# 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

Report for the European Commission DG Environment under Framework Contract No ENV.C.2/FRA/2011/0020

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*Disclaimer*

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# 7.0 Exemption Request 2013-2 “Cadmium in Color Converting II-VI LEDs (< 10 µg Cd per mm² of Light-Emitting Area) for Use in Solid State Illumination or Display Systems”; and Exemption Request 2013-5 “Cadmium in Light Control Materials Used for Display Devices”

## Abbreviations

| | |
|---|---|
| BEF / DBEF | Brightness enhancement film / Dual brightness enhancement film |
| BLU | Back light unit |
| CCFL | Cold cathode fluorescent (LCD) |
| Cd | Cadmium |
| CF | Colour filter |
| CFL | Compact Fluorescent bulbs |
| CFQD | Cadmium-free quantum dots |
| CIE | International Commission on Illumination |
| CRT | Cathode ray tube |
| FWHM | Full width at half maximum |
| InGaN | Indium gallium nitride [based LED] |
| InP | Indium phosphide |
| LCD / LCM | Liquid crystal display / Liquid Crystal Module |
| LED | Light-emitting diode |
| OLED | Organic light-emitting diode |
| QD / QLED | Quantum dot / Quantum-dot-based LEDs |
| RGB | RGB colour model with the three additive primary colours: red, green, and blue |
| NTSC | National Television Systems Committee |
| QDs | Quantum Dots |
| QDEF | Quantum Dot Enhancement Film |
| RoHS 2 | Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast) |

| | |
|---|---|
| RoHS 1 | Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment |
| TV | Television |
| UCS | Uniform colour space |
| YAG | Yttrium aluminium garnet |

## 7.1 General Issues Concerning Exemption Requests 2 and 5

QD Vision, Inc. and 3M Optical Systems Division have submitted exemption requests No. 2 and No. 5

- Cadmium in II-VI LED Down-conversion (Request No. 2, applicant QD Vision, Inc.[37])
- Cadmium in LCD Quantum Dot Light Control Films and Components (Request No. 5, applicant 3M Optical Systems Division[38])

Both the applications have been subjected to stakeholder consultation. Following the stakeholder consultation, a one day stakeholder meeting was organised to allow a discussion and better understanding of technical details. The participants included both applicants as well as several stakeholders from industry[39].

Besides information that is specific for each of the requested exemptions, both applicants put forward overarching arguments related to the general features of quantum dots (QDs) technology and concerning unit components intended for use as part of a liquid crystal display (LCD) system. This information, as well as some of the information provided by stakeholders is reflected in Sections 7.2 to avoid repetition. This is followed by individual sections relaying information relevant as background information for each of the requests in Section 7.3. A brief description of the environmental arguments made by the applicants appears in Section 7.3.4. Afterwards information concerning substance alternatives and design alternatives is compiled in Section 7.4.1 and Section 7.4.2 respectively, followed by the information

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[37] QD Vision (2013a), QD Vision original exemption request document concerning exemption request 2; available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20132301_NON-CONFIDENTIAL_Request_for_renewal_of_exemption_39.pdf, retrieved on 12.12.2013

[38] 3M (2013a), 3M Optical Systems Division original exemption request document concerning exemption request 2; available under http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-5/3M_QDEF_Exemption_Dossier.pdf, retrieved on 05 June 2013

[39] Documentation of the presentations held at the meeting are available under: the exemption request 2 webpage: http://rohs.exemptions.oeko.info/index.php?id=182 and under the exemption request 5 webpage http://rohs.exemptions.oeko.info/index.php?id=185

contributed by stakeholders summarized in Section 7.5. Finally, a critical review of the various issues of interest resumes the report in Section 0.

Sections 7.2 to 7.5 are mainly based on information provided by the applicants and other stakeholders and do not necessarily reflect the views of the consultants, unless specifically stated.

## 7.2 Background

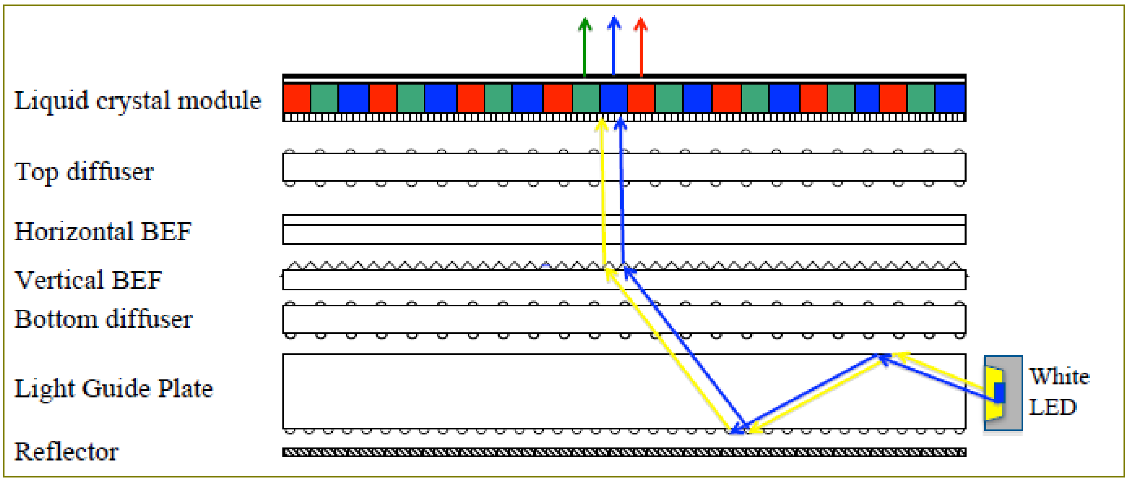
Sections 7.2 through 7.5 are heavily based on information provided by the applicant and other stakeholders and do not necessarily reflect the view of the consultants.

