LUMILEDS

Oeko-Institut e.V.
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Via E-Mail: rohs.exemptions@oeko.de

Aachen, December 14, 2015

Input for stakeholder consultation for RoHS exemption requests 2013-2 and 2013-5

Dear Dr. Gensch,

We appreciate the opportunity to provide input on the aforementioned RoHS exemption requests. Further to the letter sent by LightingEurope on December 9, 2015, we would like to provide the attached technical input and responses to your questions. Please also find a preliminary life-cycle assessment enclosed. We are in the process of verifying the life-cycle assessment with an independent third party and will submit the verified report at a later time.

Sincerely,

Mircea Buzgar
Senior Vice President

Willi Thelen
Managing Director

Response to “Consultation Questionnaire Regarding CdQD Exemptions” by Oeko Institut

1. The two applicants originally requested exemptions with different wording formulations, however in the course of the first evaluation it was understood that both exemptions are to allow placing Cd QD technologies on the EU market in various products. During the first evaluation the applicants were asked to confirm if the following formulation would cover the applications for which the exemptions had been requested:
Cadmium in components for lighting applications and display lighting applications, containing downshifting cadmium based semiconductor nanocrystal quantum dots, where the cadmium per display screen area is limited to less than 0.2 ug/mm².

This formulation was later used as a basis to separate between display lighting and solid-state lighting applications in the context of a possible exemption. If the exemption is to be recommended, a split shall most likely be proposed between the use of such cadmium components in solid state lighting applications and in display lighting applications. Exemption evaluation under Directive 2011/65/EU

a. Do you agree that the formulation above covers the cadmium quantum dot technologies addressed in the two exemption requests? If not, please explain why.

In principle, the above wording is adequate and covers the two exemption requests. However, we believe the wording can be improved. Please see our response to question 1c.

We understand the concentration limit of 0.2 µg/mm² to be applicable only to display products. If a maximum limit for lighting applications were proposed, the exact definition and limit value would need to be reconsidered as the definition of display screen area is not applicable to lighting products.

b. If the exemption is to be split according to application field (SSL and display lighting) please specify what wording formulation would best cover each of the application areas.

We propose the following wording:

- *“Cadmium in light control materials used for lighting devices”*
- *“Cadmium in light control materials used for display devices”*

c. Please suggest an alternative wording and explain your proposal, if you do not agree with the proposed exemption wording or with the proposed split.

The terms “nanocrystal” and “quantum dot” seem redundant. At least one of the two terms should be removed. In addition, both terms are not clearly defined within the context of this regulation. This may lead to unnecessary uncertainty and misunderstandings.

For the reasons stated in the letter of LightingEurope in response to consultations 2013-2 and 2013-5 (dated November 11, 2013)[1], we believe it is preferable not to specify a maximum concentration.

We recommend the following wording, as proposed by LightingEurope in the aforementioned letter: *“Cadmium in light control materials used for lighting- and display devices”*

d. Please explain why you either support the applicant’s request or object to it. To support your views, please provide detailed technical argumentation / evidence in line with the criteria in Art. 5(1)(a) to support your statement.

We agree with the request to grant an exemption for the use of cadmium in solid-state lighting.

As explained by UNEP, “Electricity for lighting accounts for between 15% (UNEP, 2014) and 19% (IEA, 2006) of global electricity consumption and between 5 and 6% of worldwide CO_2 emissions. A global transition to widely available efficient solutions in all lighting sectors (residential, commercial/industrial and outdoor) by 2030 could

[1] http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20131111_Lighting_Europe_WG_Material_support_letter_RoHSexemption39_Ex_Re_2013-2-5_final.pdf

reduce electricity demand for lighting by more than 32%, and avoid 3.5 Gt of CO_2. […] If the world leapfrogged to LED lamps in all sectors, it would reduce global electricity consumption for lighting by more than 52% and avoid 735 million tonnes of CO_2 emissions each year."[2] The application of quantum dot technology will accelerate this transition and further increase the potential savings of current LED lamps in electricity consumption and resulting CO_2 emissions, as outlined below.

The safe use of minimal amounts of cadmium can lead to a significant increase in the luminous efficacy of LED lamps, especially for warm-white light sources (as used for example in residential buildings) with high color quality. The same energy savings cannot currently be reached with similar technologies while maintaining product reliability and lifetime.

