Questionnaire on CD QD applications and their substitutes

Consultation as part of the RoHS CD QD Follow-up Study

Abbreviations and Definitions

Cd	Cadmium
EEE	Electrical and Electronic Equipment
LE	LightingEurope (applicant of exemption)
Najing	Najing technology Co. Ltd (applicant of exemption)
OSRAM	OSRAM Opto Semiconductor GmbH (applicant of exemption)
CRI	Color Rendering Index
RoHS	Directive 2011/65/EU on the Restriction of Hazardous Substances in Electrical and Electronic Equipment
SSL	Solid-state lighting
QD	Quantum dots

Background

The Oeko-Institut has been appointed by the European Commission, to provide technical and scientific support in a review of cadmium (Cd) quantum dot (QD) applications. Such applications were subject of an assessment of exemptions performed as Pack 15 Task 5 "Assessing three exemption requests for the use of cadmium in quantum dot applications in displays and lighting", finalised in 2020 and published in January 2021 (European Commission. Directorate General for Environment. et al. 2021).

The following table below specifies the three exemptions that were requested in the RoHS Pack 15 assessment, their respective applicant and the recommendations given in the assessment study.

A decision on the fate of these exemptions is still pending, and Oeko-Institut has been requested to review the current state of scientific and technical progress of Cd QDs in lighting and display applications and the comparative status of possible Cd-free substitutes for such applications, to consider if exemptions for Cd in these applications are still justified under the regime of Directive 2011/65/EU (RoHS 2).

Your organisation has expressed interest to contribute information to this study, has already contributed to the past assessment and/or is of special interest due to insights into recycling systems treating Cadmium. We would thus request you to provide information to the questions specified below, or any other information that you find to be relevant to this process.

Table 1-1: Overview of the exemption requested, associated recommendation and proposed expiry date

Ex. Req. No.	Requested exemption wording	Applicant/s	Recommendation	Expiry date and scope
Request 2018-1	"Cadmium (<1000 ppm) in luminescent material for on-chip application on LED semiconductor chips for use in lighting applications of at least CRI 80" requested to be valid for 5 years	*LE*	*"Cadmium in downshifting semiconductor nanocrystal quantum dots* *I. directly deposited on LED semiconductor chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface)* *II. directly deposited on LED semiconductor chips for use in lighting applications of at least CRI 90 (< 1.000 ppm in the luminescent material)* *provided that applications comply with entry 72 of Annex XVII of Regulation 1907/2006."*	5 years
Annex III, Ex. 39a	"Cadmium in downshifting semiconductor nanocrystal quantum dots directly deposited on LED chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface)" requested to be valid for 5 years	*Osram*		
Annex III, Ex. 39a	"Cadmium selenide in downshifting cadmium-based semiconductor nanocrystal quantum dots for use in display lighting applications (<0.1 µg per mm2 of display screen area)" requested to be valid until October 31, 2021	Najing	Denied	

Source: Oeko-Institut e.V, own compilation

1. Summary on CD QD applications and the status of their potential substitutes

QD are tiny crystals ranging from 1~100 nm. Their electrons are confined and thus exhibit a discrete energy spectrum. As the size can be tailor-made, this technology can be used for optical applications. QDs are used among others in display applications and in lighting applications.

From prior evaluations, the consultants are aware that there are three strategies or configurations in which QDs can be applied:

- '<u>On-edge technology</u>' has QDs incorporated into a remote component situated near the LED chips. This can be done for instance in an adjacent capillary. On-edge technologies allow a compromise between the risk of thermal degradation and the respective QD material requirements. This configuration was addressed in past evaluations but was not initially mentioned by the applicants in the Pack 15 review. It is understood to have become obsolete (Nanosys 2019).
- In '<u>on-surface technology</u>' the QDs are encapsulated in a film that covers the complete display area. This technology is the most intensive in terms of QD material usage, but can operate at near room temperatures, so that the thermal degradation risk is not an obstacle for practical application. On-surface technologies are also known as QD-films. Najing addressed such configurations in their request, referring only to display applications.
- In '<u>on-chip technology</u>', the QDs are placed on the LED surface, encapsulated within its package. This technology requires the lowest amount of QD material, however, due to the proximity to the light source, practical application was difficult to accomplish in the past as the QD material undergoes thermal degradation due to the proximity to the light emitting source. This configuration was addressed in the requests of LightingEurope and OSRAM and can be applied in both solid-state lighting and display applications. OSRAM (2019) further explains that there are two sub-cases for on-chip applications:
  - the dots are used close to the chip, around it, confined by the dimensions of an LED package, or
  - the quantum dots are highly concentrated in a thin layer on top of the chip whereas this layer has got similar outer dimensions as the chip i.e., smaller than the package.