### 7.2.1 Display Lighting Applications

According to Coe-Sullivan et al.[40], LEDs are used as the source of light in most backlights of cell phones, tablets, laptops, most monitors, and roughly half of all TVs. This is due to the thin dimensions in which they can be manufactured, their high energy efficiency and their decreasing costs as blue light sources. In most of these systems, the components in use are referred to as white LEDs, since they are based on a blue indium gallium nitride (InGaN) LED chip coated with down-conversion material, which mixed with the source light produces white light. These white lights are used in combination with a series of diffusers and [brightness enhancing] films (see Figure 7-1 below) to produce a uniformly spread light over the display area. The white light passes through the liquid crystal array and then through colour filters to create the three primary colours that make up the colour gamut of the display.

[40] S. Coe-Sullivan, W. Liu, P. Allen & J.S. Steckel (2013), "Quantum Dots for LED Down-conversion in Display Applications", ECS J. Solid State Sci. Technol., 2013, 2, R3026

Figure 7-1: Illustration of LCDs with White LEDs as a Light




*Source: Nanosys (2013)*[41]

According to 3M[42], there are two classes of LCD lighting approaches; edge lighting and direct lighting. The edge lighting approach uses LEDs coupled into a light guide plate to provide uniform back lighting. The direct lighting approach uses a matrix of LEDs to directly illuminate the LCD panel. In the direct lighting approach, particularly common in TV application, there is no “edge” (no light guide plate) to which to place the QDs. It is estimated that in 2013 the direct lit TV sales were 34% of the total TV market, and by 2017 it is projected that 65% of TV sales will be direct lit systems[43].

3M[44] provide background information concerning the application, stating that LCD refresh rates, resolution, and contrast levels have all improved dramatically. However, they indicate colour performance as the one area where development is still forthcoming. They emphasize that this is particularly true for smaller sized displays, such as smartphones and tablets, where the range of colours that can be presented is only 50%-70% that of cathode ray tube (CRT) technology, when it was first introduced. 3M continue to name a number of relatively new display technologies, claiming that none of these exist commercially for high quality colour displays at a state which is easily adoptable for all applications, as well as being energy efficient.

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[41] Nanosys (2013), Presentation held at Stakeholder Consultation concerning Ex. Re. 20132 and 2013-5 on 13.12.2013, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/RoHS_Nanosys_12_13_2013_final.pdf

[42] 3M (2014b), Additional Information provided by 3M in response to clarification questions, Document submitted 06.02.2014

[43] Quoted in 3M (2014b) as iSuppli TV tracker Q1 2013

[44] Op. cit. 3M (2013a)

*Sections 7.1 through 7.5 are heavily based on information provided by the applicant and other stakeholders. Alterations have been made mainly to ensure comprehension and to avoid repetition.

These include:

- Traditional LED LCDs (higher absorptive colour filters);
- Organic light emitting diode (OLED) displays;
- Red/Green/Blue (RGB) LEDs;
- Wide colour gamut phosphors;
- Hybrid LEDs.

A main factor that determines the maximum colour performance of an LCD is the spectral interaction between the light emitted from the backlight and the liquid crystal panel colour filters. An LCD has two main components, the liquid crystal panel and the back light unit (BLU). The panel consists of millions of individually addressable pixels, each of those made up of red, green and blue sub-pixels. The sub-pixels get their colour properties from absorptive colour filters (CFs) that overlay them. The BLU contains light sources (typically white yttrium aluminium garnet (YAG) based LEDs at present) and provides spatially uniform light to the back side of the panel. The spectral distribution of the light sources in the BLU convolved with the spectral transmission of the panel colour filters mainly determines the final spectra of the light exiting an LCD. The white LED based spectral output of the BLU passes through the three (red, green, and blue = RGB) colour filters (CF) to produce the final LCD spectral distribution. This distribution then determines the colour quality of the display (See Figure 7-1 above for illustration of typical spectral distribution for display with white-LED back lighting).[45]

To maximize the colour performance of an LCD, the output spectral distribution of each sub-pixel should be as narrow as possible. Narrow spectral distributions of the primary RGB sub-pixels result in a large colour gamut area. Colour gamut[46] is a measure of a display's ability to generate a range of colours, and is typically defined by the tristimulus RGB area in the CIE (International Commission on Illumination) 1931 2° Chromaticity space or the CIE 1976 UCS (Uniform Colour Space) Chromaticity Space. The blue horseshoe shape in Figure 7-2 represents all of the colours visible to the human eye, and the red and green triangles represent the colours that a standard LED-LCD and a QD film based LCD are capable of displaying. The narrower spectral distributions (particularly the red and green distributions) of an LCD with QD films produce a larger colour gamut (~94% NTSC) than a traditional LCD (~65% NTSC). BLU+CFX denote the spectral light distribution coming from the BLU through the blue, green or red colour filter (CFB, CFG, and CFR respectively). [47]