Introduction to quantum dot technology

Conventional solid-state lighting technology is based on blue LEDs exciting a garnet and red phosphor (phosphorescent light downconverter) to generate green, yellow and some red light, which is mixed to form white light for illumination purposes. To create warm white light (CCT<3500K) with a high quality of light (CRI>90) it is necessary to add a significantly higher amount of red phosphor of longer wavelengths to produce the warm tones missing from the garnet phosphor spectrum. The problem with conventional red phosphors is that they have a broad spectrum and are therefore less efficient than green phosphors. LEDs with CRI>90 have lower luminous efficiency than LEDs with CRI of 80 because of the greater fraction of LED emission spectra needed in the far-red wavelength region. The broad spectrum of conventional red phosphors exacerbates the drop in luminous efficacy as the emission further reaches deep red and infrared wavelengths where the eye sensitivity is low. Similar to incandescent bulbs, a significant part of the generated light is wasted as infrared radiation.

Quantum dots (QDs) are a relatively new material class that, like phosphors, down-convert light from higher energy wavelengths of typically blue light to lower energy wavelengths of green or red light. Key characteristics of quantum dots are their potentially very high efficiency, their narrow emission spectrum, and that their emission frequency can be accurately tuned across the entire visible spectrum. The narrow emission spectrum prevents the needless generation of invisible infrared radiation (see Figure 1). No other downconverter exists which exhibits narrow emission (<35nm FWHM), is emission tunable to within a nm, and has extremely high photoluminescence quantum efficiencies, both at room temperature and LED operating temperatures.

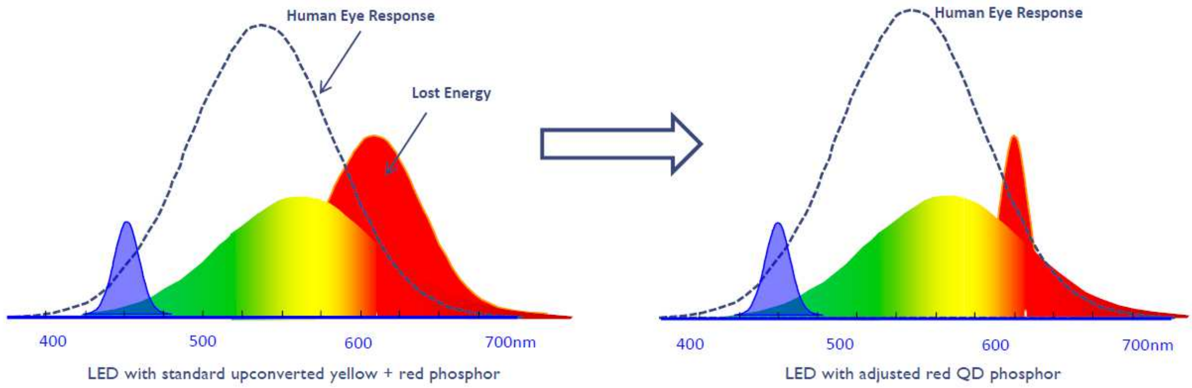

Figure 1: Comparison of QD and conventional phosphor spectrum (Source: Yole Développement, "Phosphors and Quantum Dots 2015: LED Downconverters for Lighting and Display Applications", 2015)

Until now, quantum dots could not be used directly in LED packages because their reliability and performance at the high operating temperatures encountered in LED packages was not sufficient. However, new developments allow quantum dots to be placed inside the LED package, directly on top of the semiconductor material (i.e. the LED die), which will finally enable their use in LED lighting. At the moment, the only type of quantum dot that can be used in this configuration and has the aforementioned advantageous properties is a cadmium containing quantum dot. Cadmium

[2] Sustainable Energy for All Initiative, United Nations, "Global Energy Efficiency Accelerator Platform – Lighting", http://www.se4all.org/energyefficiencyplatform/lighting/, accessed November 25, 2015

is a component in II-IV semiconductor quantum dots (typically based on CdSe or CdS) and is used in the quantum dot core or quantum dot shell.

Expected performance improvements

Luminous efficacy improvements are especially significant for warm-white lamps with a high quality of light (i.e. good color rendering properties). The higher the CRI, the larger the red content and the greater the visual impact and benefit of the quantum dots. Improvements of more than 20% are possible[3] [4]. Based on internal data we expect that the following efficacy improvements can be achieved within the next two years (at a given CCT/CRI combination, relative to current conventional phosphors):

		CCT		
CRI	**R9**	2700K	3000K	4000K
80	0	4.5%* (6.5%**)	5%**	3%**
90	50	25%*	22%**	16%**

*experimentally validated; **expected performance from modeling.

