luminance distribution show an aging dependent increase of the non-uniformity of the phosphor layer of the LEDs increasing the “roughness” of the angular luminance distribution with operating time.

The thermal investigation of the luminance distribution of the LEDs show that for uniform LED chip structures the luminance level decreases very uniform along the chip surface with higher LED chip temperatures.

Nowadays, so called 5 dimensional ray-files are used to fully describe the optical behaviour of sources. The provided results are very important, as local changes of the luminance and colour of LEDs can directly influence the ray data condensed in such ray-files. As a conclusion it may be summarised that, taking the actual estimated uncertainty of luminous distributions calculated from ray-file data into account, the thermal and temporal changes in the luminance characteristics of single LEDs will increase the noise but will most cases not affect the averaged outputs generated by ray-files which are determined under standard test conditions.

Ray files are typically determined using near-field goniophotometers. One goal of this project was to develop procedure to assign uncertainties for the calculation of LEDs using ray-files and to write a guideline for the calibration of near-field goniophotometersThe basic principle of measurement and known uncertainty components have been investigated using examples. But not all camera-related components are quantifiable by users – especially if hidden camera-internal correction procedures are implemented. In these cases the user has to rely on the data from the manufacturer.

At international level, the technical committees TC2-59 and TC2-62 of CIE are working on the characterization of imaging luminance measurement devices and near-field goniophotometers. However, not all characteristics dealing with cameras and near-field goniophotometers are finally discussed up to now. Therefore, the given model of evaluation in the report and the uncertainty budget is the build-up of the most important components to describe the uncertainty of a luminance image of a LED source which have at least to be taken into account. The most dominant components in the budget are the calibration factor of the camera, which converts the pixel response to a luminance value and the signal noise, which strongly depends on how many pixels may be clustered to describe the luminance at a locus of the source to be uniform.

The uncertainty of the angular luminance distribution was calculated for five selected locations on a high power LED, represented by a cluster of 3 x 3 camera pixels each, at nine different angles in a plane (i.e. for 45 rays) using a Monte Carlo method. As this process is very time consuming, it is strongly recommended to use only a few defined positions at critical locations on the source to describe the variability of uncertainty for single rays.

The validation of the near-field data was accomplished by comparison with far-field measurements. Near-field and far-field measurements have be carried out at PTB using the same goniometer setup to minimise systematic effects. Two different metrics were used describing the matching index of the different luminous intensity distributions. For the setups used at PTB, the averaged deviations were in the range of ≤ 3 %.

In conclusion, as lighting design depends heavily on models which take as input information in the form of ‘ray files’ that contain the angular and spatial distribution of light coming from a source. Traceable facilities for the determination of such ray files have been developed and these have been used to validate and improve models for the light distribution from high-power LEDs. An important issue is the reliability of the modelling predictions against deviations from the input ray files due to e.g. aging or temperature effects. These effects have been investigated in the project and recommendations for improved procedures for using input ray files for lighting design have been produced.

Environmental dependence

One of the application areas where the adoption of SSL can lead to considerable energy savings is in outdoor lighting, e.g. for street lighting. The performance of SSL sources however can be highly temperature dependent. The spatial luminous intensity distribution and spectral distribution may change significantly when the junction temperature is changed by a few Kelvin. For this reason the rated efficacy and other metrics are specified at one (non-practical) ambient temperature, typically at 25°C. In practical applications the ambient temperature can vary from below freezing point to more than 30°C. Methods for predicting the effects of this temperature variation on the SSL performance are therefore needed.

VSL has developed a special instrument to instantly measure the angular distribution of light from e.g. street light sources. For experiments where the temperature is varied, or which are performed outside, it is important to capture the light output for all angles in one go because of drift. A scanning measurement will typically be too slow to get reliable data. The instrument, shown in Fig. 3.11, consists of a semi-arc containing an array of parallel photometers, to perform an instantaneous measurement of one C-plane.

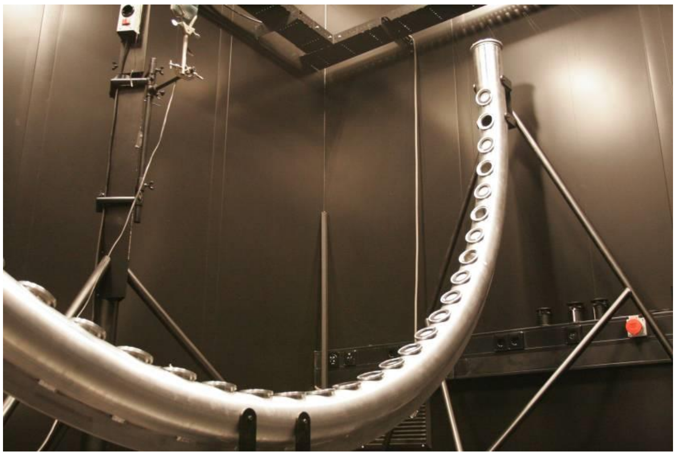

Fig. 3.11: Instrument for instantaneous C-plane measurements

The main outcome of the investigation showed that environmental temperature variations have insignificant effect on the spatial distribution of the illumination of SSL products (both indoor and outdoor).

Lifetime estimation

SSL devices are claimed to have long lifetime, most rated with 50 % - 70 % lumen maintenance after 30.000 to 50.000 hours of operation. Verifying such long lifetime claims directly is not practical and there is a need to find alternative methods for predicting the lifetime of SSL products. However, reliable lifetime estimation is found to be non-trivial and very difficult to model. Given the complexity of lifetime prediction, the project focussed on monitoring junction temperature and spectral changes of SSL products, as these are believed to be intimately connected to SSL lifetime. Also existing ageing tests capabilities were used to evaluate current state-of-the-art in lifetime measurements. Using elevated temperatures accelerates the ageing process allowing testing to be performed in a much shorter time and so provides time for more testing to be done and thus more accurate estimations of product lifetime.

Five different types of LED lamps from Osram and Philips were studied for their ageing by LNE and Aalto. LNE performed two 6-month accelerated ageing tests on two sets of the lamps at the elevated temperatures of 45 °C and 60 °C. The results were compared to those obtained with the natural ageing conducted at Aalto on a third set of lamps. To the authors' knowledge, there is no published work comparing natural and accelerated ageing of lamps/luminaires. Results are shown in Fig. 3.12.

In three of the five lamp types, the ageing behaved as expected. The luminous flux of the lamps gradually decreased. In two of the lamp types, the luminous flux was constant or even increased with time. The results clearly show that ageing can be accelerated with operation at elevated temperatures. If the two lamps not ageing are excluded, heating to 45 ºC accelerates the ageing by a factor of 3, and heating to 60 ºC by a factor of 4.5. If the two lamps not ageing are included, these numbers reduce to 1.3 and 3.