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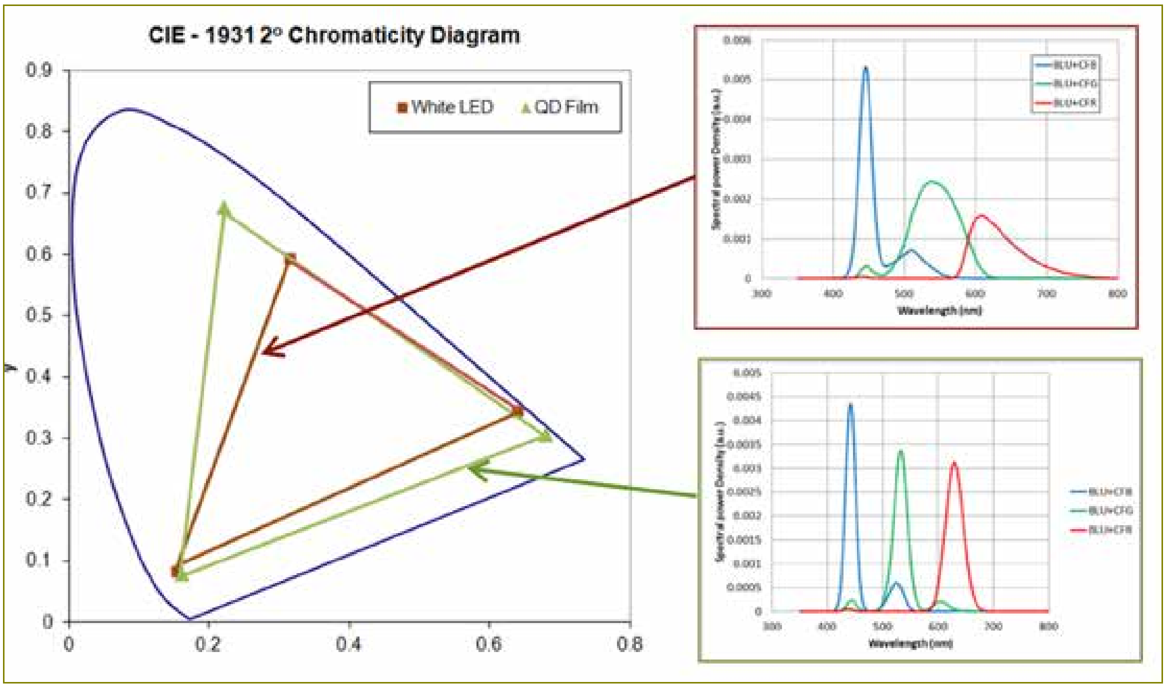
[45] Op. cit. 3M (2013a)

[46] Colour gamut is often represented as percentage of area relative to a standardized colour gamut space, such as the 1953 NTSC (National Television System Committee) colour space. A larger colour gamut area (with a higher % NTSC) means that the display can generate a larger range of colours than a display with a lower % NTSC.

[47] Op. cit. 3M (2013a)

Figure 7-2: Primary Sub-pixel Spectra and Colour Gamut Size




*Source: 3M (2013a)*

To achieve narrow sub-pixel output spectral distributions in an LCD, either:[48]

- Ø The colour filters have to be highly absorptive, which is not desirable due to significantly lower efficiency (of coloured light output as a % of BLU light output) and higher energy consumption; or
- Ø The input spectral distribution from the BLU must have narrow spectral ranges and be closely matched in peak wavelength to the transmission of the colour filters.

Currently, the YAG based white LEDs used in most LCDs have broad spectral distributions in the green and red regions and do not match the colour filters in peak wavelengths (see Figure 7-3). [49]

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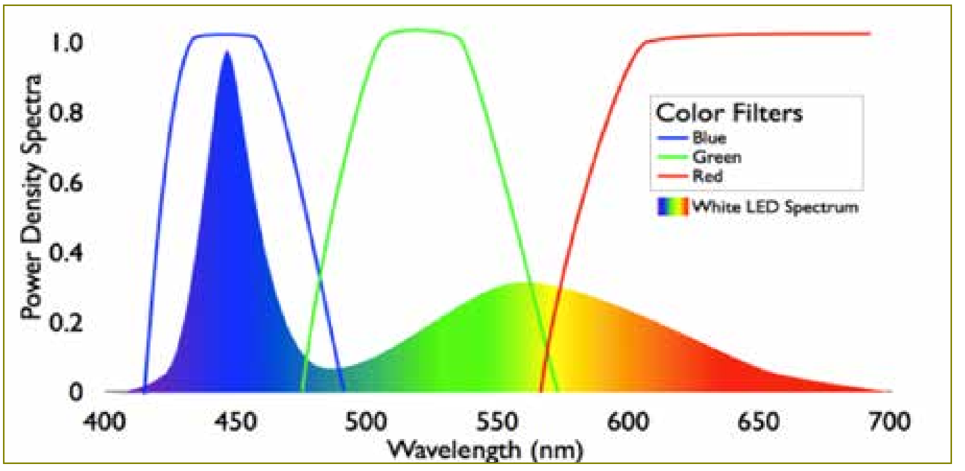
[48] Op. cit. 3M (2013a)

[49] Op. cit. 3M (2013a)

Figure 7-3: Spectrum of a Typical White YAG Based LED BLU, Compared with an Example set of Red, Green and Blue Colour Filters




*The spectrum of the light sources does not match well with the colour filters (CFs) resulting in a limited colour gamut size.*
*Source: 3M (2013a)*

### 7.2.2 Quantum Dot Technology

3M[50] explain that Quantum dots (QDs) are a new class of non-naturally occurring materials that can be tuned to efficiently emit narrow spectral distribution light at the optimum wavelength for LCDs.[51]

QDs are semiconductor nano-crystals, on the order of 3-7nm in size, in which excitons (an electron and hole excited pair) are confined on all three spatial dimensions. The wavelength of the light output from a semiconducting material is dependent on the band gap between normal and excited electron energy states. The spatial confinement of the electrons and holes of the quantum dot materials leads to higher band gaps compared to the band gap of same material in bulk. As a result, the band gaps of the quantum dots can be changed continuously by changing their physical size. Quantum dots are typically synthesized via solution chemistry (carefully controlled precipitation processes). By controlling different synthesis conditions, e.g., precursor; ligand concentrations; temperature; and time of the reaction, QDs of different sizes can be obtained. Quantum dot emission can be tuned across most of the visual spectrum by controlling the size of the quantum dot as it is fabricated; larger quantum dots emit light of longer peak wavelengths, see Figure 7-4.[52]