Please refer to section 4b for an explanation of the relevance of the parameters (CCT, CRI, and R9).

The table below shows the performance of two LED lamps (with and without quantum dots) with similar performance as that of a 60W incandescent lamp (CCT of 2700K, CRI of 90).

	LED lamp using conventional phosphors	**LED lamp using quantum dots**
Light output	843lm	843lm
Number of LED packages	12	12
LED package efficacy	92lm/W	115lm/W
Amount of cadmium per LED package		2.55µg
Amount of cadmium per LED lamp		30.6µg
Efficiency losses due to drivers/optics	15%	15%
Lamp efficacy	78lm/W	98lm/W
Lamp power consumption	10.8W	8.60W

The power consumption of the LED lamp containing quantum dots is 2.20W lower than that of the LED lamp using conventional phosphors. The resulting savings by far outweigh any potential negative health, safety and environmental effects that cadmium inside the products may have. The environmental impact of this typical lamp, as well as the performance of a typical luminaire, is analyzed in detail in the enclosed life cycle analysis.

The efficiency gains from the use of quantum dots are biggest for warm-white, high CRI products with a high quality of light, i.e. they are similar to the light from incandescent or halogen lamps commonly used in residential applications. Quality of light is often seen as one of the blocking points for the adoption of new lighting technologies. Slow uptake of compact fluorescent lamps is attributed in part to their poor quality of light when the technology was first introduced to consumers[5]. Poor quality of light also risks the slow adoption of efficient LED lighting technologies[6]. Enabling LED products with superior light quality through the use of quantum dots will further accelerate the uptake of efficient solid-state lighting technology.

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[3] Yole Développement, "Phosphors and Quantum Dots 2015: LED Downconverters for Lighting and Display Applications", 2015

[4] S. Nizamoglu, T. Erdem, X. W. Sun and H. V. Demir, "Warm-white light-emitting diodes integrated with colloidal quantum dots for high luminous efficacy and color rendering," Optics letters, vol. 35, no. 20, pp. 3372-3374, 2010

[5] Sandahl, at al., "Solid-State Lighting: Early Lessons Learned on the Way to Market," 2014

[6] Sandahl, et al., "Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market", 2006

Total energy savings and total cadmium use

In Europe, an estimated 7.5 billion (assuming EU has 27% market share of global market)[7] to 10 billion[8] lamps are installed (2012). We expect that about 2.55µg of cadmium will initially be used per white LED package[9]. For a reference lamp (as described above) containing 12 LED packages, the cadmium content per light source is expected to be about 30.6µg. If all light sources in the entire EU were converted to cadmium containing quantum dot LEDs overnight, an estimated 230kg – 306kg of cadmium would be needed. A similar estimate, focusing on the residential sector only[10], is possible based on the total lighting capacity installed. In the EU, the lighting capacity in the residential sector is 3.92Tlm (Tera lumen, 10^{12})[8]. The following table compares the scenarios of using LED lamps based on conventional phosphors and LED lamps based on quantum dots to provide this light output

	Lighting with LED lamps based on conventional phosphors	Lighting with LED lamps based on quantum dots
Total light output in residential sector	3.92Tlm	3.92Tlm
Light output per lamp	843lm	843lm
Number of 843lm lamps required	4.65 billion	4.65 billion
Power consumption of 843lm lamp	10.8W	8.60W
Annual operating hours of lamp[8]	500h	500h
Total power consumption (per year)	25.1TWh	20.0TWh
Total amount of cadmium		142kg

The use of quantum dot LED lamps would reduce electricity consumption by 5.1TWh per year (compared to a baseline scenario where all residential light is provided by LED lamps). This reduced electricity use would lower CO_2 emissions by 2.69 million tonnes per year (assuming CO_2 emission intensity of 528 g/kWh[11]).

In addition to the reduction in CO_2 emissions, also other emissions from power plants will be reduced, including cadmium emissions. With the current EU energy mix, about 3.8µg of cadmium are emitted per kWh[12] [13]. A quantum dot LED lamp that uses 2.20W less than a conventional LED lamp, and which lasts for 20000h, will consume 44kWh less than the conventional LED lamp over its entire lifetime. This reduces cadmium emissions from electricity generation by 167µg per LED lamp, over the entire lifecycle of the LED lamp (assuming current energy mix). As the LED lamp contains 30.6µg cadmium, using a quantum dot LED lamp will result in net savings of 136µg per LED lamp. At 4.65 billion lamps, the total net savings amount to 634kg.

