

# 1 **Best practices for measuring emerging light-emitting diode technologies**

2 Miguel Anaya<sup>1</sup>, Barry P. Rand<sup>2</sup>, Russell J. Holmes<sup>3</sup>, Dan Credgington<sup>1</sup>, Henk J. Bolink<sup>4</sup>, Richard H.  
3 Friend<sup>1</sup>, Jianpu Wang<sup>5</sup>, Neil C. Greenham<sup>1</sup>, Samuel D. Stranks<sup>1</sup>

4 <sup>1</sup> Cavendish Laboratory, University of Cambridge, UK.

5 <sup>2</sup> Department of Electrical Engineering & Andlinger Center for Energy and the Environment, Princeton  
6 University, USA.

7 <sup>3</sup> Department of Chemical Engineering and Materials Science, University of Minnesota, USA.

8 <sup>4</sup> Instituto de Ciencia Molecular, Universidad de Valencia, Spain.

9 <sup>5</sup> Institute of Advanced Materials, Nanjing Tech University, China.

10 \*sds65@cam.ac.uk

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12 Emerging light emitting devices based on organic semiconductors (OLEDs), inorganic quantum dots  
13 (QLEDs) and metal-halide perovskites (PeLEDs) are pushing current solid-state lighting into a new  
14 era in which light can be manipulated in a number of ways. The unprecedented control over colour,  
15 brightness and directionality of these emerging light sources, in addition to inexpensive fabrication  
16 routes, has opened up a world of new applications, with OLEDs already showing a growing presence  
17 in display markets. Historically, the adoption of standardised protocols by the LED community to  
18 assess the performance of new materials and architectures has provided emerging LED technologies  
19 with the necessary self-reliance to mature.<sup>1,2,3</sup> The recent development of disruptive concepts in  
20 OLEDs and QLEDs,<sup>4,5</sup> and the arrival of very new technologies such as PeLEDs – based on a diverse  
21 class of emitters such as 3D, 2D, 0D or double perovskites<sup>6,7,8</sup> – has aroused great excitement about  
22 further potential impact in the lighting and display industries. However, these findings at the laboratory  
23 stage are often not described in a consistent and uniform way, owing in large part to a range of  
24 peculiar phenomena in these emerging technologies such as transient effects. This leads to  
25 challenges in making real comparisons between reported devices, difficulties with reproducibility, and  
26 a lack of clarity regarding the realistic technology readiness level of new concepts and technologies.  
27 Next-generation solar cells, for example those based on perovskite absorbers, have recently  
28 transitioned through a similar “coming of age” as they have become more competitive with incumbent  
29 technologies. This has been aided by the clear standards in the photovoltaics field that are broadly  
30 followed by both the academic and industrial research communities. In this Comment, we highlight  
31 key considerations for reporting the characterisation of new LED technologies, in particular drawing  
32 on historical guidelines to discuss how these approaches should be used and interpreted in the  
33 context of such new LED technologies. Furthermore, we demonstrate typical calculation procedures

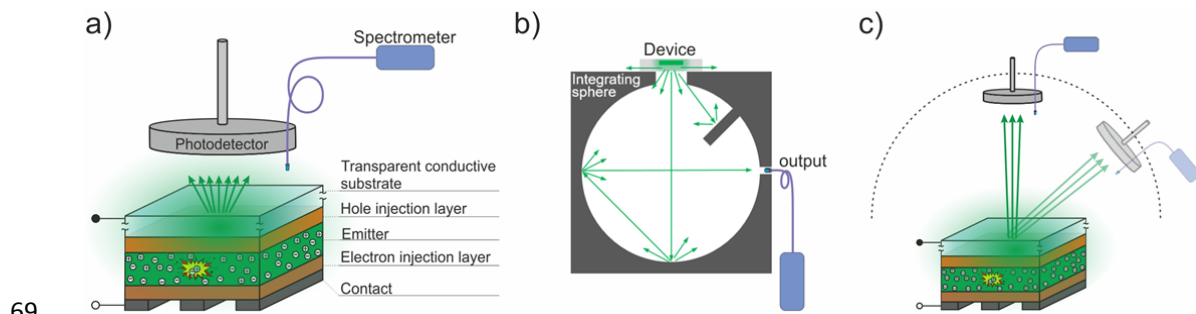
34 in the Supplementary Information (SI). By doing so, we propose guidelines for reviewers,  
35 experimenters and industry alike with the aim of facilitating rationalised and precise comparison  
36 between novel LED technologies utilising different emitter classes and architectures.