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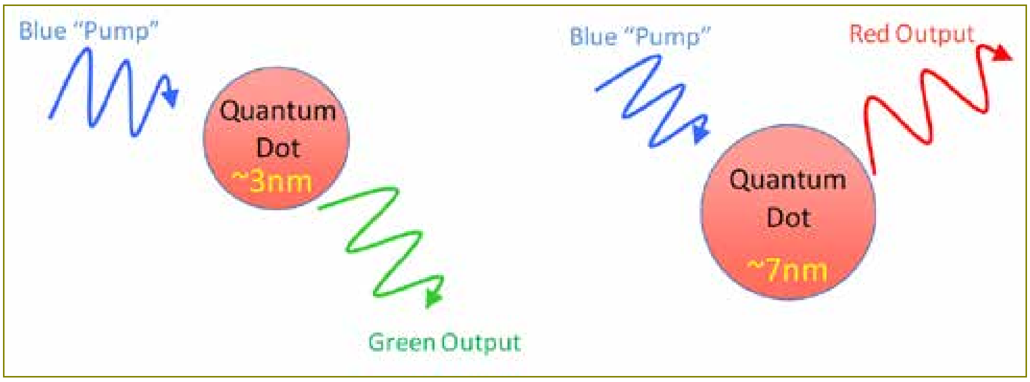
[50] Op. cit. 3M (2013a)

[51] Quoted by 3M (2013a) as: Hartlove, J. 2011. Quantum dots unleash high-colour-gamut performance in LED-backlit displays. LEDs Magazine

[52] Op. cit. 3M (2013a)

Figure 7-4: Effects of Quantum Dots Size on Spectral Output (Smaller QDs emit shorter wavelength light when exposed to a blue source)




*Source: 3M (2013a)*

Quantum dots can be pumped with a blue source, such as the GaN LED, to emit at any wavelength beyond the pump source wavelength. The emission spectra of QDs have narrow line-widths and are free of satellite peaks, thus making them ideal candidates for display backlights to achieve high colour purity and increased system energy efficiency. QDs convert light with very high efficiency (>88% quantum efficiency) and with very narrow output spectral distribution of only 30 – 40nm full width at half maximum (FWHM). Due to their tuneability, narrow spectral output distributions, and high quantum efficiencies, quantum dots are ideal for creating BLU light sources to increase colour gamut size and maximize LCD colour performance.[53]

QD Vision[54] provides some information concerning qualities of Cadmium in the application that are of relevance for possible substance alternatives. Cadmium functions as the group II element in the II-VI semiconductors described in the exemption. The group II element functions to complete the 8 electron bonding that is characteristic of tetrahedral $sp^3$ hybridized, tetrahedral bonded semiconductors. As such, cadmium contributes two outer orbital electrons to the bonding of such a semiconductor solid, and the result is a material with a completely filled valence band and unfilled conduction band. Other Group II elements provide a band-gap that is either too high and hence luminescence in the deep blue and ultraviolet (e.g. zinc), or too low and hence luminescence that is in the infrared (e.g. mercury), and/or makes a material that is more salt than semiconductor and hence decomposes in aqueous or humid environments (e.g. magnesium) and fails to meet reliability requirements. Cadmium is thus essential to the light emitting property of the material. Unlike any other known materials, these Cadmium-containing II-VI down-conversion materials (quantum dots) emit very *narrowband* light, which can be *tuned* throughout the visible spectrum. These materials are *stable* enough for long-lived (25,000 hours) LED lit products. They are also extremely efficient (essentially 100% at room temperature), and unlike most known down-conversion materials, can now be made to maintain

[53] Op. cit. 3M (2013a)

[54] Op. cit. QD Vision (2013a)

97% of this room temperature efficiency at high operating temperatures up to 140°C. Characteristics are described to include:

- Efficient: In the context of both lighting and display products, narrowband light is equivalent to more efficient light (see explanation below). Narrowband spectra means that all of the light produced comes out with the same narrow range of colour. In all down-conversion applications, one is essentially converting light of an undesirable colour to one that is more useful in an application. Emitting all of the down-converted light in a narrow range at the desired colour means that less total photons are used to have the same effect, and are not 'wasted' – e.g. by emitting deep red or infrared photons that humans cannot see. II-VI down-conversion materials can routinely achieve a spectral full width at half maximum (FWHM) of 30nm or less, compared to conventional LED phosphors that have FWHM of greater than 60nm, and in most cases greater than 90nm (e.g. the most common LED phosphor Yttrium Aluminium Garnet doped with Cerium, YAG:Ce). Such a step change in FWHM is equivalent to getting twice as many lumens for the same number of photons in the red and blue regions of the spectrum. This factor of 2× in the red is what leads to the 20-40% increase in overall white light efficiency in warm white lighting.
- Tuneable: because down-conversion is in essence tailoring a light spectrum to be more desirable, the tuneable nature of II-VI down-conversion materials allows precise control and selection of the light that is most desirable, and hence most efficient, (see explanation below) for a particular application. Colour can typically be tuned in 2nm increments for customers, improving the quality and efficacy of light production as a result.
- Stable: Many other down-conversion materials have a limited lifetime, which limits the lifetime of the overall product. The cadmium containing II-VI down-conversion materials now have sufficient lifetime to be included in the longest lived, most reliable products on the market, those that rely on LEDs as the primary light source. By combining these materials with LEDs, lighting bulbs and fixtures with high colour quality and lifetime in excess of 25,000 hours can be created. Similarly, displays which can be rated at 30,000+ hours can be delivered to the market. This parameter of reliability is another key factor in determining environmental effects, along with efficiency.