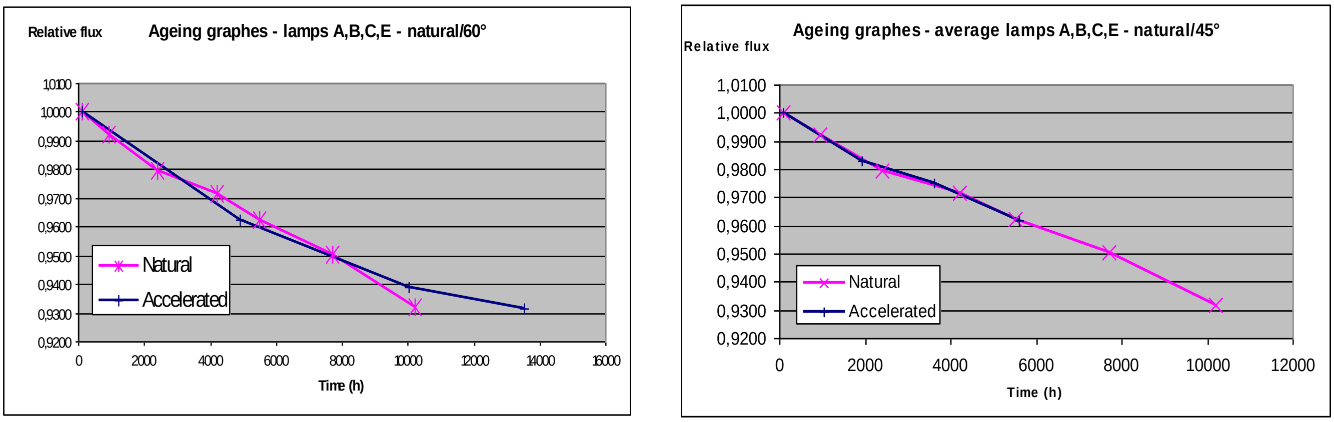

Fig. 3.12: Flux deprecation with natural and accelerated ageing at 45°C (left) and 60°C (right) averaged on 4 types of lamps (4 samples per type for natural, 3 samples per type for accelerated). The time scale for accelerated ageing at 45°C and 60°C are respectively multiplied by a factor of 1.34 and 2.96. The good match between natural/accelerated – especially for 45°C - curves demonstrates the effectiveness of ambient thermal stress to accelerate ageing of SSL.

The electronics did not get damaged, and only one LED broke in all tests. This work shows the potential of accelerated ageing by thermal stress and could be used for lifetime expectancy determination of lamps/luminaires with reduced test time. Group efforts of the participating laboratories were essential for conducting the work.

Aalto and MKEH together studied the possibility of deriving the junction temperature of an LED from its spectrum. Characterisations needed to apply the results to lamp measurements were also considered. The five lamp types studied in the project were disassembled resulting in five LED types to study.

MKEH first measured the electrical-thermal behaviour of the LEDs using oil baths and electrical measurements, as shown in Fig. 3.13. Short current pulses were fed to pre-heated LEDs, after which the forward voltage measured could be used to derive junction temperature of a lit LED. Aalto measured the same LEDs for their spectra at varied junction temperatures. The oil baths and the electrical expertise of MKEH nicely complemented the spectral measurement facilities and knowledge at Aalto.

Fig. 3.13: Circuit boards containg the LEDs were removed from the lamp housings for measurements. The left figure shows LED boards of Philips Masterled lamps, with external wiring soldered to them. The figure on the right shows how the circuit boards were immersed in a an oil bath to control their temperatures, and the electrical characteristics were measured through the external wiring.

A Maxwell-Boltzman distribution was fitted to the spectra of red, blue and white LEDs. Results are shown in Fig. 3.14. It appeared that a practical method for obtaining the temperature for an LED spectrum can be derived, but it is more complicated as anticipated. Uncertainty of 5 K should be achievable. The electrical-optical relationship of the LEDs vary, even within one LED type, which means that at least one supplementary measurement on each LED specimen is needed to accurately obtain the temperature. When measuring the spectrum of the lamp, the apparent temperature obtained represents the average of the temperatures of the individual LEDs.

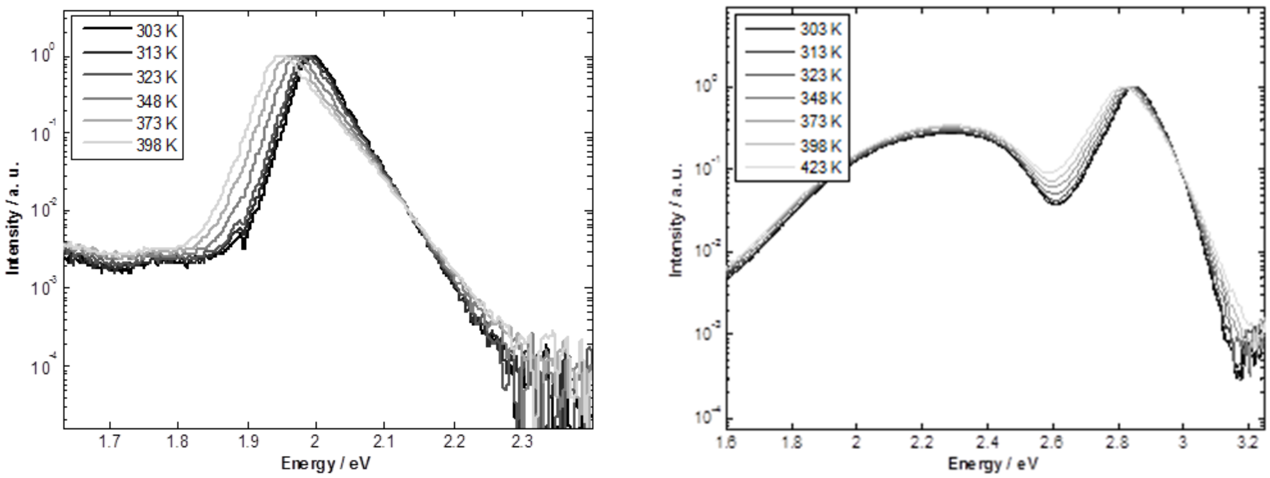

Fig. 3.14: Left: Normalised spectra of a red LED at various temperatures. The high energy side of the spectrum follows Maxwell-Boltzman and the slope is proportional to temperature. Right: Normalised spectra of a white LED. The Maxwell-Boltzman distribution is present on the high energy side, but other phenomena complicate the structure.

This was the first study reported to

- model the spectrum of white LEDs;
- to model the spectrum of commercial LEDs actually used in lamps;
- to consider inter-specimen variations of LEDs;
- to study relationships between lamp spectra (temperatures) and individual LED spectra (temperatures).

Several findings merit publishing:

- new type of temperature controller at Aalto with combined liquid cooling and resistor heating;
- experiences with spectral modelling;
- application of modeling to lamps.

The research produced systematic datasets of spectra as a function of junction temperature for 6 types of LEDs and various specimens.

In a parallel investigation, NPL developed a completely new method to determine the junction temperature of an LED using the fact that LEDs can be used to detect light as well as emit it – producing an electrical signal when illuminated. The principle is summarized in Fig. 3.15. The temperature of an LED can be measured with great accuracy while it is in use and without the need for any extra measuring equipment – just a slightly different drive circuit. The finding enables new type of adaptive lighting control utilizing the in-situ junction temperature measurement for better accuracy and efficiency. The research resulted in two patents.