From past assessments the consultants understand that CD QDs are used in lighting applications (SSL) and displays. The resulting recommendation of the last assessment was to grant an exemption only to on-chip technologies, as on-edge was already out-dated and on-surface was expected to be replaced within the following two years. For displays, one of the applicants stated that for on-surface technologies "t*he performance of Cd-free quantum dots (based on InP) is expected to reach the current colour quality and energy consumption performance of cadmium quantum dots by 2020. Full commercialization will be achieved by 2022*." Najing (2019). Thus, in the following, we will implicitly refer to on-chip technologies if not otherwise stated.

In displays, Cd-QD can be used to generate white light whose spectrum is tuned to match the colours of LCD pixels. In such displays, the LED spectrum contains the three RGB colours as a backlight. Other applications are in the field of lighting where especially narrow spectra are required. The main reason to use Cd-QD is its narrow full width half maximum of less than 30nm. If Cd-QD supplement green phosphor instead of red phosphors, the spectrum of the emitted light does not lean as much into the IR, meaning that less invisible heat radiation is wasted.

OSRAM (2018) explained that there were no alternatives at the time to Cd QD in the on-chip configurations as the operation conditions on the LED are too severe and existing alternatives at the time did not provide sufficient reliability. In a later communication, OSRAM (2019) provided a comparison of two types of on-chip applications in LED with a phosphor alternative. It was explained that one type uses less than 100 ppm cadmium and can be placed on the market already without an exemption due to the small amount of Cd. In contrast, the other type requires a higher content of Cd (<1000 ppm) but would also be more efficient in terms of energy consumption. Its placing on the market relies on the granting of an exemption. Benchmark testing of Cd-free QD on-chip has shown immediate loss of optical performance in minutes/few hours (OSRAM 2019).

Additional detail from the past assessment can be viewed in the assessment report[1] as well as in the webpage of the consultation[2] held as part of the last assessment.

Please consider details provided in the last assessment when answering the questions specified below.

The answers included in the questionnaire below are relevant for both:

The "*LightingEurope exemption request for a new exemption for the use of cadmium in luminescent material for on-chip application on LED semiconductor chips (lighting), Annex III of RoHS Directive 2011/65/EU"* from Sept. 29, 2017

OSRAM *"Request to renew Exemption 39(a) under Annex III of the RoHS Directive 2011/65/EU: Cadmium selenide in downshifting cadmium-based semiconductor nanocrystal quantum dots for use in display lighting applications (< 0,2 µg Cd per mm^2 of display screen area),* Date: April 30, 2018

OSRAM still requests both exemption requests. We believe it is justified according to the conditions of the RoHS Directive. This was also the recommendation in the Pack 15 Final Report published in January 2021. The proposed wordings in the report is fully supported by us, it should not be changed.

We are available for any further question.

We have attached documents with pictures that are protected by Copyrights. These graphs are only shared with the consultant in order to explain our answers, they shall not be distributed used in any publication.

2. Clarification Questions

If relevant, please differentiate between lighting and display applications in your answers.

In the past assessment, the main argument for an exemption was that for alternative non-cadmium materials, the quantum efficiency and reliability under on-chip operating conditions had not been resolved yet.

The consultants understood that an alternative technology for on-surface quantum dots based on indium phosphide (InP) would reach a comparable performance level to that of Cd QDs by about 2020. Thus, it was concluded that CD QDs are no longer used in on-surface display applications placed on the EU market.