The chart below shows the CO_2 reduction, cadmium use and reductions in cadmium emissions as a function of market share (relative to scenario with 100% conventional LED lamps, for residential lighting, based on above

[7] McKinsey & Company, "Lighting the way: Perspectives on the global lighting market", 2012

[8] VHK, "Model for European Light Source Analysis (MELISA) version 0", prepared for the European Commission, Brussels, 31 January 2015

[9] For comparison, the amount of cadmium in a single cigarette is approximately 0.5µg – 1.5µg. Bernhard, David, Andrea Rossmann, and Georg Wick. "Metals in cigarette smoke." Iubmb Life 57.12, p. 805, 2005

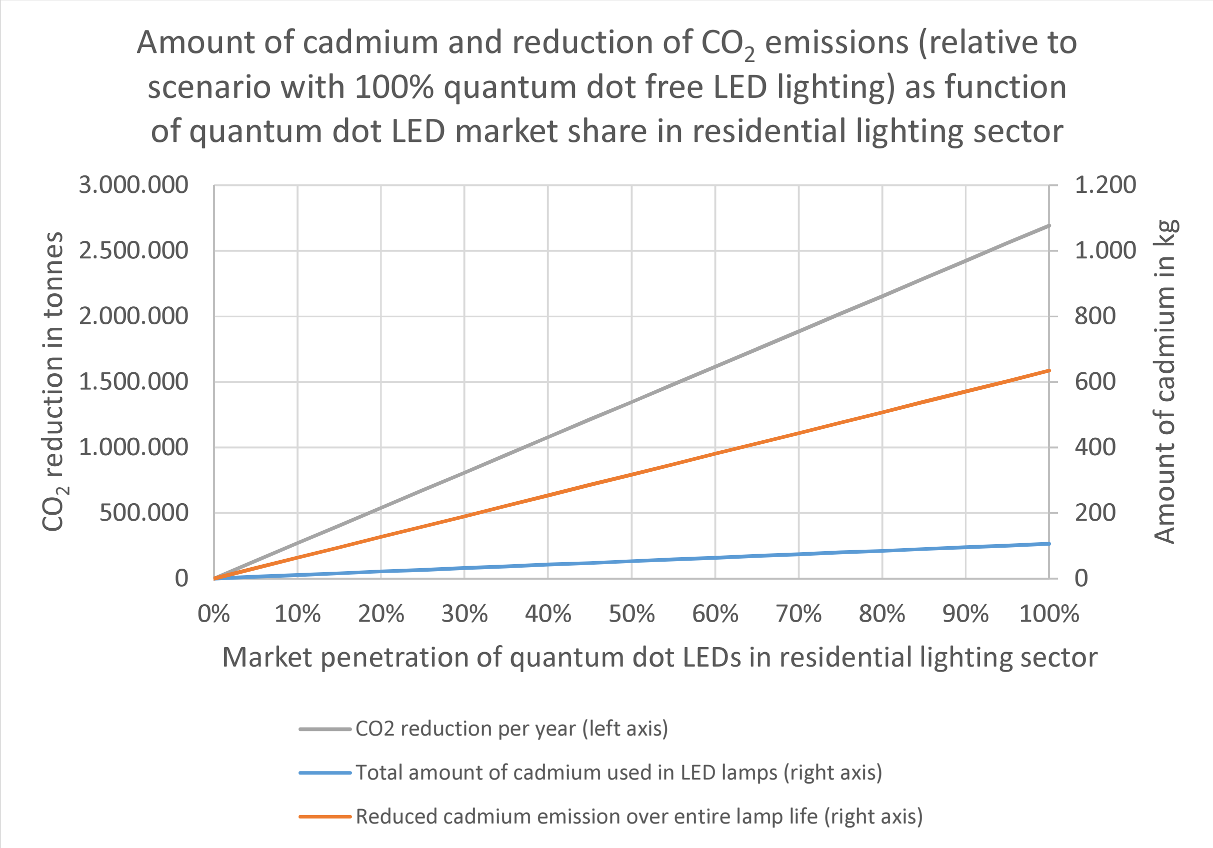
[10] Quantum dot products show biggest performance improvements for warm-white, high CRI products. These products are commonly used in residential applications and less frequently in e.g. industrial applications.