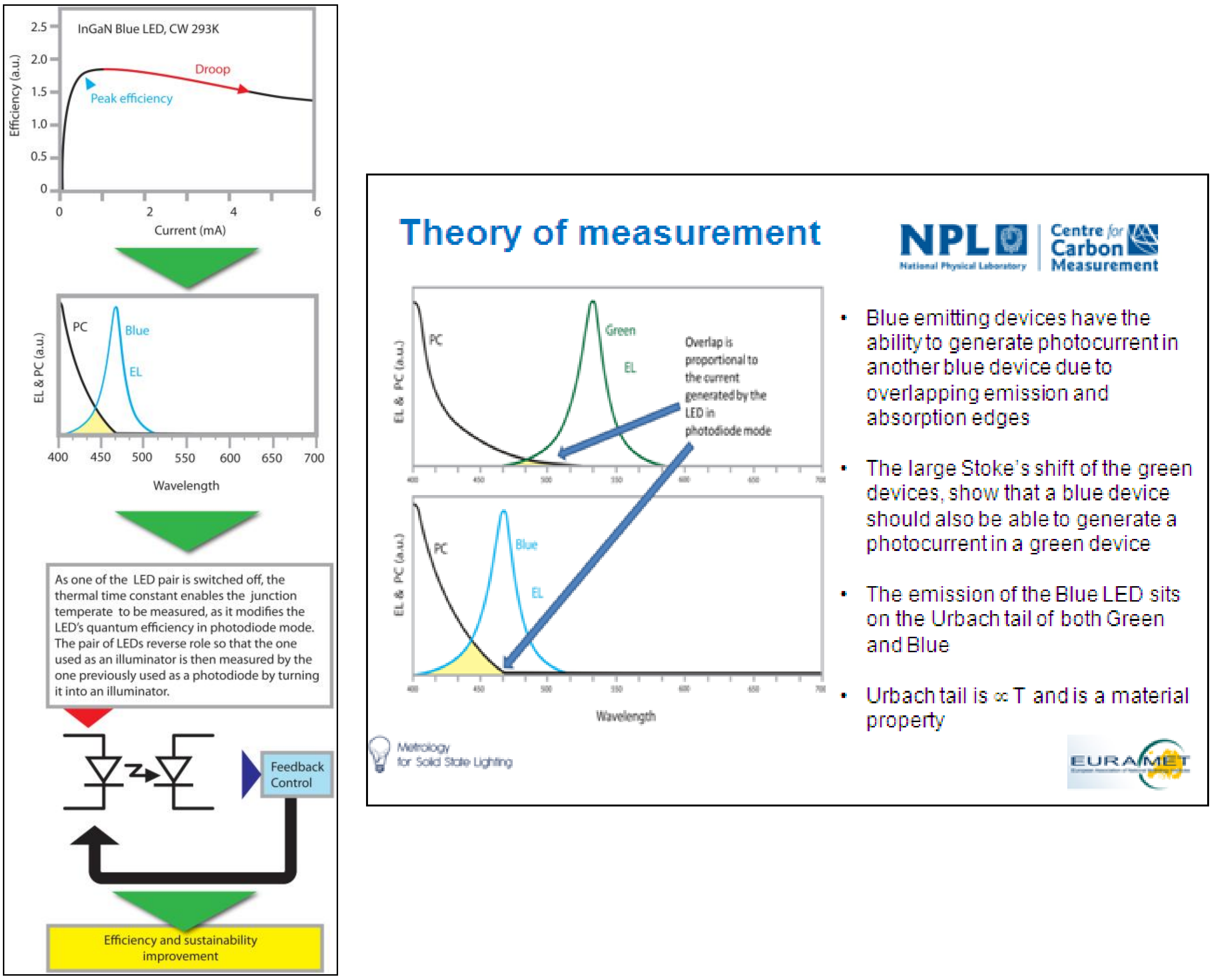

Fig. 3.15: Patented NPL junction temperature method

The main outcome of this work is the ability to perform accurate accelerated aging using heat. This can reduce testing time by a factor of 4. This work has resulted in two patent applications being made relating to junction temperature measurement, ultimately leading to better life-time prediction.

3.2 Human Perception

Mesopic Conditions

Although the scotopic efficiency function of dark adapted human eyes for low luminance values has been already standardized since 1951 and adopted by CIPM in 1982, nearly all photometric measurements and all traceable calibrations are carried out with respect to photopic conditions only. Measurements in the scotopic and intermediate or mesopic regime (in the range of 5 mcd/m² to 5 cd/m²) are however becoming increasingly important. A good example is road lighting, where good design in the mesopic conditions can have a great economical and environmental impact. Road lighting is also one of the main application areas for SSL. The spectra emitted by SSL luminaires change with the angular direction of emission, so the ratio photopic/mesopic luminous intensity is not constant with direction. As a consequence, a road lighting installation designed considering photopic quantities could not satisfy uniformity and average requirements when measured in mesopic conditions.

The CIE 191:2010 documentation provides the fundamental algorithms to implement mesopic photometry based on photopic and scotopic measurements. As part of this project, PTB has set up up the first calibration chain for scotopic and mesopic instruments, using specially designed and extensively characterised photopic and scotopic illuminance and luminance meters developed by the collaborating company LMT. Following the metrological calibration chain for photopic luminance meters via luminous intensity standards, the photometric sensitivity of illuminance meters and the determination the average luminance of luminance standards, it could be shown that the scotopic calibration of luminance standards is possible at an uncertainty level of 0.6%. This leads to an uncertainty for the calibration factor for a scotopic luminance meter in the range of 2%, while the uncertainty for the calibration of a photopic luminance meter is about 1% depending on the field of view and the quality of the instrument. The linearity of the used instruments from LMT, and hence, the operating condition of the traceability chain was characterized down to illuminance values of 10 mlux at one meter distance according to luminance values of 10 mcd/m², respectively.

Aalto and CMI developed and produced a two-channel spot luminance meter utilising photopic and scotopic measurement channels, and using the algorithms from CIE 191:2010, had the potential to measure in the mesopic region. The finished instrument is shown in Fig. 3.16. Expertise of both participants was a key factor in developing the device. CMI built the high-sensitivity electronics for the device, and Aalto used their optical experience in designing and building the optical and mechanical parts of the luminance meter. This device is the first of its kind and capable of measuring down to the scotopic luminance levels. The noise level at the (high) scotopic region is below <1%. The photometer quality factor f1' is 3.6% for the photopic and 6.0% for the scotopic channels. The linearity over the region 0.005 cd/m2 – 0.5 cd/m2 is better than 0.3%. Measurement uncertainty of 3% is presently achievable and can be improved to 2%. The measured response curves are shown in Fig. 3.17.

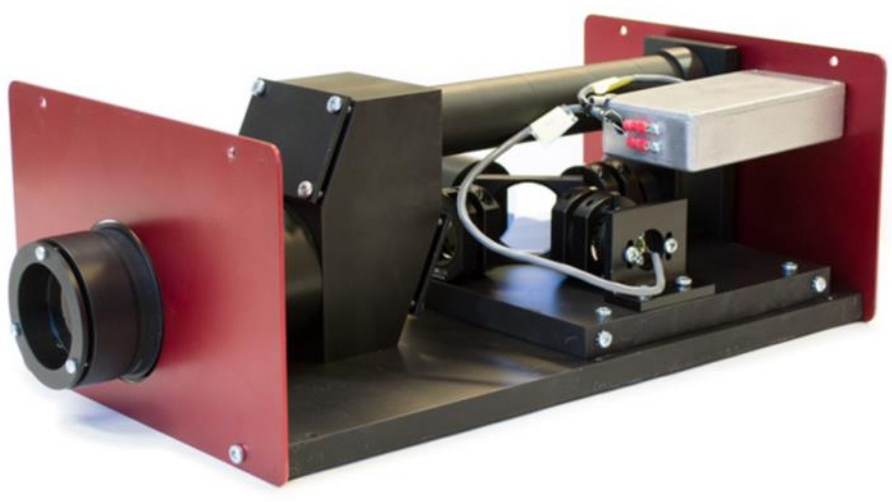

Fig. 3.16: Scotopic-photopic luminance meter with its cover removed. The grey box contains the low-noise amplifiers used to amplify photocurrents of the two photodiodes measuring photopic and scotopic luminances.

This instrument has therefore been demonstrated to be capable of measuring directly luminance values under mesopic conditions. However, to be applicable in practical situations, the knowledge of the adaptation level described by the value of the photopic/scotopic mixing parameter *m* is indispensable. CIE is working on the determination of *m*. However, during the runtime of this project, there was no agreed procedure available, but they are close to. Hence, it will be the task of a future project to implement the determination of *m* into the developed instrument from Aalto and CMI and to show its realizability. From scientific point of view it was demonstrated that building a two-channel device is feasible, and the signals remain measurable. Special emphasis has to be given to the electrical measurements, as the currents are of the order of 0,1 pA already in the high scotopic region.