[1] Please see Pack 15 report, Annex A.11.0: https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/Final_Results/RoHS_Pack_15_Final_Report_2020_compressed_version.pdf

[2] Please see the past consultation webpage under: https://rohs.exemptions.oeko.info/exemption-consultations/2019-consultation-1/cd-quantum-dot-joint-evaluation

1. Can you confirm that such development took place, meaning that Cd-free quantum dot alternatives, providing a comparable performance level to that of **on-surface** CD QDs, are available on the market and therefore an exemption is no longer required for Cd-QD in on-surface display applications? If not,
    a. please specify for which applications you regard an exemption as necessary: lamps/ displays, consumer/ laboratory, mobile/ stationary, and

On Surface / remote films are not current focus of the exemption request of LightingEurope nor for the exemption renewal request for displays (Exemption 39(a)) issued by OSRAM. For lighting CdQD technology *on-surface* is not available on the market. Conventional LED are available with much better energy efficiency and quality performance. Only on-chip configuration is suitable, only LED in *on chip* configuration can achieve the high CRI90 energy efficiency, see answers below.

,

    b. please explain why you consider an exemption to still be justified, providing technical data and evidence to support your views.

LightingEurope has applied for a new exemption for LED with CdQD *on-chip* configuration for lighting. The technology can achieve highest CRI 90 energy efficiency currently available. *On-surface* configuration are not practicable.
OSRAM does not have detailed information on current applications and the technology status using *on surface* or *on edge* configuration for displays, with or without Cadmium > 100 ppm in homogenous material. Information is available in market reports such as the Yole report

For displays OSRAM also only focusses on the development of LED with *on-chip* configuration.

2. Are Cd-QD used in **on-chip** configurations in lighting and or displays on the market? If so,
    a. how do they compare with alternative lighting/display technologies with respect to technical performance, reliability and environmental, health and consumer safety impacts?
    b. Please explain if an exemption for such applications is justified in your view, providing technical data and evidence to support your views.

Lighting using *on chip* configuration:
Products with CdQD technology are on the market in lamps and luminaires. These products do not exceed 100 ppm Cd in homogenous materials.

Osconiq 3030 QD was brought to market using <100ppm Cd content. Information on this product was shared during the consultation, e.g.

Press Release May 2019:
„Quantum Dots from Osram make LEDs even more efficient“

https://www.osram.us/cb/press/press-releases/05_20_19_quantum_dots.jsp

This was at the time still viable but the 100ppm limit severely limited the achievable efficacy values. Device based on the Cd QDs passed all the relevant reliability test, Lifetime data is comparable to current Phosphor based solutions.

Winner of 2020 Edison Award for new LED Component: 2020 Edison Awards® Winners

> *https://edisonawards.com/winners2020.php*
> *“The white Mid-Power LED features a unique Quantum Dot material with a narrow band red emission. Its high spectral purity enables excellent light quality with a minimum CRI of 90 while delivering record breaking efficacy (lm/W).”*

Further development of this Ro ***Press release July 2021***

> Follow up product **Osconiq E 2835 CRI90 (QD) – July 2021**
> ***“Premium lighting redefined – ams OSRAM presents new Quantum Dot LED”***
> https://ams-osram.com/news/press-releases/pr-22-07-2021
> Datasheet
> OSRAM OSCONIQ® E 2835, GW QTLTS2.QM White LEDs | ams OSRAM (ams-osram.com)

CdQD LED for lighting are currently limited by <100ppm Cd content & chip performance. A higher concentration of Cd in the homogenous material, not exceeding 1000 ppm, improves energy efficiency of high CRI products significantly. Products are ready for the market based on above chip with the following performance data:

Latest Cd QD Technical Performance

Best performance in illumination shown to date using Cd QDs in development runs (E2835) using 400 – 800 ppm Cd.

25 °C optical data					
PhiV	lm/W	LER	CCT	CRI	R9
39	222.7	345.1	4009	91.7	33.3

These results are only possible at Cd loading that would be allowed under the proposed exemption. The products are not on the market as they are not allowed in the EU. They are also not marketed outside EU.

Further improvements of the energy efficiency are expected to be achievable. Due to the lack of the exemption and the long waiting time and uncertainty research and development activities are currently reduced.