### 37 Quantum efficiencies

38 We first define the most important metrics to determine LED performance. The external quantum  
39 efficiency (EQE) is defined as the ratio of photons that escape the LED to the number of electrons  
40 flowing in the external circuit. For many applications, EQE is defined specifically for photons that  
41 escape into the forward viewing hemisphere, as defined by Forrest et al.<sup>2</sup> To properly quantify the  
42 EQE at a given current density ( $J$ ), there are three approaches, each of which is in principle  
43 equivalent provided the measurements are performed carefully with appropriate calibration. A first  
44 approach utilises a large photodetector at close proximity to the LED to collect the photons emitted in  
45 the forward hemisphere (Figure 1a). Here, the measurement design (distance and geometry) must  
46 ensure a good compromise between detection of light, by maximising collection solid angle, and  
47 mitigation of detection inaccuracies such as reflection losses at small angle or edge effects in the  
48 photodetector. The detector should not be in contact with the device, which would otherwise lead to a  
49 modification of light out-coupling and reflectance losses by altering the device/air interface. A second  
50 approach to measure EQE is by collecting all photons in the forward-emitting hemisphere through use  
51 of an integrating sphere in a  $2\pi$  geometry and a spectrometer (Figure 1b).

52 A third approach is to place the photodiode at a large distance compared to the dimensions of the  
53 emitting area and the thickness of the device (Figure 1c; see SI for example calculations). This  
54 approach might be desired for applications in which the forward-emitting direction (perpendicular to  
55 the substrate) is most important, such as for displays. Although it must be accurately determined, the  
56 exact solid angle subtended by the photodetector is not strictly important provided that both the  
57 response of the photodetector to light arriving at different angles of incidence, and the directionality of  
58 emitted light from the LED, are known; Lambertian emission profiles are commonly observed for most  
59 practical LED devices. Given the potential for significant systematic error in these assumptions, one  
60 can perform a measurement to confirm the angular distribution of the emission, particularly if novel  
61 architectures and/or emitters are employed, or for devices that have substantial scattering due to  
62 layer roughness, among other factors. Since the Lambertian assumption may not hold in these cases,  
63 the simple use of a photodetector subtending a small solid angle could conceal any substantial

64 emission away from the perpendicular direction for superlambertian emitters or overestimate the EQE  
65 value in sublambertian emitters. For this reason, one can employ a photodetector mounted on a  
66 goniometer with the aim of determining the full angular distribution of emitted photons (see Figure 1c).  
67 To eliminate any influence from the angular dependence of detection, the photodetector should  
68 subtend as small a solid angle as practical.



70 **Figure 1.** Proposed characterisation setups for emerging LEDs. (a) A typical EQE measurement in  
71 which a photodiode placed at an appropriate distance from the device is used to measure emitted  
72 photons. Along with charge injection characteristics (i.e. current and voltage), this is used to  
73 determine the radiance and luminous efficacy. A spectrometer is used to extract spectral information.  
74 (b) A direct EQE measurement by using an integrating sphere and a spectrometer. (c) A  
75 photodetector mounted on a goniometer to determine the full angular distribution of emission.

76

77 In order to accurately determine the emission quantum efficiency in each case, it is essential to  
78 account for the spectral-dependent losses caused by any element of the measurement setup placed  
79 between the LED and the photodetector (e.g. lenses, filters, optical fibers, gratings, mirrors, sample  
80 holder). Likewise, one must perform a careful spectral response calibration of the photodetector at the  
81 device emission wavelengths; this of course first necessitates a measurement of the  
82 electroluminescence (EL) spectrum using a spectrometer (cf. Figure 1). In the case of emitters having  
83 a broad emission spectral spread, the average responsivity of the photodetector weighted by the  
84 emission spectrum should be used, as outlined by Forrest et al (see also SI).<sup>2</sup> One may also consider  
85 the use of a well-calibrated spectroradiometer as an alternative to a calibrated photodetector, and one  
86 can then determine EQE through accurate measurement of the device active area; this approach is  
87 widely employed in industry. In any case, any measurement setup including detector must be  
88 carefully and regularly calibrated. We also advise the use of well-aligned aperture masks to avoid  
89 detecting waveguided emission contributions from the substrate edges or light scattered out from  
90 beyond the pixel area, though care must be taken to account for the thickness of the glass and to not  
91 interfere with the escape cone, which can be a particular issue for measuring the angular