In a later communication, QD Vision[55] elaborates as to the use of the term efficiency in the above text excerpts. They explain that they generally use the term concerning the creation of light for an application such that it meets that application's needs, while consuming less power. "*The original application covers the two applications of lighting and displays.*

[55] QD Vision (2014c), Respnose to 4th round of clarification questions, submitted per email on 17.03.2014

- Ø *For **lighting**, the most useful metric of efficiency is lm/W (lumens per Watt, or sometimes LPW). Lumens are units of perceived brightness, and in this context the Watts are electrical Watts of input power to the system. However, optimizing for lumens per Watt without taking into account colour would mean creating narrowband green lighting fixtures, since 555nm green light is perceived the brightest of any colour by the human eye. Colour must be taken into account to create light that meets the applications needs. Hence, the tuneable nature of QDs allows as much of the light as possible to be emitted where the human eye perceives it brightly, while simultaneously meeting the need of the application to emit white light of a certain colour temperature (warmth) with a certain colour rendering (CRI, or how accurately colours look when illuminated by a light source).*
- Ø *For **displays**, the arguments are quite similar. The white light spectrum that is desired by the application is different, emphasizing colour gamut and saturation over colour rendering. However, the need to deliver the light that is desirable, at wavelengths where it is perceived brightly, also requires a narrowband and tuneable light source. Lm/W are still relevant units, but are much harder to isolate since the system has many more optical components (colour filters, polarizers, etc.) that are part of the system efficiency. Hence, the industry (and our own* [the applicant's] *writings) will usually quote efficiencies on a relative basis to some well-known reference. Today, that reference is usually an LCD system lit by a white LED comprised of a blue LED with yellow [cerium doped] YAG:Ce phosphor."*

#### 7.2.2.1 Implementation of QDs into Display Lighting Applications

Nanoco-Dow[56] explains that **three potential strategies** exist through which QDs can be integrated into conventional LCD BLUs: "on-chip", "on-edge" and "on-surface", as defined by Coe-Sullivan et al.[57] (see Figure 7-5 below):

- Ø In '*on-chip technology'*, the QDs are placed on the LED surface, encapsulated within its package. This technology requires the lowest amount of QD material, however in light of the proximity to the light source, practical application is difficult to accomplish as the QD material undergoes thermal degradation in light of the proximity to the light emitting source.
- Ø *'On-edge technology'* has QDs incorporated into a remote component situated in close proximity to the LED chips. This can be done for instance in an

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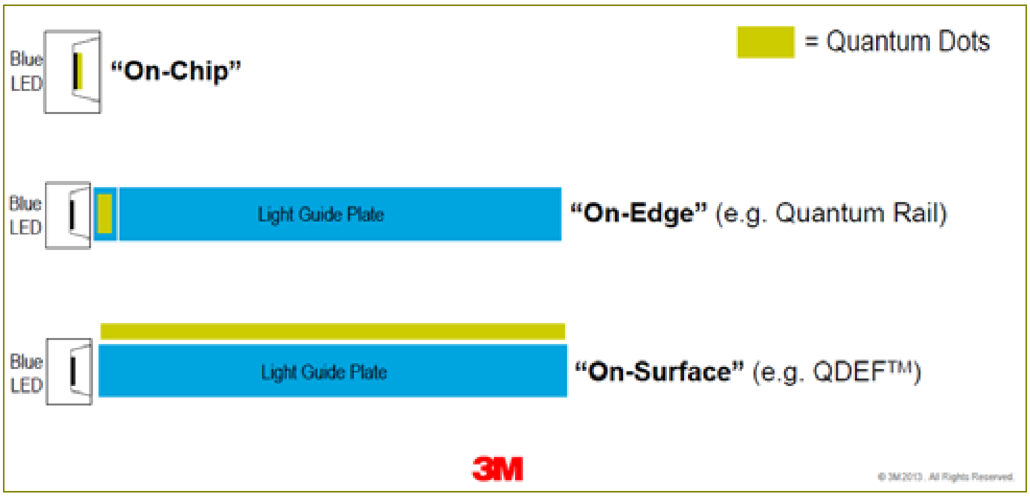
[56] Nanoco-Dow (2013a), Contribution made concerning Ex. Re. 2013-2 – answers to RoHS Consultation Questionnaire, submitted by Nanoco Technologies Limited & Dow Electronic Materials on 06.11.2013, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20131106_Nanoco_Dow_Contribution_Ex_2013-2_Response_to_RoHS_Questionnaire.pdf

[57] Quoted in Nanoco-Dow (2013a) as: S. Coe-Sullivan, W. Liu, P. Allen and J.S. Steckel, *ECS J. Solid State Sci. Technol.*, 2013, 2, R3026

adjacent capillary. On-edge technologies allow a compromise between the risk of thermal degradation and the respective QD material requirements.

- In '*on-surface technology*' 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.

Figure 7-5: Possible Configurations for Integrating QDs into an LCD System




*Source: 3M (2013b[58])*

Nonoco-Dow further provides an estimation of the amounts of Cd that would be allowed in the QD material based on the allowances that the current exemption (Ex. 39) allows per $mm^2$. The comparison is estimated for the light emitting area relevant in the application of each configuration for a 40" screen, based on the various technologies, as specified in Table 7-1 below.

[58] 3M (2013b), Presentation given at Targeted Stakeholder Meeting, held on 13.12.2014, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/12-13-13_3M_RoHS_Exemption_Request_2013-5__Meeting_-_Presentation_Handouts_01.pdf

Table 7-1: Estimated Light-emitting Area and the Corresponding Maximum "Allowed" Cadmium Concentration (according to the proposed exemption request) for On-chip, On-edge and On-surface QD BLU Designs for a 40" screen

| Design | Estimated Light-Emitting Area, $mm^2$ | Maximum Cd Content "Allowed" (Ex. 39) |
|---|---|---|
| On-chip | 48 (light-emitting area, based on LED area within each chip of the two LED light bars) | 480 µg |
| On-edge | 1 x $10^4$ [=10,000] (surface area of two glass capillaries) | 100 mg |
| On-surface | 4 x $10^5$ [=400,000] (display area of a 16:9, 40" screen) | 4 g |

*Source: Nanoco-Dow (2013a)*

It should be noted that the comparative estimation made by Nanoco-Dow does not necessarily correspond to the amounts present in actual applications, but rather to the allowances that the current Ex. 39 would allow for each configuration. This is calculated based on an interpretation of the term "light emitting area" referenced to in the current Ex. wording, relevant for each configuration. Table 7-5 in Section 7.6.3 provides some additional information in this regard. In the provided example, on-chip configurations are estimated to have the lowest of Cd allowance per product, whereas on-surface configurations are estimated to have the highest allowance, in light of the reference to the emitting area.