Comparison Cd vs. Cd free LED :

Product	**Phosphor**	**Lm/W**	**Colour Temp**	**CRI**	**Flux Range** (I_F 65mA, 25°C
Samsung	Standard	184)[1]	4000	min 90	31,5 – 33,5 lm

Bridgelux	KSF	204)[1]	4000	88	36 lm (typ)
OSRAM Osconiq E2835	CdQD <100 ppm Cd	195-200	4000	92	31,5 – 40 lm
OSRAM CdQD (not marketed)	CdQD, 400 ppm in hom. Mat.	223	4009	91,7	39 lm

Calculated or copied from data sheet values, see below:

- ➔ Typical conditions in an application at 25°C: 0,065 Ampere, 2,72 Volt → 0,1768 Watt
- ➔ Efficacy (lm/W) = 32,5 lumen (from datasheet, 4000K, CRI90) / 0,1768 W → 183,8 Watt

		Typ bin			
	CRI	Flux (lm)	Vf (V)	If (A)	Efficacy (lm/W)
Samsung	>=90	32.5	2.72	0.065	183.8
Bridgelux	88	36	2.72	0.065	203.6

It is noteworthy that the Bridgelux CRI in this example is not reaching 90.

Sources:

LED with Standard Phosphor solutions ~190lm/W CRI 90 @ 4000K
(Samsung LM281B+Pro - Top Bin)

PDF
Data_Sheet_LM281B
_Plus_Pro_VL_Rev.1.(

LED with KSF phosphor solution ~204 lm/W, CRI 88, 4000K, 25°C Bridgelux DS503 SMD 2835)

PDF
DS503 SMD 2835
0.2W 3V 65mA CRI9(

Due to the high energy efficiency increase and the increase in light quality, cadmium Quantum Dot LED based lamps and luminaires can substantially contribute to the transition of lighting from mercury-containing lamps to mercury-free solutions:

- CdQD based LED for Lighting reveal the highest energy efficiency measured for high CRI (>90). Further development is expected to improve products even more. Lamps with Energy Efficiency class “C” are considered to be possible, if the exemption is granted.

Currently high CRI (>90) lamps with E27/806 lumen have energy efficiency class E-F. The energy efficiency gap between CRI80 and CRI 90 gets closed.

- Shorter return of investment costs, especially in the professional area where high quality sensor-based luminaires have to be replaced due to the lack of compatible retrofit solutions
- Lower total costs for EU member states (schools, hospitals, public and private non-residential buildings)
- Better and desired light quality (high CRI).

Granting this exemption would have an overall net positive impact for the EU - more energy efficient products on the EU that would deliver energy savings and therefore reduce the total amount of cadmium emitted by power plants in the EU energy mix (see our renewal application and LCA for details). In addition it would lead to the reduction of other toxic and hazardous substances and emissions, e.g. Hg, Pb, CO_2 and ozone depleting substances.

These improvements would even count more in regions outside EU where less effort is spent to change power production.

Work is still being actively pursued on Cd-free QDs both through company internal projects and externally funded projects.

For example, ams-OSRAM is currently running a DOE funded project :" Cadmium-Free Quantum Dot Building Blocks for Human-Centric Lighting" which will run until end of 2023. https://www.energy.gov/eere/ssl/articles/cadmium-free-quantum-dot-building-blocks-human-centric-lighting

However, InP based QDs for on chip LED usage are still at an early-stage development. No Cd-free QD currently exists that can be used in on chip LED applications. Likely 4-5 year until technology is mature enough for products

Both lamp (Lm/W efficacy) and display (enabling technologies for next generation displays) stand to benefit from this exemption

CdQD in display applications

For displays OSRAM also only focusses on the development of LED with on-chip configuration. Illumination for displays is more efficient with the use of materials with narrow spectra (small full width half max FWHM).

While InP-based Quantum Dots catched up in efficiency during the last years their band widths did not improve in similar ways [cite A, slide 47]. With this improvement they are used in on-surface configurations. For on-chip configuration they lack tremendously in lifetime as seen in internal experiments but from other groups as well [cite A, slide 216].

For on-chip technology a high concentration of quantum dots on the chip is required, however, the overall amount of dots is much less than compared to on-surface solutions.

	On-chip	On-surface

Amount of Cd in 55” TV	< 0.2-0,4 mg	~40mg Cd or ~30mg InP

See also:
Feedback to the 1st Oeko Clarification Questionnaire on the OSRAM Exemption Renewal Request for the use of Cadmium in Quantum Dot LEDs for Display applications, March 2019
OSRAM / OSRAM Opto Semiconductor “Comments to the Webinar of Öko-Institute/EU Commission on RoHS Pack 15 Exemption Evaluation Methodology, May 2020

Despite the low amount of Cadmium the exemption is required to enable such products.