92 dependence. Furthermore, cross-checking EQE measurements using two different methods, for  
93 example through use of a photodetector via the first method and a spectroradiometer via the third  
94 method, would be good practice to validate the measurement and calibration procedures. This  
95 approach would also help to mitigate any significant errors arising, for example, through errors in the  
96 measurement of the distance between the detector and device active area that may result in large  
97 errors in the calculated EQE. In the interests of transparency, research groups should carefully  
98 describe their device design, measurement geometry, and calibration approaches; it would be good  
99 practice to also make their calibration files available through open repositories or supporting  
100 information files in publications. In principle, any of the aforementioned characterisation protocols to  
101 report quantum efficiencies are equivalent as long as they are conducted correctly and transparently.  
102 Quantum efficiency values must be quoted in context with the carrier density (ascertained through  
103 proxies such as luminance or current density) under which they are measured. Ideally, the  
104 dependence of the EQE should be provided across several orders of magnitude of luminance or  
105 current density to understand the emission characteristics and limitations including current leakage,  
106 peak EQE and “roll-off” (aka “droop”).

107 The internal quantum efficiency (IQE) is defined as the ratio of photons generated within the device to  
108 the number of charge carriers injected. It is related to the EQE through the extraction efficiency, which  
109 is the ratio of photons escaping the device to those generated. There are a plethora of internal optical  
110 processes occurring within the device such as waveguiding, reabsorption, surface plasmon losses  
111 and multi-layer reflections, among others, which render this ratio difficult to calculate; detailed  
112 knowledge of device interfaces and optical properties are therefore essential in order to best estimate  
113 the IQE. To this end, it is prudent to use a properly sized integrating sphere in a  $4\pi$  geometry, that is,  
114 in which the device is mounted in the centre to collect emitted photons at an output port of the sphere.  
115 One must then take care to calibrate the measurement to account for internal losses within the device  
116 stack; one way to do so would be to perform an identical measurement but placing a “test” LED in the  
117 integrating sphere with exactly the same absorption and reflection spectra as the device under  
118 investigation. Accurate calibration and modelling must take into account absorption and reflection  
119 losses from parasitic elements in the light path (e.g. device backside, material between pixels) but  
120 also model how other internal processes affect light out-coupling. Furthermore, the performance of  
121 some novel LED structures are substantially influenced by additional internal processes such as

122 efficient photon recycling, for example in many of those based on crystalline semiconductors,  
123 including the halide perovskites, which exhibit small Stokes' shifts between absorption and emission  
124 energies. These phenomena have an important impact on both the IQE and EQE because the  
125 opportunity for forward emission is substantially increased due to the larger number of absorption and  
126 re-emission events taking place within the device.<sup>8,9</sup> Similarly, any potentially anisotropic transition-  
127 dipole moment orientation, as is the case in many OLED devices, must also be taken in to account  
128 when calculating the extraction efficiency.<sup>10</sup> Further information about the internal processes of the  
129 device can be ascertained by correlating the EL and EQE (IQE when provided) with their photo-  
130 induced counterparts – photoluminescence (PL) and photoluminescence quantum efficiency (PLQE).  
131 Careful comparisons between these quantities in a full device stack configuration allows identification  
132 of injection issues, the specific location (e.g. depth) of recombination within the device, and  
133 nonradiative recombination processes taking place in both standalone emissive films and interfaces.<sup>9</sup>  
134 Efforts to quantify the IQE and extraction efficiency precisely are needed to unravel the working  
135 principles of the LED and understand how close a particular emitter and device stack combination is  
136 to maximum performance.