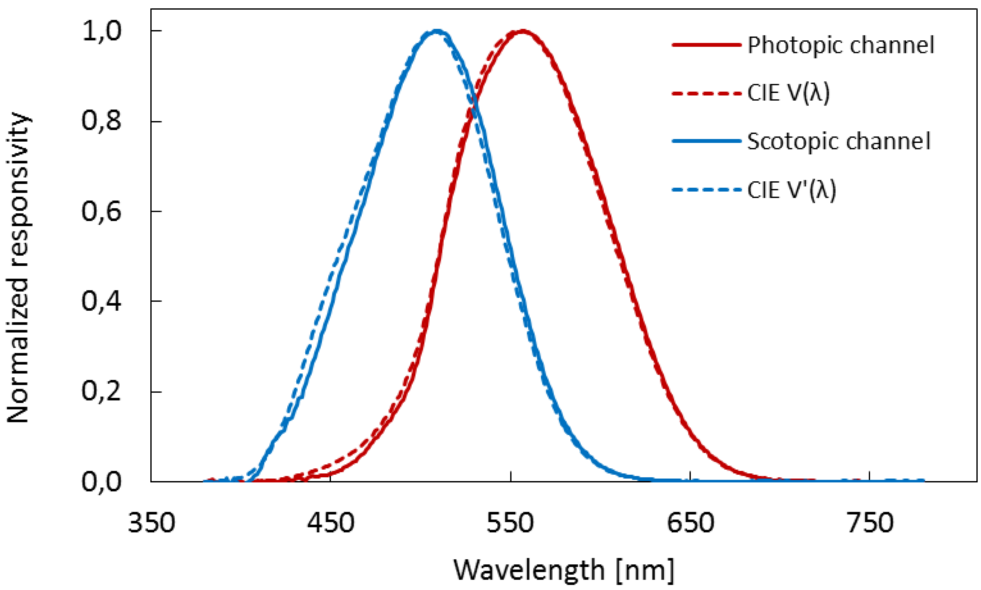

Fig. 3.17: Measured responsivities of the photopic and scotopic channels as compared to their target values. The photometer quality factor f1' is 3.6% for the photopic and 6.0% for the scotopic channels.

Although the viewing conditions in many applications, at night-time or within barely illuminated environments like street lighting or road-tunnels, is in the mesopic range of the sensitivity of the human eye, the lamps and luminaires used for such illumination are, according to current standards, characterized under photopic condition. However, to evaluate the scotopic and especially the mesopic effectiveness of such sources, spectral information is indispensible. INRIM developed a measurement system useable for industrial testing laboratories to additionally perform traceable measurements to spectrally characterize the luminous intensity distribution of luminaires. The measurement system, based on a calibrated high-end photometer with f_1'< 1%, and a spectroradiometer for the wavelength range from 350 nm to 850 nm was installed in INRIMs goniometer with a working distance of 2,793 m. Example measurements of an LED luminaire used for tunnel lighting show, how beneficial such additional data is. The achieved uncertainty for the measurements is in the range of 1%.

For data transfer, i.e. to transfer lamp data and lamp characteristics from the manufacturer to the lighting designers, defined file formats are used. For the EU currently the CEN file format for electronic data transfer is defined in EN 13032 part 1. It is a slightly modified version of the international file format described in CIE 102:1993. However, these formats are not really suited to include comprehensive spectral information needed for the characterization of lamps which are used also in mesopic conditions. In the "Report on suitability of spectroradiometers for scotopic and mesopic luminance – illuminance measurements" [9] INRIM provides two proposals for future data file formats to be implemented in current international or CEN or CIE standards but also a proposal for a file format based on Extensible Markup Language (XML) format.

The detector developed by INRIM was used for some field trials: the procedure is to evaluate photopic luminance and illuminance on the normative grid and, at the same time to obtain information about the spectrum of the incident radiation (illuminance) or reflected radiation (luminance). Based on the illuminance and luminance levels it is possible to determine the correct adaptation coefficient *m* of the mesopic model and to evaluate the mesopic efficacy of the lighting plant, and finally that provides the opportunity to introduce visual conditions and lighting levels relying on mesopic conditions in future standard requirements.

Colour rendition

One of the pressing problems in SSL metrology is the lack of a universally accepted quality parameter to express colour rendition. The International Commission of Illumination (CIE) does not recommend using the current developed Colour Rendering Index of publication 13.3 to rank a set of light sources comprising LED-based light sources. Many proposals of colour rendering metrics have been published, but CIE has not yet endorsed any of these proposals while diverging opinions exist among CIE members.

Within this project, LNE together with SMU addressed the complex issues of colour rendering for interior lighting. The main goal was to assess the current metric and proposed alternatives.

First of all, to analyse the current state-of-the-art of new research on colour rendering, all proposed metrics by key principles, the calculation methods identified and the related subjective experiments, if available, considered. This literature review with in-depth analyses of principles, methods, and supporting subjective experiments has been reported in detail in a report, featuring also approaches and conclusions of the authors [10].

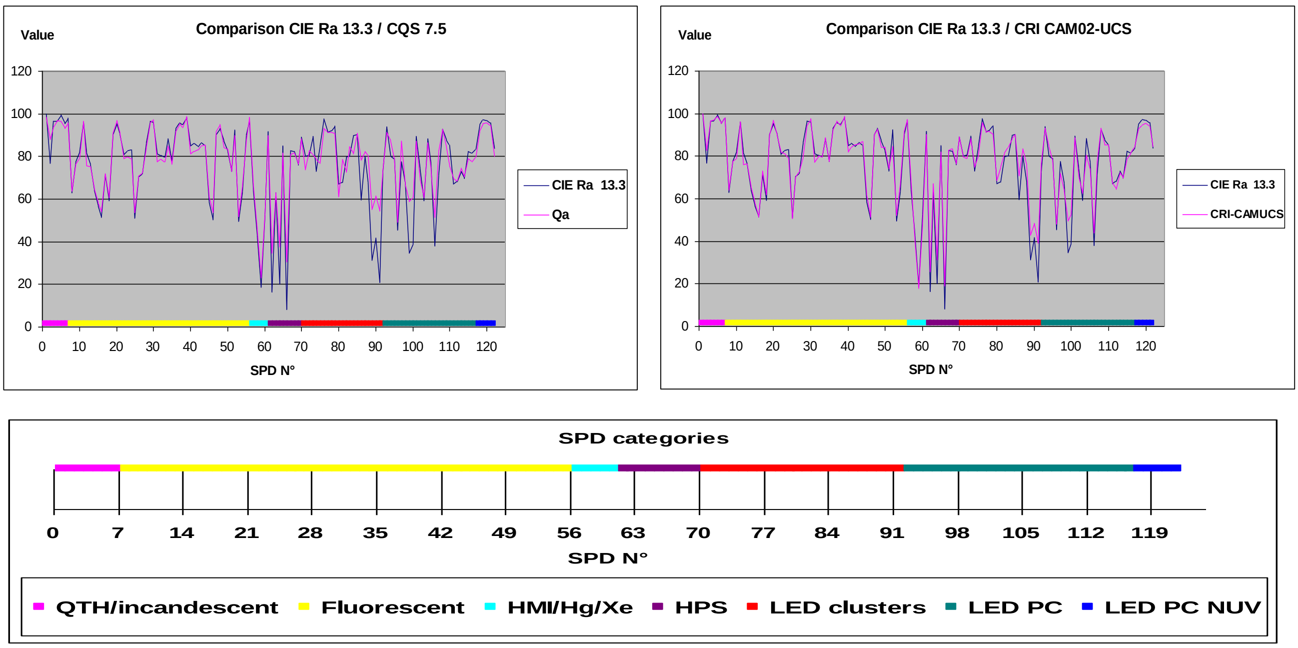

Fig. 3.18: Examples of computation over 122 sorted SPDs enabling the comparison of metrics represented by graphs of scores between current metric (CRI Ra) and proposals, CQS 7.5 (left) and CRI-CAM02UCS (right). We can see on the graphs the improvements of LED lighting scores (LED cluster and LED PC) obtained for the proposals.