With on-going uncertainty of the RoHS status there is no qualified product yet on the market from ams-OSRAM.

Micro LED display applications require a thin film conversion layer that can only be realized using QDs. Cd QD are currently only QDs that are stable enough to satisfy the requirements. Proof of principle for full conversion has been demonstrated in very thin layers (<3µm, internal development project). This is an enabling and key technology for small (<10µm) Micro LED application for next generation display applications.

c. How high are the mass and concentration (ppm, mg/mm^2 screen or LED area) of Cd in such applications?

   i. How is the amount expected to change in the next 5 years?

Fundamental limits are not expected to change (set by material properties)

   ii. How do the mass and concentration of Cd relate to each other in terms of: Cd per mm^2 screen area/LED, concentration by weight in homogeneous materials, ppm, weight per screen/lighting application?

Lighting:

See contribution of LightingEurope to EU Commission (Oct 8, 2021)

The cadmium content is:

- 2.3 micrograms cadmium per LED (1 Watt) used in residential applications (e.g. LED retrofit bulb, 800 lumen, 12 LED = 27,7 micrograms cadmium)

- 1,3 microgram cadmium per LED (0,5 Watt) used in professional market (troffer luminaire for office lighting, 2000 lumen, 64 LED = 84,5 microgram cadmium)

- Average cadmium amount of above values per 1 Mio pieces: 1,97 grams

Display applications:

Different to on surface applications a certain amount of Cd is needed per light emitting area and not per screen size. Estimated theoretical minimum is 2µg / mm² for 99% conversion assuming all Cd is active in optical absorption, realistically 2-5 µg are required.

This reduces the total amount of hazardous substances such as Cd or InP in on surface applications by >99%. In a 55 inch TV set 0,2 – 0,4 **less than 0,5 mg Cd** (0,2-0,4 mg), would be needed on chip compared to ca 30 mg InP or 40 mg Cd on surface. (See exemption renewal application Apr. 2018, e.g. 4.2.4).

This corresponds to 0,00045µg per mm² TV screen

Other displays like µ-displays for AR (augmented reality) work with 0.2-0.3" screen on glasses. With one or two displays a total amount of 185 µg per glasses is expected.

iii. Which part of Cd-QD/ LEDs/ screens/ solid state lighting is regarded as the homogeneous material?

Luminescent material on the chip.

d. How developed is the market of displays for RoHS compliant Cd-QD and for Cd-free QD for consumer/ professional, stationary/ mobile displays?

Market not developed for displays. RoHS compliant CdQD LED are not possible due to the different distribution of Cd in the luminescent material. The exemption is required to enable use of the technology and to start development of applications using the technology. Due to the long time since renewal application and missing decision the research and development on such applications is significantly reduced. No customer spends money on an application if the exemption is not granted..

e. How developed is the market of solid-state lighting for RoHS compliant Cd-QD and for Cd-free QD for consumer/ professional, stationary/ mobile displays?

Lighting: First products with RoHS conform CdQD are released, highest performance demonstrated but only with more Cd per LED the highest energy efficiency can be achieved. Our estimation for lighting is that CRI 90 is only a small portion of the LED market. Due to higher costs, CRI 90 is only used in high quality lamps and luminaires where the improved Colour Rendering Index is desired and required. The main market for LED lighting is in the CRI 80 range.

Display: No Cd Free QD products *on chip* on the market due to missing exemption. Data for the InP based *on surface* QD display market are not available

3. Should an exemption be granted,
   a. are there additional applications where Cd-QD could be used and where it provides benefits to the environment, health and/or to consumer safety?

LightingEurope is not aware of other CdQD applications. There are QD applications in development needing lead (Pb) for applications such as sensing. QD technology is very promising for a range of potential applications.

   b. what is the expected amount of Cd entering the EU market annually? Please specify clearly to which application area and for which configuration type your answer refers.

All answers apply to *on chip* configuration as on surface is technically not practicable for lighting and not in development by OSRAM or LightingEurope members for display applications. In Oct.