The relation of these estimations with the actual Cd quantities required in the application of various configurations is unclear. However, in the consultants view it clarifies that the quantities relevant for different applications, along with the limitations of using a specific configuration throughout the product range need to be better understood. The differences between the application of on-edge and on-surface technologies are thus further explained in the following sections, based on the material submitted by each applicant.

## 7.3 Description of Requested Exemptions

### 7.3.1 Exemption No. 2

QD Vision, Inc.[59] has requested an exemption for *"Cadmium in II-VI LED Down-conversion"* and asks for a renewal of existing exemption 39 under RoHS 2, currently valid until 30 June 2014.

Exemption 39, listed in Annex III of the RoHS 2 Directive is worded as follows:

> *Ex. 39: "CADMIUM in colour converting II-VI LEDs (< 10 µg Cd per $mm^2$ of light-emitting area) for use in solid state illumination or display systems*
> *Expires on 1 July 2014"*

[59] Op. cit. QD Vision (2013a)

*Sections 7.1 through 7.5 are heavily based on information provided by the applicant and other stakeholders. Alterations have been made mainly to ensure comprehension and to avoid repetition.

A further alternative for the exemption wording was proposed in the application as follows:

> *"Cadmium in II-VI colour converting material (< 10 µg Cd per mm² of light-emitting area) for LEDs for use in solid state illumination or display systems"*

Furthermore, QD Vision requests the renewal for an additional period of 5 years pursuant to Article 5(2) of Directive 2011/65, as well as the possibility that cadmium may be used in spare parts for EEE placed on the market before the "expiry date".

According to the applicant, this exemption renewal is required to enable manufacturers to bring to the market a quantum dot down-conversion material for use in lighting and displays. The II-VI down-conversion materials (e.g. quantum dots), due to their narrowband, tuneable, stable and efficient properties, will provide consumer products with the superior performance, efficiency, and net benefit to the environment for which there currently is no substitute available. In lighting, narrowband emission translates to warmer light sources with 20 - 40% greater efficacy. Such products have already been placed on the market in the US. In the display market, narrowband emission translates to televisions, monitors, tablets and cell-phones that can achieve 100% of colour gamut (as defined by NTSC). This property has the added benefit of increasing light throughput through the display, which can in turn reduce energy consumption for identical perceived brightness by as much as 20%.[60]

QD Vision[61] describes the applications relevant for this request:

- *A backlighting unit component that includes a colour-converting II-VI semiconductor material (including cadmium bound in a crystalline material), which is bound in an organic polymer host, which is further sealed within glass (e.g. a sealed glass tube) and which is positioned between and in optical communication with one or more LEDs and a light guide plate. The colour-converting II-VI semiconductor converts at least a portion (the amount is predetermined) of the light emitted by the LED into one or more predetermined colours to provide colour converted light. This backlighting unit component is intended to be included as a part of a liquid crystal display (LCD) system.*
- *Similarly, the substance has been used as a colour-converting plate between one or more LEDs and the light output face of a general illumination device (lamp / lightbulb).*

#### 7.3.1.1 History of the Exemption

The original request for exemption 39 was submitted in 2008 by 3M as part of an earlier evaluation in 2008 and 2009.

Originally the requested exemption was formulated as follows:

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[60] Op. cit. QD Vision (2013a)

[61] Op. cit. QD Vision (2013a)

*“Cadmium within a colour converting single crystal semiconductor film for use in solid state illumination or display systems”*

3M submitted this request for exemption from the RoHS Directive because the II-VI-LEDs were intended to be used as replacements for Hg-containing lamps and conventional LEDs – especially in the mobile projector sector. At the time of the request, the technology was not yet commercial – even on the US market – but was planned to be placed on the European market by 3M in 2009.

Based on the evaluation of the submitted information, Gensch et al.[62] recommended a re-wording and restructuring of the above wording, resulting in the existing exemption No. 39. The Commission adopted this recommendation.

#### 7.3.1.2 Applicant’s Justification for Exemption No. 2

QD Vision[63] state that the net benefit to the environment, of allowing the use of cadmium in the mentioned applications, is a result of the system level increase in efficiency that is achieved using the II-VI down-conversion materials, due to their narrowband, tuneable, and efficient nature (for further detail see section 7.3.4). QD Vision[64] provides estimations for the Cd content that is present in various products manufactured with Cd QDs:

- *“Large Display (TV): Average = 500-1500ppm, 1200 ppm (µg/gram) of homogeneous material (quantum dots distributed in polymer matrix) typical, 1.5mg total cadmium per unit.*
- *Medium Display (Computer Monitor): Average = 1000-3000ppm, 2000 ppm typical, 0.2mg cadmium per unit.*
- *Small display (Cellphone): Average = 1000-5000ppm, 3000 ppm typical, 10 ug cadmium per unit.*
- *Lighting device (bulb/fixture): Average = 1000-5000ppm, 3000 ppm typical, 20 ug cadmium per unit.*

*...At 100% penetration of II-VI down-conversion materials for both lighting and displays, our calculations show that a maximum of 120kg of cadmium could enter the EU annually under this exemption. Given the current lack of product on the market, a reasonable product ramp projection and the proposed 2019 expiry of the renewed exemption, 44kg of total cadmium would enter the EU over the*