137

#### 138 Device emission colour and intensity

139 In order to assess the emissivity of an LED under operating conditions, one should estimate the  
140 radiance [ $\text{W}\cdot\text{sr}^{-1}\cdot\text{m}^{-2}$ ], which corresponds to the power from photons emitted per unit area per unit  
141 solid angle. Nevertheless, most LED applications require one to account for the perceived emission  
142 colour of the LED in the visible range of the electromagnetic spectrum. This is typically done by  
143 recasting radiance as luminance [ $\text{cd}/\text{m}^2$ ] and EQE in terms of current efficacy [ $\text{cd}/\text{A}$ ], by weighting the  
144 emitted photon energies by the photopic response of the human eye (see SI). These metrics as a  
145 function of current or voltage are critical for understanding to what extent the device is relevant for  
146 applications such as displays or lighting. Indeed, from a technological viewpoint, outstanding EQE is  
147 only meaningful if it can be realized at practical luminance values. A typical operating value of  
148 luminance for a given colour for display applications is at least  $100 \text{ cd}/\text{m}^2$ , but often above  $1000 \text{ cd}/\text{m}^2$   
149 for OLED displays and other lighting applications.<sup>11,12,13</sup> By contrast, when considering LEDs with  
150 predominantly UV or NIR electroluminescence, one should refer directly to the measured radiance  
151 due to the very low photopic response at these wavelengths; similarly, one should avoid inverting

152 measured photometric units (such as those measured through a spectroradiometer) for spectral  
153 regions outside the calibrated range or where the photopic response tends to zero. We also note here  
154 that using “low turn-on” voltage in a subjective way should be discouraged, and instead suggest  
155 reporting the voltage corresponding to a reasonable emission output, for example luminance on the  
156 order of 1 or 10 cd/m<sup>2</sup> or the equivalent radiance for non-visible emitters. A useful metric for  
157 applications where electrical power consumption is important (e.g. lighting), i.e. accounting for both  
158 current and voltage, is the luminous efficacy [lm/electrical W]; this metric also integrates emitted  
159 photons across all angles.

160 The colour of the emission (e.g. peak wavelength) and its quality (e.g. full width at half maximum) is  
161 given by the EL spectrum. One can precisely define colour using the chromaticity coordinates (x,y)  
162 established by the Commission Internationale de l'Eclairage (CIE).<sup>14</sup> These are obtained through the  
163 tristimulus values X, Y and Z, which reproduce the behaviour of the three different cone cells present  
164 in the human eye, and are widely employed to judge the suitability of a light source for the application  
165 pursued. In the case of white lighting, one can use the spectrum emitted by an ideal black body  
166 radiator as a reference to assign the correlated colour temperature (CCT) [K]. In addition, for  
167 illumination purposes, the colour rendering index (CRI) quantifies how well a given light source  
168 reproduces the colour of illuminated objects versus an ideal black body light source.<sup>15</sup> We note that  
169 the multi-layered thin film character of emerging LEDs, and the integration of optically active  
170 structures to control light out-coupling, can lead to variations of the spectral output (colour) of the  
171 device with the angle of emission.

172

### 173 Stability and device lifetime

174 Evaluating the lifetime of emerging LEDs is critical, particularly for technologies that typically suffer  
175 from substantial changes in performance over operation time. The following approaches can assess  
176 performance in a reasonable manner at the laboratory scale; once emerging LEDs demonstrate  
177 sufficient laboratory stability, they would then need to pass more demanding industry-standard stress  
178 tests.<sup>3</sup>

179 Researchers should first ensure that their devices emit light long enough to be measured and that  
180 their stability over the measurement duration has minimal impact on the extracted device performance  
181 parameters. For this, we propose considering the following simple procedures. Current-voltage scans

182 should be carried out at two different rates; first a rapid scan (e.g. steps of 0.5 V), and then a slow  
183 scan (e.g. steps of 0.1 or 0.01 V) from low to higher voltages and back. Measurements should be  
184 checked to ensure that the device current-voltage-luminance characteristics are not evolving during  
185 acquisition at a given voltage bias. Asynchronous readout of current and radiance can lead to  
186 significant errors in calculated EQE. The backwards scans will also allow one to decouple whether the  
187 maximum achievable brightness and subsequent roll-off at higher operational conditions occurs  
188 because of degradation or changes in recombination regime (e.g. due to non-radiative Auger  
189 recombination outcompeting radiative processes at high carrier densities). The EL spectrum should  
190 ideally be confirmed at the maximum EQE as well as at the maximum achievable brightness, and  
191 consideration given for any resulting change in photodetector response. Use of a spectroradiometer  
192 may give a more reliable estimation of the EQE than a photodetector if the EL spectrum is changing  
193 over time during characterisation.