2021 a forecast was calculated for the EU Commission (see attachment) resulting in max. 1,65 kg Cd per year in the EU in 840 Mio pieces high CRI CdQD LED.

TV-sets with Cd quantum dots are superior leading to higher colour gamut with better energy and resource efficiency (see slide 34 of Yole report).

The table below compares substance amounts (Cd, InP) for an amount of **10 Mio TV** sets.

		Amount per screen	Mio Units 55" TV sets	kg Cd	
LCD-NBP	On-chip, could be replaced by QD	< 0,5 mg	10	< 5kg	Exemption with 5µg/mm² light emitting chip surface required
LCD-QDEF	On-surface	30 mg InP or 40 mg Cd	10	300 kg InP or 400kg Cd	Covered by existing exemption

See also:
Yole: Next Generation TV Panels: New Technologies, Features and Market Impact (2020)

OSRAMs research and development focus is on µ-displays e.g resource- and energy efficient augmented reality applications . Below are market predictions from Yole for Augmented Reality µ displays.

Augmented Reality		World market 2027 *	
Display size	0,2"-0,3" diagonal	28 mio. pieces	µ displays
Screen size	~25mm²	25%	EU share
1-2 displays per glasses	~37mm² average	5,18kg Cd	World market
Cd/mm²	5µg	1,295 kg Cd	EU market
Cd/glasses	185µg		

Estimation Yole report: Displays & optics for AR & VR 2022, Market and Technology Report, p. 69; The cadmium estimation is a worst-case scenario, if all devices would be produced with this technology. This is far from being realistic at the current development status.

4. What **substitutes** are of relevance on the **substance level** (i.e., QD that do not include Cd such as InP and InGaN)?
    a. What is their status of development and in what applications on the market are they already applied?

It is still the case that no Cd free QD currently exists that can work in “On-chip” LED applications

Work is still being actively pursued on Cd-free QDs both through company internal projects and externally funded projects. For example, ams-OSRAM is currently running a DOE funded project:” Cadmium-Free Quantum Dot Building Blocks for Human-Centric Lighting” which will run until end of 2023. https://www.energy.gov/eere/ssl/articles/cadmium-free-quantum-dot-building-blocks-human-centric-lighting

However, InP based QDs for on chip LED usage are still at an early-stage development. No Cd-free QD currently exists that can be used in on chip LED applications. Likely 4-5 year until technology is mature enough for products

Both Lamp (Lm/W efficacy) and Display (enabling technologies for next generation displays) stand to benefit from this exemption.

b. How developed are dye-doped rather than quantum dot-doped nanoparticles?

Conventional phosphors can be designed as nanoparticles. Doing so they reveal strong size effects that lead to extreme light loss and fast degradation making it non-usable for any application. In addition they lack colour purity needed for display applications.

No Organic Dyes known that are usable in these applications. The use of organic dyes in LEDs had been investigated thoroughly in several projects. One of it as a funded project with the expertise of experienced partners to stabilize the dye against degradation (see press release). It could be seen that the effects of the stabilization strategies were orders of magnitude too small to overcome the fundamental metastability of organic material (study funded by German Ministry for Education and Research BMBF).

c. How do the substitutes compare to Cd-QD with respect to energy-efficiency, light quality (CRI or colour gamut) and lifetime?

InP does not reach acceptable energy efficiency and is not usable due to lack of reliability. Organic dyes are even broader, i.e. less efficient after color filters in displays and instable as well. Perovskit quantum dots are nicely narrow but instable. The best perovskites contain lead.

d. What are the environmental, health and consumer safety advantages and disadvantages of their use as compared to CD QD?

Not applicable at all for lighting. For displays the amount of InP (carcinogenic nanomaterial) in *on-surface* configuration is about 100 times higher compared to Cd *on chip*.

e. Do the substitutes contain other substances of concern? Which and in what quantities?

InP has been subject to a study to include the substance in Annex II RoHS Directive. Perovskites contain lead.

f. Are obstacles to their application technical or economical?

Obstacles are only technical

5. What substitutes exist at the **device technology level** (alternative components or alternative lamp/display technologies)?
    a. As there are different display technologies on the market, some using white backlight and others not, would it be technically feasible to substitute white backlight and thus Cd-QD in all display applications?

For regular BLU – competing phosphors are not as spectrally narrow in green and so cannot deliver same color gamut.