[11] Weidema, B.P.; Bauer, Ch.; Hischier, R.; Mutel, Ch.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O.; Wernet, G, 2013, The ecoinvent database: Overview and methodology, Data quality guideline for the ecoinvent database version 3, www.ecoinvent.org

[12] Gensch, Carl-Otto, Yifaat Baron, Markus Blepp and Otmar Deubzer, Assistance to the Commission on Technological Socio-Economic and Cost-Benefit Assessment Related to Exemptions from the Substance Restrictions in Electrical and Electronic Equipment (RoHS Directive) Final Report – Pack 4, p. 80, 2014

[13] As a reference solar cells have lifecycle cadmium emissions of 0.3µg/kWh – 0.9µg/kWh as mentioned by E. Alsema, M. de Wild-Scholten and V. Fthenakis, "Environmental Impacts of PV Electricity Generation - A Critical Comparison of Energy Supply Options," in 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 2006

assumptions):



Recyclability and potential risks from the use of quantum dots

As mentioned by the other applicants, without exposure to the quantum dot, there is no health risk[14]. Similar to display products, quantum dot solid-state lighting products are not likely to be handled, mechanically treated, or otherwise modified by a consumer in such a way that cadmium could be released. The cadmium element is bound by covalent bonds within the semiconductor material, the semiconductor quantum dots themselves are in turn bound inside the carrier silicone matrix cured on top of the LED chip, thus forming an LED package, which is in turn integrated into the lamp or luminaire, so the risk of consumer exposure to cadmium during the use phase is extremely low. Similarly, exposure of consumers to cadmium released to the environment from these products as a consequence of end-of-life or recycling operations is very unlikely.

In production, cadmium can be handled safely so as to pose no risk to workers. Cadmium is used in various production processes, e.g. for nickel-cadmium (NiCd) batteries, electrical contacts, and filter glass. Adequate measures are in place to safeguard workers in factories. The industry has extensive experience with handling dangerous substances and can do so safely.

As pointed out by Linnunmaa, “occupational exposure to cadmium from quantum dot products could potentially take place during end-of-life or recycling operations, but only under exceptional circumstances. […] The occupational exposure limit of cadmium is 0.02 mg/m^3 […]. It is unlikely that such a high dust concentration could be formed in a realistic occupational exposure scenario. […] In quantum dot lighting devices and displays, cadmium concentrations

[14] 3M Display Materials & Systems Division, “Re: 1st Questionnaire Regarding CdQD Exemptions”, 2015

are maximally 5000 ppm or 0.5%. Therefore the theoretical risk for occupational cadmium exposure due to quantum dot products is insignificant as compared with operations with nickel-cadmium batteries."[15]

LED lamps are in scope of the WEEE directive[16]. Manufacturers are responsible for end of life products; collection and recycling targets are in place. European lamp companies have founded collection and recycling organizations in the EU member-states (e.g. Recolight in the UK or Lightcycle in Germany) with the objective to organize the collection and recycling of lamps. Recyclers have confirmed that recycling of displays containing cadmium can be done safely[17], and the same applies for LED lamps. In recycling, a high level of cadmium extraction from the polymer matrix can be achieved by using strong acids such as nitric acid[18]. Recycling of cadmium from NiCd batteries is possible[19], as is recycling of mercury containing fluorescent lamps[20].

If, for some reason, full recycling of cadmium from quantum dot LEDs should not be feasible, some part of the waste will have to go to landfill. Hazardous waste landfills exist[21] and can be constructed in such a way that hazardous waste does not leach into groundwater[22]. In addition, cadmium is typically not produced specifically for the use in quantum dots. Instead, cadmium is a by-product of zinc production[23] [24]. Per the European Chemicals Bureau, "Cadmium is a naturally occurring element with ubiquitous distribution. Although cadmium ores also exist (greenockite) these are not commercially important. Zinc (sulphide) ores are the primary source for cadmium production. Smaller amounts of cadmium are produced during the production of other non-ferrous metals such as lead. In the refining of these ores cadmium is obtained as a by-product."[25] Cadmium from zinc production needs to be treated anyhow. Using cadmium in LED lamps shifts treatment to a different point in the waste stream, i.e. after the cadmium has been put to meaningful use.