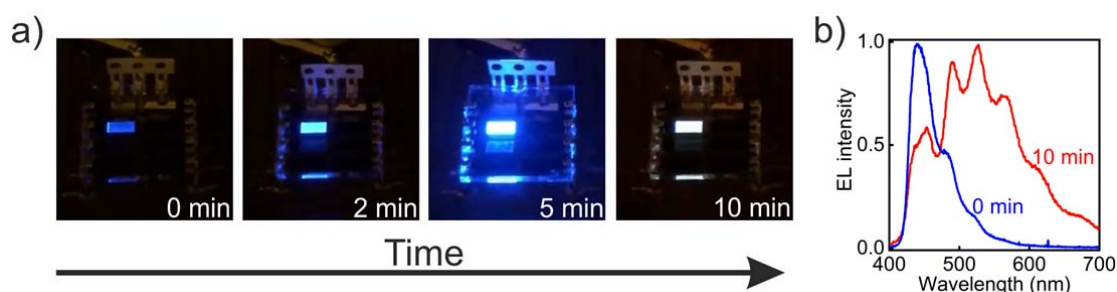
194 If a significant claim of a piece of research is a long-term stability enhancement, such reports must  
195 appropriately capture the operational stability of the devices over time. For this, EQE, or a proxy such  
196 as luminance, should be presented as a function of time at a constant operational condition relevant  
197 to the application, for example constant current density corresponding to a starting luminance of 100  
198  $\text{cd/m}^2$ . It would be useful to also present results at both lower (e.g. starting at 10  $\text{cd/m}^2$ ) and higher  
199 ( $1000 \text{ cd/m}^2$ ) operational conditions to learn more about the limitations of the operating device.  
200 Typical metrics for this are the “T50” and “T95” values, or similar, which reflect the time taken by the  
201 LED to drop to 50% and 95% of their initial output, respectively. We strongly discourage the  
202 extrapolation of lifetimes extracted from measurement at one operating condition to a different  
203 operating condition; operating lifetime must always be directly measured unless lifetimes are so long  
204 that this is impractical. In this latter case, acceleration factors, for example acquired by operating at  
205 elevated current density and/or temperature, would be required to assess device stability in a practical  
206 period of time; such factors also yield valuable insight into degradation mechanisms. In addition,  
207 researchers should confirm the colour stability of the operating devices. Phase segregation in mixed  
208 halide perovskites, nanocrystal aggregation in confined systems and chemical degradation of organic  
209 species are examples that lead to colour instabilities (see example in Figure 2). One relevant example  
210 is in the case of blue LEDs, where one can overestimate the EQE if the emission shifts to the green  
211 during operation, a region at which many photodiodes have better sensitivities. We recommend

212 reporting the EL spectrum of the device before and after the operational stability test. Researchers  
213 need not shy away from reporting LEDs incorporating emitting materials that have not yet reached  
214 sufficient stability levels, but rather these stability deficiencies should be transparently and honestly  
215 reported to allow further development by the wider community.

216 We also emphasise the importance of stating all measurement conditions including environment  
217 (humidity, oxygen) and, ideally, temperature. For rigorous stability testing, we recommend maintaining  
218 device temperatures in the range between 25 °C and 35 °C to ensure typical and reproducible  
219 laboratory conditions. Minimising exposure of the device to moisture and oxygen from the  
220 surroundings is important due to the detrimental (and, often, unpredictable) effect on material  
221 performance. Any packaging or encapsulation protocols must be specified in detail to allow them to  
222 be reproduced and adequately compared.