Secondly, the relevant metrics, including those judged worthy of consideration by the CIE, have been successfully implemented in a modular software model, which enabled us to change the parameters, methods and data. These implemented metrics had been applied to a set of 122 selected Test Colour Samples (TCS) to visualize the differences between metric results as well as some parameter/method change effects. To see how the different metrics behave against the different lighting technologies and how they correlate with respect to the technology types, a dataset of spectral power distributions (SPDs) of 122 light sources has been built up and clustered according to the type of technology. Correlations between metrics for the different SPD subsets have been computed, delivering general and comparative information on metrics predictions. Results are shown in Fig. 3.18. Most of the predictions of assessed metrics present strong correlations for fluorescent lightings (Pearson coefficient of 0.90) and present significantly lower correlations for LED cluster based lightings (Pearson coefficient of 0.57). From the detailed review, we concluded that the lighting community is far from consensus on a colour rendering metric to rank the new light sources, especially LED light sources.

Thirdly, to assess how the different proposed metrics correlate with human judgement, a large subjective experiment has been carried out at LNE. A special test room has been built enabling to position and to control 12 sets of lamps representing 12 lighting types. The selected lighting lamps illuminate the room through a translucent diffuser in the centre of the ceiling. The test room has been built, furnished and decorated as a common living room. Fig. 3.19 shows the furnished test room. In that test room 43 observers underwent the experiment with 9 lamp types: incandescent, fluorescent, CFL and 6 types of LED lamps, while 8 colour attributes were assessed: preference, quality of vividness, fidelity, overall naturalness and specific naturalness and colour chart quality. The correlation calculation with 14 computed indices/metrics have been performed, analysed and reported.

Fig. 3.19: views of the test room with the translucent diffusing panel in the ceiling. The room is furnished as a living room with many decorative objects of different materials and pigment, with real plants and a basket of real fruits/vegetables.

The subjective experiment did not yield to specific relationship between the rated subjective attributes; all the attributes, in such a testing environment, co-vary in the same way and are determined at 66% by the first component of a Principal Component Analysis (PCA). The experiment seems robust: the 1st group of individuals (numbers 1 to 20) and second group of individuals (numbers 21 to 43) ranked in the same order 8 light sources, and for all the individuals the first rating sequence and the second rating sequence led to the same ranking for 8 light sources. Just one test light source was rated with very small difference with respect to the group of individuals and the rating sequence; the scores of the two rating sequences have no statistical dependence. Thus we conclude that the overall average ratings of preference of this experiment well represent the subjective preference for general interior lighting with minimum bias for a common European panel of people. This is an important point: CIE and industry will only adopt thoroughly tested metrics for colour rendering, and then subjective methods are key referees for metric evolution. The performances of metrics were analysed with the Pearson and Spearman correlations for the different sets of test light sources: all (9), cold (4), warm (5), cold LED (3), warm LED (3).

The predictions of fidelity metrics, current and proposals, will correlate with the subjective ratings for the cold test light sources, the proposed metrics give better predictions for warm sources than the current CRI. Gamut and memory colour metrics rank well the warm led sources but not the cold light sources. The CRI with updated colour metric – i.e. the CRI-CAM02UCS obtained the best overall correlation with subjective ratings. Examples of the metrics assessment are shown in Fig. 3.20.

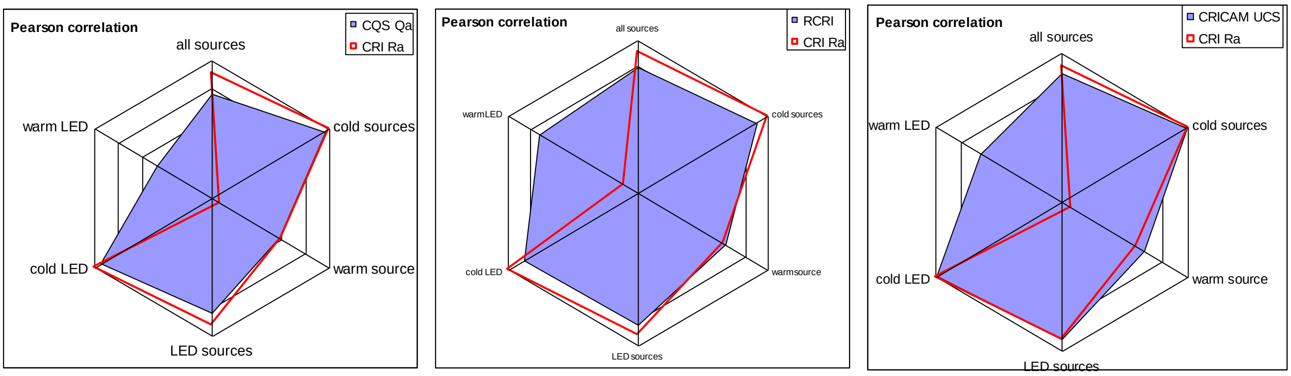

Fig. 3.20: example of metrics assessments with radar charts of the coefficient of Pearson correlation with the subjective ratings of overall preference for the following proposals of metric (left to right): CQS 7.5, RCRI, CRI-CAM02UCS. The coefficients of correlation are computed on subset of the lighting set, poles of the radar charts: all lighting sources, cold lighting sources, warm lighting sources, all LEDs, warm LEDs, cold LEDs. The red lines represent the current metric, i.e. the CRI 13.3 Ra, the gain in correlation can be easily visualized for the proposals.

A recommendation report to CIE for an improved colour quality metric has been drafted highlighting the interesting results of this work.

CMI focused on luminaires characterisation for outdoor lighting with regard to the colour rendering index and the luminous output with the MES2 method. Ten street-lighting luminaires have been characterized in the laboratory: nine LED-based and one using a HPS lamp. A report has been drafted presenting results, comments and a synthesis on the benefit of SSL luminaires for street lighting.

In summary the conclusion of the work carried out was to show that the proposed metrics for colour rendering lead to different performance rankings for SSL-based lighting. Depending on the specific type of LED lighting (warm or cold), the correlation with human subjective ratings was different for the proposed metrics. Best overall correlation with human perception ratings was obtained for the CRI-CAM02UCS metric.

Visual comfort

The well-known indices measuring visual comfort, specifically the CIE UGR and the IESNA VCP, rely on the measurement of discomfort glare perception established with traditional light sources. The new lighting features of SSL as very bright point-like sources and very specific spectrum with a prominent peak in the blue region of the spectrum, give rise to new assessments yielding to contradictory results. Specifically, visual comfort for SSL is not determined by glare alone, and further work was required in determining the other root causes of discomfort.

A large subjective experiment has been conducted at LNE with 50 observers. Four test setups have been arranged: (1) the living room used for the colour rendering experiment; (2) a glare setup comprising a viewing box, a lamp support and a large uniform background; (3) a large room comprising four lighting compartments; (4) an office room with two desks. Pictures of the setups can be seen in Fig. 3.21. The total number of lighting configurations is 17, randomly presented to observers. The measurement instrumentation comprised a photometric camera mounted on a goniometer and two spectro-radiometers. High resolution and high dynamic luminance maps of the observer field of view for each lighting configuration have been established. Parameters of visual comfort have been calculated from the luminance map and the colorimetric parameters of each lighting configuration. A model of visual comfort combining these parameters has been designed and its prediction compared to subjective ratings of visual comfort. The agreement is quite good with Pearson coefficients of correlation of 0.97, 0.94 and 0,91 for respectively the office, the living room and the compartments configurations.