Unfortunately it is possible that LED lamps containing cadmium are not properly collected and recycled. At the moment, LED lamps, due to their long lifetime, only make up a very small fraction of all lamps that are being collected[26]. By the time that cadmium containing LED lamps enter the waste stream it is expected that collection rates will have increased further, but even then 100% collection cannot be guaranteed. Lamps that were disposed off together with household waste will most likely go to landfill or will be incinerated. If the products are placed in a landfill, it is theoretically possible that materials leach from the product over time. We have performed leaching tests on LED packages that contain cadmium quantum dots. Cadmium could not be detected in the leachate, showing that the cadmium is securely bound inside the LED package. If, on the other hand, the products are incinerated it is expected that the polymer will be destroyed and "the core CdSe material will be converted to a CdO compound that will become part of the incinerator ash. Generally waste incinerators have excellent ash controls and release little

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[15] QD Vision, Inc., Linnunmaa Ltd, "Expert statement on LCA of Cd vs. non-Cd options for colour conversion in displays and lighting systems", 2012

[16] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)

[17] A. Krebs, Letter to Oeko Institute dated November 5, 2013, Blubox Trading AG

[18] QD Vision, Inc., Linnunmaa Ltd, "Expert statement on LCA of Cd vs. non-Cd options for colour conversion in displays and lighting systems", 2012

[19] European Chemicals Bureau, "European Union Risk Assessment Report, Cadmium and cadmium oxide", 2007

[20] LightingEurope, Request to renew Exemption 1(a) under the RoHS Directive 2011/65/EU for Mercury in single-capped (compact) fluorescent lamps below 30 W, 2015

[21] European Commission, "Waste – Introduction", http://ec.europa.eu/environment/waste/landfill_index.htm, accessed November 27, 2015

[22] Encyclopaedia Britannica, "Hazardous-waste management", http://www.britannica.com/technology/hazardous-waste-management, accessed November 27, 2015

[23] E. Alsema, M. de Wild-Scholten and V. Fthenakis, "Environmental Impacts of PV Electricity Generation - A Critical Comparison of Energy Supply Options," in 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 2006.

[24] V. M. Fthenakis, "Life cycle impact analysis of cadmium in CdTe PV production," Renewable and Sustainable Energy Reviews, vol. 8, pp. 303-334, 2004.

[25] European Chemicals Bureau, "European Union Risk Assessment Report, Cadmium and cadmium oxide", 2007

[26] Recolight, "LED recycling," http://www.recolight.co.uk/lighting-producers/how-we-recycle/led-recycling.aspx, accessed October 30 2015

solid material in the flue gas" (assumption is that ninety percent removal of ash from flue gas is possible).[27] This means that very little cadmium would be released into the environment (and the method of release is similar to the cadmium release from current coal power plants).

In summary, we believe that using cadmium in quantum dot LEDs has the potential to significantly improve energy efficiency. The potential negative impact of this use of cadmium is very small in comparison. We therefore believe that an exemption is justified under the requirements of RoHS Article 5(1)(a).

2. At the time of the first review, difficulties regarding the comparison of Cd QDs in display applications and Cd-free QDs in display applications, did not allow making a well-balanced comparison of these technologies. In the meantime, it has become apparent that the market situation of these products has changed, possibly allowing a better comparison and evaluation as to the environmental performance of these technologies and other related aspects. The two applicants and a manufacturer of a substitute candidate have provided information regarding applications that are already on the market using the Cd based and Cd free technologies. Please review this information and comment:

We do not have additional insights into display applications and do not wish to submit comments to display related questions.

3. Please specify on the basis of what regulations/standards a comparison of these technologies in relation to the performance of the relevant product (TV, display, tablet, mobile-phone, solid state illumination applications) can be made, in particular in relation to the consumption of energy during various use modes (standby and other operation modes, operation with different brightness/contrast settings; display of images with higher or lower contrast or differing hues; etc.)

Relevant standards and regulations for lighting applications are:

- EU implementing measure 1194/2012 (Ecodesign requirements for directional lamps, light emitting diode lamps and related equipment)
- Standard CIE S 025 (Test Method for LED Lamps, LED Luminaires and LED Modules)

More information regarding the applicability of these standards is provided in our response to question 4b.

4. At the time of the first review, it was understood from various stakeholders that the Cd-based and Cd-free quantum dot technologies were also being developed for possible future use in solid-state illumination applications. The two applicants and a manufacturer of a substitute candidate have provided information regarding applications that are already on the market using the Cd based and Cd free technologies. Please review this information and comment:

a. If additional lighting products (solid state illumination) have become available on the EU market since 2014.

We are not aware of any additional lighting products employing quantum dot technology having been placed on the market. LED products using quantum dot technology – with or without cadmium – are currently not widely available, though years of investment toward their development are paying off: Lumileds intends to launch LED packages containing cadmium-based quantum dots in 2016.