### 223 Concluding remarks

224 This Comment outlines critical performance measurement considerations for emerging LEDs to  
225 ensure best practice. We encourage the reporting of device failures in any of the key parameters  
226 since this will open up new research paths to address such issues. Furthermore, researchers should  
227 appropriately report the statistics of device performance, including not only the champion  
228 performances but also the metrics such as the mean and standard deviation; in this context, one  
229 should also clearly state whether the presented statistics relate to the evaluation of several pixels  
230 from the same device substrate, from different substrates and/or from independent device batches.  
231 Indeed, we urge researchers to report all details of materials synthesis, device fabrication and  
232 measurement protocols, no matter how seemingly insignificant, to provide better reproducibility  
233 between laboratories. Furthermore, we encourage independent measurement of device performance  
234 through external laboratories or industry, for example through round-robin studies, to better validate  
235 measured performances. Independent certification centres similar to those existing for photovoltaic  
236 technologies may be an interesting concept to explore provided there is sufficient demand, though  
237 this may only be needed when devices are approaching performance limits and further efficiency  
238 increments require exceptional precision and validation. The proper implementation of the protocols  
239 discussed in this Comment will allow the unambiguous characterisation of novel LEDs at the  
240 laboratory scale, ultimately leading to more rapid progress in performance and stability towards  
241 downstream applications.



243

244 **Figure 2.** Example of colour instability: from blue to white in a suboptimal TFB-based OLED at a  
 245 constant bias of 8 V during 10 minutes exposure in air. (a) Digital camera pictures of the device during  
 246 degradation. (b) Electroluminescence spectra of the device at the initial and the final stage.

247

248 Table. **Checklist for papers reporting emerging LEDs.**

- 249 i) *EQE vs J* and, if appropriate, *luminous efficacy vs J* or *luminance*.  
 250 ii) *J* and *luminance/radiance vs V* (carefully monitoring for any transient changes); comment on  
 251 maximum achievable brightness and roll-off.  
 252 iii) *EL* spectrum, wavelength of the peak maximum and *FWHM*.  
 253 iv) Colour coordinates (CIE). Only applies for visible emission.  
 254 v) Correlated colour temperature (CCT) and colour rendering index (CRI). Only applies for white-  
 255 light LEDs.  
 256 vi) Full details on calibration protocols, measurement setup (physical dimensions of the device and  
 257 the detector, and the distance between them) and assumptions made regarding  
 258 emission/collection profiles.

259 For reports focussing on long-term stability:

- 260 vii) Operational stability. Emitted photons over time vs constant *J* (or constant detection).  
 261 viii) Colour stability. *EL* spectrum at  $t=0$  and  $t=\text{final}$  for fixed *J*.

1 Greenham, N. C., Friend, R. H. & Bradley, D. D. C. *Adv. Mater.* **6**, 491-494 (1994).

2 Forrest, S. R., Bradley, D. D. C. & Thomson M. E. *Adv. Mater.* **15**, 1043-1048 (2003).

3 Methods approved by the Illuminating Engineering Society of North America (IESNA): LM-79-08, LM-80-08, TM-21-11, and LM-82-12.

4 Ai, X. *et al. Nature* **563**, 536-540 (2018).

5 Yang, Y. *et al. Nature Photonics* **9**, 259-266 (2015).

6 Cao, Y. *et al. Nature* **562**, 249-253 (2018).

7 Lin, K. *et al. Nature* **562**, 245-248 (2018).

8 Zhao, B. *et al. Nature Photonics* **12**, 783-789 (2018).

9 Stranks, S. D., Hoyer, R. L. Z., Di, D., Friend, R. H. & Deschler, F. *Adv. Mater.* 1803336 (2018).

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10 Kim, K.-H. *et al.* *Nat. Commun.* 5:4769 (2014).

11 Lee, E. *et al.* *J. Inf. Disp.* **17**, 151-158 (2016).

12 Light and lighting. Lighting at work places. European Standard EN 12464-1:2011 and EN 12464-2:2014.

13 US General Services Administration, GSA, 6.15 Lighting, 2014.

14 Commission Internationale de l'Eclairage, Colorimetry, 3rd edition, CIE 15:2004.

15 Commission Internationale de l'Eclairage, Method of Measuring and Specifying Colour Rendering of Light Sources, CIE 13.3-1995.

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