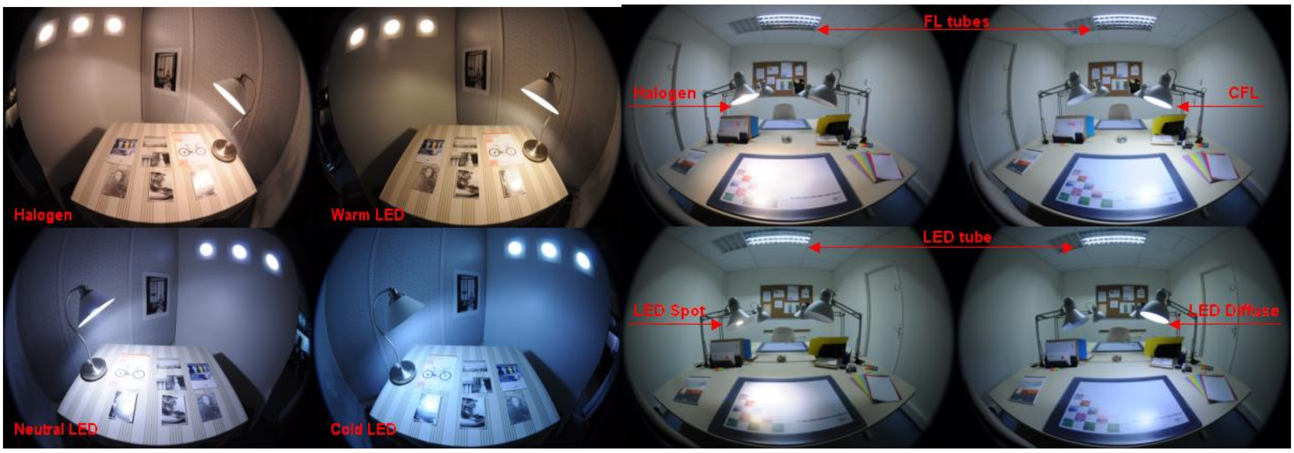

Fig. 3.21: views of four the identical compartments (left) and the four identical desks configuration (right) to assess visual comfort against the spectrum and the luminance distributions and the derived parameters (CCT, glare indices, gamut and colour rendition indices, light levels, light and distributions).

The measurement conditions to correctly evaluate glare have been investigated by INRIM. After a review on available research on glare, two subjective studies have been carried out to evaluate glare effects on contrast threshold and pupil diameters produced by SSL and traditional sources. Three lamps were used in the experiment - incandescent (2900 K), metal-halide (2800 K) and LED (5500 K) - producing the same illuminance at the observer's eyes. The results on contrast threshold showed no significant differences between the effects of the three sources spectra (a diffusing glass was in front of the sources, so only the effects of spectral distribution was involved). Then for evaluating effects on pupil diameters, the same sources with different shapes were presented: uniform circular, sparse dots, crowded dots. The light sources were presented in two diameters: 25 mm and 100 mm. The outcome of the experiment is that the pupil size is dependent both of the source spectrum and of the source shape: the pupil sizes are much greater with the incandescent source and with a source diameter of 25 mm. The importance of uncertainty in glare measurements or evaluations (during the design phase of the lighting installation) was a clear outcome of the investigation, resulting in a proposal for a general tolerance analysis method and recommendations for the main influence parameters.

Beyond the two type of receptors (rods and cones) responsible for vision and typically simulated by broad band photometers, a third receptor in our eye is responsible for non-vision photobiological effects. Its action spectrum has it maximum, where the peak of the blue LED of white phosphor LED is typically located. The knowledge about the interdependencies between SSL and such receptors is important to adapt lighting environments to human wellbeing. The University of Ilmenau, as unfunded partner, worked out a comprehensive report on the current status of "Biological effects of light" [11], focusing on circadian effective radiation.

3.3 Quality metrics

General quality metrics

The introduction on the market of Solid State Lighting (SSL) represents a revolution for lighting engineering. The features of SSLs allow for the development of luminaires with a compact size and a sharp intensity distribution and the design of adaptive lighting installations where luminance levels or colour rendering conditions change according to the user needs. However, the evaluation of expected performances, with adequate uncertainty estimation, is still a problem. The current methods do not always provide reliable results when SSL is involved. The metrological research carried out in this project is extremely important to establish the groundwork for reliable SSL characterisation, but needs be translated into new and easy to use tools for stakeholders, i.e. users and manufacturers. The developed quality metrics need to permit the characterisation of SSL performance for actual needs and give guidelines for indoor and outdoor applications useful for normalization bodies, scientific communities, stakeholder and partners.

Usually, “quality” is a distinctive attribute or a characteristic that express the degree of excellence or performance of something. For example it is common to refer to “quality parameters” as a set of standard requirements a lighting installation shall satisfy to guaranty adequate vision conditions for a given visual task. Any qualitative judgment about lighting quality depends on subjective expectations, safety needs and different physiological or psychological aspects. Observers judge lighting quality also according to visual comfort, colour rendering, glare and modelling conditions.
The first goal achieved by all partners involved (INRIM, NPL, AALTO, SP, LNE, SMU, VSL and CCR) was to formulate a common definition of “quality metric for SSL”:

> The quality metric for SSL is a set of parameters, which is able to characterize: i) performances of SSL (as stand-alone devices and luminaires) and ii) performances of the illuminated environments when SSL are used.

Such parameters can be physical or psychophysical quantities, quality factors and performance criteria. The quality metric provides a numerical value, obtained by means of traceable measurements, for these parameters. The set of parameters quantifies photometrical, optical and electrical characteristics, energy efficiency, energy consumption, light perception and safety aspects. Light perception involves aspects of vision used in lighting engineering to qualify conditions like glare, contrast threshold, colour rendering and visual comfort. The correlated quantitative parameters are defined following the approach of Soft Metrology, defined as a set of measurement techniques and models that enables the objective quantification of properties determined by human perception. For each parameter, measurement methods, traceability conditions and instrument requirements should be specified.

<u>Quality metrics for SSL measurement equipment</u>

VSL and Aalto together developed quality metrics for equipment for measuring the optical emission and electrical parameters of SSL. It is emphasised that the metrology of pulsed SSL must have future priority because pulsed SSL generate harmonics below 40Hz: it will be necessary that future standards take into account this fact. The measurement of total luminous flux and chromaticity coordinates with integrating spheres or goniophotometers, when the spatial distribution of these quantities is required, has been considered, as well as aspects related to electrical wiring, measurements set ups and methods.

<u>General quality metrics for SSL</u>

Building on the technical work conducted in the project, which has been described in the previous sections, quality metrics covering different aspects of SSL were developed by NPL, INRIM, VSL and LNE:

- The analysis of the existing standards stress that new parameters must be included for a complete and useful characterisation of SSL. In particular, for particular applications it is necessary to measure the spatial distribution of CCT and chromaticity coordinates (at least).