However, the uncertainty around this exemption leads to reluctance by lamp and luminaire manufacturers to invest into the technology, explore its full potential and develop products.

As quantum dots are a new technology, we believe that the assessment should be based on the improvement potential of this new technology related to environment, consumer safety and health. The availability of products on

[27] R. E. Engler, L. S. MacDougall, J. B. Xu and J. Willis, "Supplemental Statement on Life Cycle Analysis and Comparison of Cadmium (CASRN 7440-43-9, EC 231-152-8), Cadmium Selenide (CASRN 1306-24-7, EC215-148-3) vs. Indium Phosphide (CASRN 22398-80-7,EC 244-959-5) for Color Conversion in Displays", The Acta Group, L.L.C. on behalf of QD Vision, Inc., 2015

the market should not be a prerequisite as long as sufficient evidence supporting the claims can be provided. This is in line with the focus of the EU on eco-innovation.

When products become available, their environmental performance can be assessed and the exemption can be re-evaluated. If deemed necessary an exemption could even be withdrawn at that time. Manufacturers are aware of this, so they are unlikely to make the investments required for placing such products on the market unless the claimed performance can be reached.

b. Please clarify for Cd-based and Cd-free products as described in a), what parameters are relevant for enabling a comprehensive comparison of performance to clarify how the technologies compare in relation to performance in general and in particular to environmental performance;

Product performance

In the case of lamps producing white light for general illumination, product performance is measured by:

- luminous flux (the amount of visible light generated by the lamp),
- luminous efficacy (the luminous flux divided by the electric input power),
- color temperature (CCT, how warm or cold/blue-ish the light appears)
- and color rendering index (CRI, how well a light source reproduces the colors of the objects it illuminates).

The luminous flux, color temperature and color rendering properties of an LED lamp must be reported according to EU implementing measure 1194/2012. In addition, the color rendering index must be at least 80. Other parameters listed by the EU implementing measure are of lesser relevance for this assessment because they relate to specific applications or to parts of the lamp that are not relevant for this assessment (e.g. beam angle or starting time).

All four parameters, CCT, CRI, efficacy and luminous flux, should be measured according to the international standard CIE S 025, issued by the International Commission on Illumination.

Environmental performance

As with any other technology, the environmental impact of LED light sources is measured by the material and energy resources used over the entire life-cycle of the product (production, use, recycling and/or disposal). In the case of all lighting technologies (incandescent, fluorescent, discharge, LED), the total life-cycle consumption is dominated by the electricity consumption during the use phase[28]. As noted by the U.S. Department of Energy, "the greatest environmental impact after energy in-use for the LED sources is the aluminum heat sink, which would be reduced in size as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat)."[29] Most other parameters will not change significantly due to the introduction of quantum dots (e.g. energy consumption of LED die and package production, material use for LED lamp). Consequently, the most important parameter by far for assessing environmental performance of a light source is its luminous efficacy, i.e. the ratio of visible light output (luminous flux, measured in lumens) and power consumption (in watts). The luminous efficacy (in lumens per watt or lm/W) should be measured according to international standard CIE S 025.

It is important to note that there is an inherent trade-off between color temperature (CCT), color rendering index (CRI) and luminous efficacy. This is due to the fact that the human eye is not equally sensitive to all wavelengths, i.e. to all colors of light. Going from CRI 80 to CRI 90 and all other things being equal is thought to result in a 20% decrease in luminous flux[30]. Newly proposed energy efficiency regulations are likely to allow products with a high CRI to have a

[28] US Department of Energy, "Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products", 2013

[29] US Department of Energy, "Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products - Part 2: LED Manufacturing and Performance", 2012

[30] http://www.ledsmagazine.com/articles/2013/01/lighting-coalition-asks-epa-to-lower-energy-star-efficacy-specs-for-high-cri-lamps.html

lower energy efficiency[31]. Due to this significant impact of CRI and CCT on the luminous efficacy, it is important to compare the energy efficiency of products with the same CCT and CRI only[32].

Related to the color rendering index is the R9 value, which is a specific measure for the ability of a light source to render deep-red colors and skin accurately. Similar to the CRI value, high R9 values will also result in lower luminous efficacy. High R9 values are generally preferred and, again, only products with similar R9 values should be compared. Like CRI, R9 is measured using CIE S 025 (for measurement of lamp spectrum) and CIE 13.3-1995 (for calculation of the CRI and R9 values).