For red emission, the KSF phosphor provides good performance but cannot be tuned to optimise any further and is limited by low absorption and long lifetimes (slower refresh rate).

For next generation displays using micro LED pixels – no competing conversion technology is known that can deliver the full optical conversion is sufficiently thin layers to enable the application.

Direct emission micro LEDs may be possible but also not currently clear if these can meet requirements.

    b. As there are different lighting technologies on the market, is it technically feasible to use such technologies in all relevant SSL lighting applications where Cd-QDs are applied?

KSF phosphors are currently best RoHS conform materials for energy efficient high CRI SSL lighting applications. With CdQD LED >10% increase can be achieved, more improvement expected.

    c. What are the environmental, health and consumer safety disadvantages of their use as compared to CD QD? Do the substitutes contain other substances of concern? Which and in what quantities?

Exact composition not available to LightingEurope members. We are not aware of restrictions or declaration requirements.

    d. Are obstacles to their application technical or economical?

KSF phosphors technically do not reach the energy efficiency of CdQD. Economically they have the advantage of lower prices.

6. What are the main parameters of the energy usage of applications/ devices in which CD QD (and their alternatives) are used? How does energy consumption change in relation to changes in the size, quality of light, periphery settings/ technology, contrast and brightness? Please consider providing a comparison in tabular form.

As explained above for lighting: CdQD LED have (to have) the same size, lifetime, quality. Energy efficiency increases. Compared to LED with lower energy efficiency less number of LED can be used per application.

Display applications: In addition to the answer for question 5(a) CdQD LED in on chip configuration are in development for new applications which are not yet possible with conventional LED e.g. Micro displays. Quality of light and energy efficiency are expected to be improved. Used for TV screens higher resource efficiency can be realized, as no converter materials are required.

The main energy losses in display is the use of filters to extract colours of high purity. The light that doesn't pass the filters is thrown away. Therefore, a strong lever to enhance the display efficiency is to use narrow spectra, i.e. pure colours as provided by Quantum Dots.

Display applications: In addition to the answer for question 5(a) CdQD LED in on chip configuration are in development for new applications which are not yet possible with conventional LED e.g. Micro displays. Quality of light and energy efficiency are expected to be improved. Used for TV screens higher resource efficiency can be realized, as no converter materials are required.

7. Which are the expected treatment routes of applications containing Cd-QD at the end-of-life stage (e.g., lighting equipment and displays)?
    a. Please explain which of these applications is collected separately and which are treated with mixed WEEE, and what treatment stages are performed for each fraction.
    b. Within the standard treatment routes applied in the EU, are the existing installations equipped to cope with the present amount of Cd in related applications?

Applications would not be treated separately from other LED lighting equipment or from TV screens. LightingEurope would like to explicitly refer to the communication to the EU Commission in Oct 2021 as attached.

Only a very small portion of LEDs would contain cadmium, see numbers in the communication. Most LEDs would not contain cadmium.

The concentration of cadmium in the waste would be very low. An 800-lumen lightbulb would have a cadmium content of < 30 microgram. Assuming a weight of 60 grams per lamp the concentration of cadmium would be below 0,3 parts per million (ppm) and therefore far below any critical concentrations in waste management. To put this number into context: this is equivalent to cadmium limits for chocolate.

To give another example, the cadmium content coming from LEDs in a 55-inch TV screen is calculated to be < 1 mg. Assuming a weight of 20 kg per TV set a concentration of clearly below 0,05 ppm cadmium in the waste stream. This amount is not considered as critical.

LED lamps are collected together with all other lamps (including mercury-containing lamps), because consumers cannot distinguish between the various technologies. Mercury lamps are treated as hazardous waste. Because LED retrofit lamps are mixed with mercury lamps, the entire batch is treated as hazardous waste.

Today, for technological and economic reasons, LEDs cannot be recycled separately. This has also been shown earlier in studies about the recycling of LED phosphors
(see study: https://cordis.europa.eu/project/id/282793/reporting)

LED technology represents approximately 10% of today's lamp waste stream at EU level, primarily because of the long technical life of this technology.

Lighting manufacturers continue to work with the producer responsibility organisations that are tasked with managing the collection and recycling of lighting products to identify viable technologies for addressing the particularities of LED lamps, also in preparation for when LED lamps will be the bulk of the technology in the waste stream.