- For applications involving pulsed SSL, the analysis of the two available methods was done with the identification of the four main relevant quantities to be considered in quality metrics (junction and charge temperature effects, power efficiency, luminous efficiency, peak shift). The effects induced by commercially available dimmers were also determined.
- For mesopic applications, the practical implementation of mesopic photometry is provided, together with a list of the relevant quality parameters for SSL mesopic (photopic luminous flux, S/P ratio, CRI and spatial distribution of luminous intensity, S/P ratio and CRI) [12].
- For colour quality a report [13] has been drafted presenting: (1) colour specification of white light sources with background information on colorimetry (chromaticities, Colour Correlated Temperature (CCT) and CCT names, metamerism index, colour spaces; (2) a synthesis on colour rendering metrics and the underlying approaches: perceptual attribute types - preserving or enhancing colour appearance, fidelity versus preference, reference illuminants or memory colours, one component versus multi-component metrics; (3) activity of the CIE; (4) a synthesis on metrics comparison on all lightings and assessment by subjective experiments of relevant proposals of metric to replace, supplement or complement the current metric. A final section concludes on the colour specification of light sources for general lighting and the best predictors today for colour rendering.
- The main conclusion regarding colour rendering was that the most important factors that affect human perception, comfort in particular, were shown to be dependent on the luminance distribution and the colorimetric parameters of the various lighting scenarios.
- For safety aspects, available standards and guidelines have been compared including some practical examples of calculations of SSL photobiological safety using radiometric and photometric SSL characteristics linked to the technical data sheet provided by manufacturers. Some unsolved problems were highlighted like the determination of apparent source size in complex systems, as well as the definition of distance assessment: improvement in the datasheet information and standardisation is needed and recommended.
- For general aspects of indoor lighting, including the problem of glare, it is clear that available literature is not completely exhaustive about differences between SSL and traditional lamps. In particular, even if some corrections of algorithm predicting glare have been made, the results are not always convincing. Considering the available research results, a unique model can't be suggested. Experiments showed that, considering only the emission spectrum, no significant differences arise between SSL and traditional sources (on glare vs. contrast threshold), while the pupil diameter is influenced both by spectra and geometrical position and dimension of glare sources, having effects on visual acuity. In indoor lighting it is suggested to use SSL set-up with sources not directly visible. A tolerance analysis in the design phase of a lighting installation permits to evaluate glare uncertainty but a better understanding of the influence of spectral and geometrical parameters to glare conditions can be obtained combining research effort into a standard defined set-up for tests.

Application-specific Quality Metrics

Apart from the general quality metrics described in the previous section, some specific applications were studied in detail.

<u>Green houses</u>

Greenhouses offer an interesting opportunity for SSL because of two reasons: the relatively high reduction of energy consumption that can be obtained by switching to energy-efficient lighting and the huge possibilities of spectrally tuning the light from SSL. VSL made a study of relevant quality metrics for this application, identifying the degree of spectral correlation γ as the key metric. Results from this project lead to the conclusion that there is significant potential for energy saving and spectral optimisation for plant growth using SSL.

<u>Lighting for art</u>

INRIM together with CCR conducted a study into the possibilities and limitations of SSL for the lighting of art works in museums The conducted tests using the setup shown in Fig. 3.22 highlight that warm SSL induce less fading on blue wool samples (fading reference samples in conservation studies) than incandescent lamps. The peculiarities of SSL spectrum allow the enhancement of saturation and brightness of artefacts using suitable combination of cold or warm SSL lighting according to dominant colour of artefacts, as suggested in the report [14]. Results showed the potential for SSL to be used to protect various exhibits from wavelengths that could otherwise damage artefacts.

Street lighting

INRIM, SMU and SP studied quality metrics for outdoor lighting, with particular attention to road and tunnel lighting. The results highlight how critical the on-site installation tolerances can be, when measurement results are compared to the design expectation. Examples of procedures for in-field measurements and uncertainty evaluation are considered. The definition of the “installation lighting factor”, a quality factor relating road luminance *vs*. road illuminance, allows to quantify the energy performances of a lighting installation and suggests the design strategies to improve these performances. The optimization of this quality parameter is indirectly related also to lighting pollution caused by road lighting installations: SSL luminaires show higher “installation lighting factor”, a lower installed flux and a lower upward luminous flux spread. In this application stakeholders were deeply involved.

Fig. 3.22: Exposure boxes equipped with different white LEDs

4 Actual and potential impact

This project was the first project to bring together metrological research on SSL in large number of countries across a broad range of topics, from fundamental aspects of traceability to application specific quality metrics. While it is not possible to resolve all measurement challenges related to SSL in the time frame of a single project, nevertheless, the foundation was laid for a traceable SSL measurement infrastructure in Europe.

4.1 Dissemination

During the course of the project, project partners participated in and hosted a range of Solid State Lighting related workshops, including Strategies in Light, and CIE events. The project was also presented at the SPIE Phototonics West 2013 conference, the largest photonics conference in the world.

A Solid State Street Lighting event was held at NPL in December 2012 and 41 companies participated. This event was unique in bringing together all elements of the value chain - LED producers, LED integrators, and the specifiers. This project directly addressed a number of the discussion points raised at this event, for example, issues surrounding disability and distraction glare, the standards governing light distribution for solid state street lights, photobiological hazard and smart controls.

An exhibition stand (shown in Fig. 4.1-4.3) was constructed which displays a comparison of solid state lighting fixtures and other technologies. The stand showed the relative energy consumption, colour rendering and aesthetics of the different technologies. The portable exhibition display stand was used in more than 25 events, covering industry, government, academia, education and civil society. More than 7,500 visitors viewed the stand and approximately 1,000 diffraction grating glasses were handed out as a means of educating the visitors about the measurement and quality of solid state lighting. The stand travelled to the largest lighting exhibition in the UK (LuxLive 2012), was successfully shipped to the National Lighting Workshop in the Netherlands, and featured in a BBC4 documentary “Marcus's Journey's into Measurement” on the SI system. Euramet has also featured an article on the stand on their website [15].

Fig. 4.1: Exhibition stand next to NPL goniometer

Fig. 4.2: Viewing spectral content of the lights using diffractive eyewear (left); Photograph of the light sources through the diffractive eyewear (right)

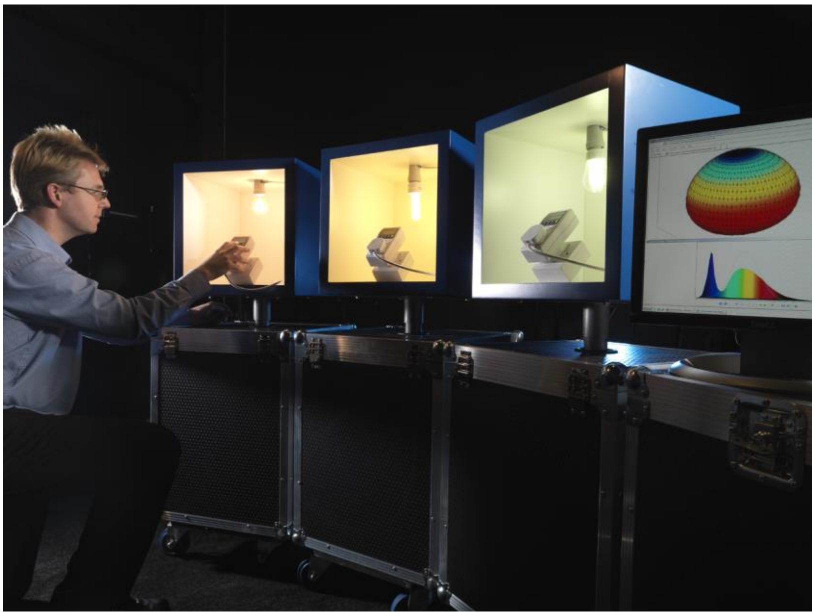

Fig. 4.3: Exhibition stand showing electrical consumption monitors

The project website (http://www.m4ssl.npl.co.uk/) has been used to promote and disseminate the results of the project. This is the main portal for stakeholders to access the work of the project. The site has been continually improved using partner feedback throughout the life of the project and will continue to be available as a source of project outputs (reports, presentations, publications etc.) for three years beyond the life of the project. A screenshot is shown in Fig 4.4.

The website is top of the list when using “metrology solid state lighting” and “measurement solid state lighting” Google search terms. It is 2nd and 3rd for “measurement SSL”. On average visitors from 17 countries visit the site each month. This majority of visits are from EU countries, but the website has also attracted visitors from USA, China, Japan, Singapore, India, Brazil and South Africa. The ratio of new to returning visitors is approximately 60/40. Keywords used to find the website include; SSL Metrology, demonstrating metrology, m4ssl, how does solid state lighting, photometric, CIE, Circadian, EMRP, IEA 4E Annex, NPL, MKEH, CMI.