In summary, the most important figure of merit to assess environmental performance is the luminous efficacy of a light source. Only products with the same color temperature (CCT), color rendering index (CRI) and R9 value should be compared.

A suitable color temperature for benchmarking is 2700K (warm white), which is equivalent to the color temperature of incandescent light bulbs and is frequently recommended for residential use[33]. CRI values of 90 and an R9 value of 50 are appropriate. The EU regulation 1194/2012 requires a minimum CRI of 80 (for residential use), but better color rendering properties are recommended[33].

c. Please state if you agree with the detailed parameters mentioned by the three actors as relevant for enabling a comprehensive comparison of performance of the technologies (general performance and environmental performance); Please explain your views and if relevant specify other parameters that should be considered.

We agree with the parameters provided by Nanoco. Luminous efficacy (in lm/W) is the key environmental parameter. CRI, CCT and R9 describe product performance, and only products with equal performance should be compared. With these independent variables fixed, luminous efficacy between products and between technologies (the dependent variable) can be compared. Additional details are provided in our response to question 4b.

5. The applicants and a manufacturer of a substitute candidate have provided information as to the compounds used in Cd-free and Cd-based technologies relevant to the exemption requests, and as to their potential hazardousness and toxicity. Please state with which of the views presented you agree or disagree and explain why;

We are of the opinion that the manufacturers of the quantum dots are in a much better position to assess the toxicity of materials used. We are incorporating the substances into our articles, but we are not the original formulator.

We agree with the views expressed by 3M: “3M believes it is difficult to determine if a cadmium selenide core QD is more toxic, less toxic, or of equal toxicity to an indium phosphide core quantum dot, since both cadmium and indium phosphide have significant human health hazard classifications.”

Overall we believe the associated risks (for both types of quantum dots) to be acceptably low during the entire product lifecycle, as expressed by both QD Vision and 3M:

- “In all fairness the risks of InP and CdSe should not be exaggerated – particularly in the QD form that they have they present no hazard to the user or the environment.” (QD Vision)
- “For the consumer who purchases an electronic device containing a 3M LCD Quantum Dot Enhancement Film, there is no exposure to the quantum dot. In the quantum dot the core is made out of CdSe encapsulated within a shell of ZnS. The quantum dot is contained within a polymer matrix, the polymer matrix is bonded on each side by a barrier film, and the final product is enclosed within the electronic device. As mentioned above, without exposure to the quantum dot, there is no health risk.” (3M)

[31] http://www.ledsmagazine.com/articles/2015/11/california-energy-commission-proposes-new-regulations-for-led-lamps.html

[32] US Department of Energy, “Energy Efficiency of LEDs,” 2013

[33] https://www.verbraucherzentrale.de/licht-richtig-auswaehlen

6. Please provide information as to research initiatives which are currently looking into the development of possible alternatives for some or all of the application range of Cd in the scope of the requested exemptions (and among others in the scope of Ex. 39);

a. Please explain what part of the application range is of relevance for such initiatives (in what applications substitution may be possible in the future).

A number of materials can be used instead of cadmium containing quantum dots, including current conventional phosphors. None of these materials possess the same combination of properties as cadmium quantum dots. Either they do not have the same thermal stability or the same efficiency.

Lumileds operates a research center for phosphor materials in Aachen, Germany, and is actively developing phosphor materials with emission properties similar to those of quantum dots. Lumileds pioneered novel strontium lithium aluminum (SLA) nitrides that demonstrate reduced width of spectrum down to 50nm (FWHM).[34] This narrow phosphor provides efficiency gains over conventional broad (70nm FWHM) phosphors. The material properties currently limit the luminous efficacy improvements to approximately 4% for color temperatures used in general illumination. We do not know if and when such materials will have equal or better performance than quantum dots.

We are also investigating the use of other types of quantum dots, but have so far not found alternatives that provide the same on-chip thermal stability and efficiency gain as cadmium quantum dots. Once quantum dots that do not contain cadmium become available with sufficient performance, they can easily be substituted for cadmium quantum dots. In that sense, cadmium quantum dots can be a stepping stone for other quantum dots.

b. Please provide a roadmap of such on-going research (phases that are to be carried out), detailing the current status as well as the estimated time needed for further stages.

We cannot provide a roadmap for research activities. In general, such fundamental research will take many years and industrialization/commercialization of the research results will also require additional time.

[34] Pust et al., "Narrow-band red-emitting Sr[LiAl3N4]:Eu2+ as a next-generation LED-phosphor material", Nature Materials 13, pp. 891-896, 2014