Attachments/References:

We would like to reference to the following documents which we consider still valid:

LED professional - LED Lighting Technology, Application Magazine (2016): LED Lamps Recycling Technology for a Circular Economy. Online verfügbar unter https://www.led-professional.com/resources-1/articles/led-lamps-recycling-technology-for-a-circular-economy, zuletzt aktualisiert am 07.09.2022, zuletzt geprüft am 07.09.2022.

OSRAM (2019): Feedback to the 1st Oeko Clarification Questionnaire on the OSRAM Exemption Renewal Request for the use of Cadmium in Quantum Dot LEDs for Display applications. Renewal Request to renew Exemption 39(a) under Annex III of the RoHS Directive 2011/65/EU: Cadmium selenide in downshifting cadmium-based semi-conductor nanocrystal quantum dots for use in display lighting applications (< 0,2 µg Cd per mm2 of display screen area). Online verfügbar unter https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/3rd_Consultation/clarification_OSRAM_Ex_39a_appl_1_RoHS15_20190313.pdf.

OSRAM / OSRAM Opto Semiconductor “Comments to the Webinar of Öko-Institute/EU Commission on RoHS Pack 15 Exemption Evaluation Methodology with regard to the presented examples from the evaluation of

- Extension of Exemption 39(a) of Annex III (April 30, 2018)
- New exemption for the use of Cadmium in luminescent material for on-chip application on LED semiconductor chips (lighting) (September 29, 2017)
- Evaluation of other exemptions applied by LightingEurope in Jan 2015

In addition a document will be provided with information from external reports. The content and grafics are copyright protected and shall not be distributed or published in any form. They are only intended for the consultants as supporting documents.

In case parts of your contribution are confidential, please provide your contribution in two versions (public /confidential). Please also note, however, that requested exemptions cannot be granted based on confidential information!

Finally, please do not forget to provide your contact details (Name, Organisation, e-mail and phone number) so that Oeko-Institut can contact you in case there are questions concerning your contribution.

3. Literaturverzeichnis

European Commission. Directorate General for Environment.; Oeko Institut e.V.; Fraunhofer IZM. (2021): Assessing three exemption requests for the use of cadmium in quantum dot applications in displays and lighting: study to support the review of the list of restricted substances and to assess a new exemption request under RoHS (RoHS Pack 15 Task 5, final): Publications Office.

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Marwede, Max; Chancerel, Perrine; Deubzer, Otmar; Jordan, Rafael; Nissen, N. F.; Lang, K. (2012): Mass flows of selected target materials in LED products. Conference Paper Electronics Goes Green 2012+ (EGG), zuletzt geprüft am 12.09.2022.

Najing (2019): Answers to 1st clarification questions regarding renewal request for Ex. 39a… Online verfügbar unter https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/3rd_Consultation/clarification_Nanjngtech_Ex_39a_1st_round_of_Questions_Response_20190227.pdf.

Nanosys (2019): Answers to consultation questionaire. Online verfügbar unter https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/3rd_Consultation/contribution_Nanosys_RoHS15_Ex_Joint_Cd_QD_20190512.pdf.

OSRAM (2018): Request to renew Exemption 39(a) under Annex III of the RoHS Directive 2011/65/EU. Cadmium selenide in downshifting cadmium-based semiconductor nanocrystal quantum dots for use in display lighting applications (< 0,2 µg Cd per mm2 of display screen area). Online verfügbar unter https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/3rd_Consultation/application_OSRAM_Ex_39_RoHS15_Ex_Renewal_Req_39a_final_20180430.pdf.

OSRAM (2019): Feedback to the 1st Oeko Clarification Questionnaire on the OSRAM Exemption Renewal Request for the use of Cadmium in Quantum Dot LEDs for Display applications. Renewal Request to renew Exemption 39(a) under Annex III of the RoHS Directive 2011/65/EU: Cadmium selenide in downshifting cadmium-based semi-conductor nanocrystal quantum dots for use in display lighting applications (< 0,2 µg Cd per mm2 of display screen area). Online verfügbar unter https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/3rd_Consultation/clarification_OSRAM_Ex_39a_appl_1_RoHS15_20190313.pdf.