Fig. 4.4: Screen shot of M4SSL project website (http://www.m4ssl.npl.co.uk/)

At the conclusion of the project a large stakeholder event was held which engaged the entire value chain for solid state lighting, including major European industrial organisations and relevant government bodies. The event presented the main findings and recommendations of the project in a format that catered to all technical abilities and provided an accessible discussion forum for participants. The workshop was highly appreciated:

> *"As a company whose experience is high volume testing, it is a great opportunity to meet the experts in one location."*
> *"Very much enjoyed the workshop. Learned an enormous amount."*

For the JRP as a whole, the stakeholders rated average scores of:

scope :	4.4 (out of 5);
scientific/technical quality:	4.3 (out of 5);
potential for impact:	4.2 (out of 5);
usefulness for stakeholder's own work:	4.2 (out of 5).

During the course of the project, the consortium collaborated with various companies, institutes and other stakeholders. In particular, we would like to thank Lichtmesstechnik GmbH, TechnoTeam GmbH, Osram, Philips Lumileds, LightingMetrics, ReverberiEnetec, Autostrade per L'Italia, ENEA, LUX-TSI, ANSES, INC, DIN and CIE for their support.

4.2 Impact

The mission of this project was to stimulate the uptake of energy efficient lighting in the form of SSL by providing user confidence in performance claims through good metrology. The impact was pursued through a three-fold approach consisting of 1) Providing traceability as the basis for reliable measurements; 2) Developing good measurement practices and promoting their use; 3) Stimulating user awareness of the need and the possibility of proper measurements, targeted specifically at SSL.

In the previous section, the scientific and technical results of the project were described in some detail. From a user perspective, the most important results can be summarized as follows:

- Solutions have been developed for the reliable measurement of the electrical characteristics of SSL products. The dominant uncertainty sources are identified and the best uncertainty that can be achieved was determined. A source impedance stabilization network was developed to ensure good comparability between measurements with different sources. All this will enable manufacturers and testing laboratories in performing reliable electrical measurements of SSL.
- Luminous efficacy is the most important performance parameter when it comes to energy savings. Access to traceable measurement services is essential for manufacturers and customers for establishing confidence in product claims. The comparison within the project has improved access to traceability in an important way, by 1) giving the participating NMIs an excellent test opportunity for their measurement capabilities in this area; 2) establishing confidence and recognition of measurement capabilities across Europe; 3) highlighting areas where additional work is required.
- One of the main differences between SSL and conventional, incandescent sources is their spectral distribution. To make the existing measurement infrastructure at manufacturers and testing laboratories suitable for the measurement of SSL, spectral corrections are needed. This project has enabled users to perform these corrections by providing procedures and traceability for spectroradiometer calibrations.
- Another area where there is a notable difference is in the directionality of the light. This is an area where the technical challenges are highly non-trivial. As a result, the project could not fully solve the problem, but nevertheless, important first results are achieved. These form a stepping stone towards full traceability for goniometric characterization of SSL, which will help designers by removing the need for costly and time-consuming design iterations.
- Important first work was done towards establishing reliable life-time estimation for SSL. Life-time is an important economic and environmental factor to consider when deciding on the adoption of SSL based lighting solutions. End-users, but also manufacturers and policy makers have a need for life-time data that they can trust. Next steps will be the creation of validated aging models and full uncertainty estimation for life-time measurements.
- Measurements under mesopic conditions are not a challenge restricted to SSL per se, but SSL have important applications precisely under these conditions, e.g. in road and tunnel lighting. The work done in this project on traceability and instrument development, specifically the two-channel device discussed in section titled 'Mesopic Conditions', will enable the lighting community to use SSL or other light sources under mesopic conditions effectively and with confidence. This will have impact on energy consumption and CO_2 emission, cost of operating e.g. road lighting systems, but also road safety.
- Quantification of colour rendition is a major area of debate in relation to SSL. The old CIE CRI 13.3 Ra colour rendering index developed for incandescent lamps does not suffice for SSL and end-users and manufacturers are in urgent need of a proper parameter to quantify reliably the colour rendering aspects of SSL. This is especially relevant since colour rendering is an area where SSL is traditionally weak and any progress must be measured using a reliable metric, in order not to spoil user confidence. This project has provided the CIE with input based on a substantial comparison study between the various proposed metrics, including subjective experiments correlating human perception of e.g. naturalness and vividness with colour quality parameters derived from physical spectra. The project can not of its own decide the debate, but a resolution is urgently needed and the only way forward is through reliable empirical evidence such as this.
- Visual comfort is another area where reliable quality parameters are important to underpin user confidence. The project contributed here as well with subjective experiments. This work has resulted in a model for visual comfort, based on the luminance distribution and color of the light, that correlates well with subjective ratings, and that can be used by lighting designers. Also, important work was done on glare evaluation, highlighting the importance of a proper uncertainty estimation in this area.

- Because of the broad range of applications for SSL, it is important that there is a good connection between what can be measured and what is relevant from a practical point of view. For this reason, the project not only focused on traceable measurement facilities and methods in the lab, but also on application-specific quality parameters. This will help bring the results to the areas where the large scale impact of SSL is achieved. Specifically the project has demonstrated the potential benefits of using SSL in three major target applications: street-lighting, greenhouses and art expositions; where energy savings, street safety and artefact colour protection would benefit.

Taken as a whole the project has contributed towards the support of:

- Designers and manufacturers to make reliable and verifiable product claims;
- Policy makers to develop fact-based policy;
- Market surveillance authorities to combat unfair trade practices;
- Users to select best-fit products for their applications and be confident in their performance;

The ultimate goal is to stimulate the uptake of energy-efficient and environmentally friendly lighting technology and help the European lighting industry.

<u>Contributions to standardization</u>

- An The consortium has documented 32 interactions with standards bodies or their members during the course of the project; 11 of these with CEN 169 (Comité Européen de Normalisation) technical committee on Light and Lighting, 15 interactions with UNI GL5 (Ente Nazionale Italiano di Unificazione); and 6 with CIE (Commission Internationale de l'Eclairage) TC2 (Physical Measurement of Light and Radiation) and Division 4 (Lighting and Signalling for Transport)
- A report on quality metrics, produced in this project, was used to review the draft standard (CEN13032). This standard will be used for LED metrology accreditation in Europe. Best practice generated throughout this project was highlighted and presented to CEN169 Committee. One of the aims of this standard is for it to become the accepted international methodology for LED measurement.
- INRIM participated in CEN 169/226 JWG12 for the revision of the European standards for road lighting (EN13201) and to CIE Div 4 Technical Committees on road lighting.
- The coordinator submitted a response to the EU Greenpaper on SSL on behalf of the consortium.

<u>Industrial Impact</u>

The project has worked closely with the lighting industry. Particular highlights include:

- Collaboratively, NPL and Surrey University have applied for 2 patents on the use of electronic circuitry to enable the in-situ measurement of light intensity by LEDs and so leading to an estimation of the junction operating temperature. The technology behind this work has been used in a further EMRP research project (ENV04 METEOC) to provide for automatic calibration of solar radiation sensors.
- As part of the efficacy of SSL measurement intercomparison exercise, industrial stakeholders in the UK made parallel measurements with NPL leading to the dissemination of methods and procedures to industrial stakeholders. This has provided LUX TSI with greater confidence in their measurement capability and consequently to apply for UKAS accreditation.
- In association with Autostrade per L'Italia of Italy, highway tunnels with LED luminaires were studied and luminaires for tunnel internal, and entrance and exit zones were characterized using the INRIM goniophotometer, enabling safety critical design parameters for tunnel lighting to be determined.
- In collaboration with photometer manufacturer LMT, a commercial mesopic light level device has been developed and is currently being marketed.

5 Website address and contact details

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