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[62] Gensch et al. (2009), Gensch, C.; Zangl, S.; Groß, R.; Weber, A. K.; Deubzer, O.; Adapta¬tion to scientific and technical progress under Directive 2002/95/EC; Final Report, Öko-Institut e.V. and Fraunhofer IZM, February 2009; http://ec.europa.eu/environment/waste/weee/pdf/report_2009.pdf

[63] Op. cit. QD Vision (2013a)

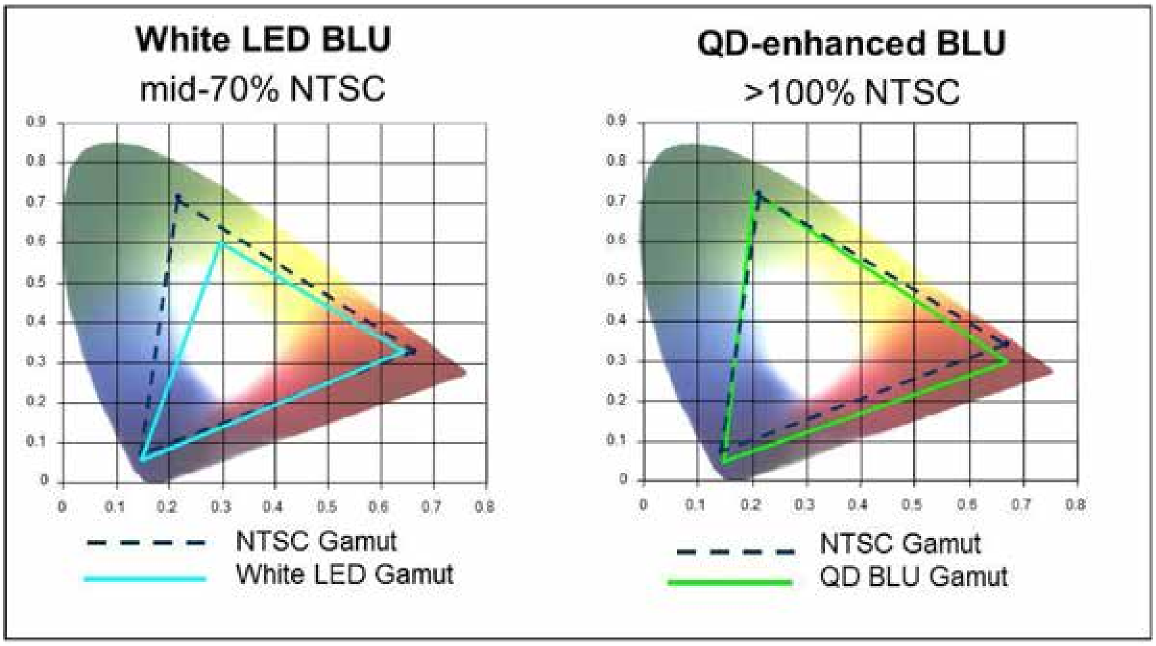
[64] Op. cit. QD Vision (2013a)

*2014-2019 time period (Annex 6[65]). This represents an average of 8.8kg per year for this time period...*

*The ... optical component ... is incorporated into LED backlight units for displays in TVs, monitors, tablets, laptops, or cell-phones. The same class of optical components is also incorporated into LED light bulbs.*

*In both cases, the component functions as a “luminescent filter”, absorbing some of the higher energy blue light, and down-converting that light to the characteristic colour of the specific II-VI material design. In lighting, red material fills in the missing light spectrum so as to render a more pleasing light than otherwise results, without sacrificing as much efficiency as other materials would lose. In display applications, red and green material is combined, and the resulting red, green, and blue light illuminates the liquid crystal display and gives the Red-Green-Blue components of light that make up the image. This is illustrated below by the CIE diagrams for standard white phosphor-LEDs and QD-enhanced BLUs”*[66]

Figure 7-6: CIE Diagrams Which Allow for a 2-Dimensional Projection of all Colours Visible to Humans (horse shoe shape)




*Left: colour gamut that can be displayed with LED backlit LCDs utilizing conventional phosphor material for down-conversion, shown relative to the NTSC colour standard; Right: colour gamut that can be displayed with LED backlit LCDs utilizing II-VI down-conversion material containing cadmium, which meets or exceeds the NTSC standard.*

*Source: QD Vision (2013a)*

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65 For more detail, see QD Vision (2013a-1), Annex 6 to QD Visions Application Dossier, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/Annex_06_Cd_calculations_summary.pdf

66 Op. cit. QD Vision (2013a)

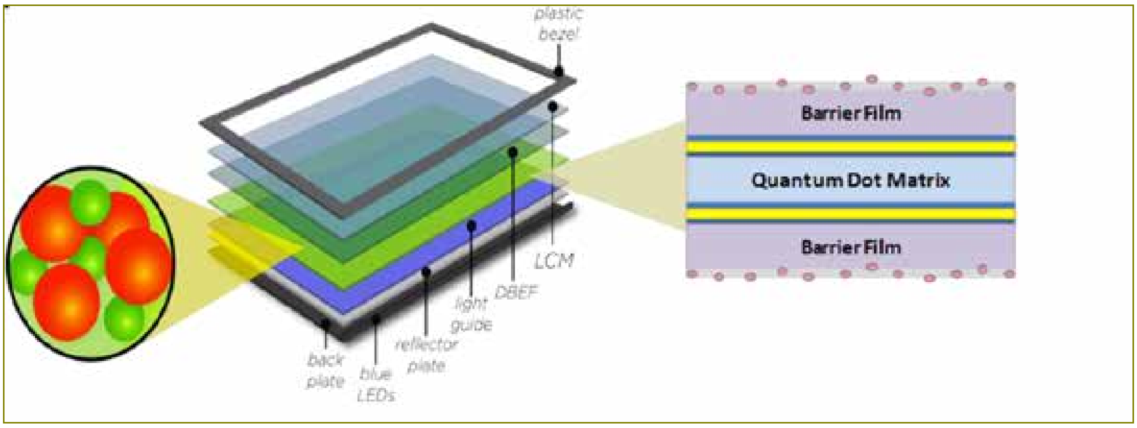
### 7.3.2 Exemption No. 5

3M[67], the applicant, explains that quantum dot light control films are a new technology that has been developed to enable liquid crystal displays (LCD) to give a technically superior image with a much higher range of colours than is currently possible with other commercially available LCD technologies. Alternative LCD technologies give broader ranges of colours which cannot be tailored to optimum wavelengths. Therefore 3M Optical Systems Division[68] has submitted a request for new exemption:

*"Cadmium in LCD Quantum Dot Light Control Films and Components"*

3M [69] explains that quantum dot light control films are polymeric films doped with small amounts of quantum dots that result in displays with very high colour quality (high colour gamuts). QD films can provide high efficiency solutions for high quality LCD colour performance that are easily scalable to any size display. When using QD film the only other change to the LCD system that is necessary is to substitute the white LEDs with blue LEDs (nominally by using the same GaN LEDs but without the YAG phosphor). See Figure 7-7 for a representative example of QD film in an LCD system.

Figure 7-7: LCD Assembly Diagram showing the Quantum Dot Film




*Source: 3M (2013a)*

Two different sized quantum dots, nominally green and red emitting, are incorporated into a polymer film. The smaller (~3nm in size) green dot would have a peak wavelength of approximately 540nm and a FWHM of approximately 30nm. The larger (~7nm in size) red dot would have a peak wavelength of approximately 615nm and a FWHM of approximately 40nm. The QD film would convert some of the blue "pump" light to green and red and allow some of the blue light to leak through unaffected. The spectral output of the blue LED has a FWHM of approximately 15nm and peak

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[67] Op. cit. 3M (2013a)

[68] Op. cit. 3M (2013a)

[69] Op. cit. 3M (2013a)

wavelength that ranges from 440nm to 460nm. In this way, narrow red, green and blue spectra of the appropriate peak wavelengths can be generated and high colour gamuts can be achieved.[70]

3M[71] further elaborate that the cadmium is bound to selenium in a core structure, encased within a shell, surrounded by ligands (various amino silicones), which is encapsulated within a matrix material (various polymer materials), and then finally encased between PET (polyethylene terephthalate) films. This QDEF film is then combined with other polymeric material layers within an LCD assembly. 3M claim that an LCD with QD film could easily be disposed of properly, ensuring that the contained cadmium does not contaminate the environment.

The total amount of quantum dots needed, as well as the ratio of green to red dots, depends on a number of factors. These include: the desired colour specifications of the display, the amount of light recycling (number and efficiency of light reflections) in the BLU, and the properties of the colour filters in the panel. The concentration of quantum dots, and therefore, the concentration of cadmium in QD film depend on these factors and the total thickness of the film. However, no more than 20 µg of cadmium/$cm^2$ of screen area should be used for any application. Typically, only 3 – 5 µg of cadmium/$cm^2$ of screen area would be used.[72]

#### 7.3.2.1 Applicant's justification for Exemption No. 5

The primary justification for this exemption is that only QD LCDs are able to achieve 100% colour gamut for all screen sizes and a secondary justification is that the potential substitutes have a greater negative environmental impact. [73]

3M[74] explain that QDs used in light control films are cadmium selenide (CdSe)/Zinc sulphide (ZnS) core/shell nanocrystals, optimized to deliver high quantum efficiency[75] as well as to meet the lifetime requirements in display applications. The high quantum efficiency, typically >88%, is necessary for QD film based backlights to deliver higher power efficiency (12%- 45% more energy efficient than traditional LED-LCDs for colour gamut sizes from 70% NTSC to 100% NTSC). QD light control films can have the sole purpose of tailoring the output spectral light distribution for high colour performance or they can have additional optical functionality (i.e., polarization, reflection, refraction, scattering).

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[70] Op. cit. 3M (2013a)

[71] Op. cit. 3M (2013a)

[72] Op. cit. 3M (2013a)

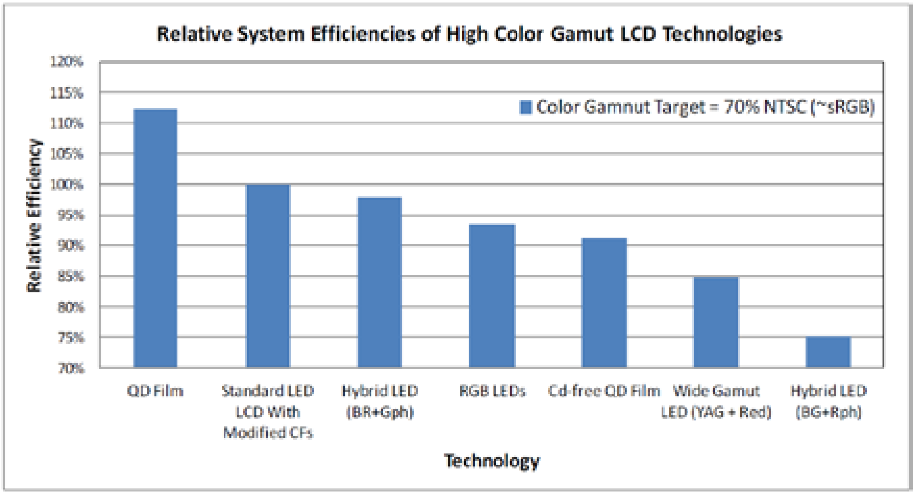
[73] Op. cit. 3M (2013a)

[74] Op. cit. 3M (2013a)

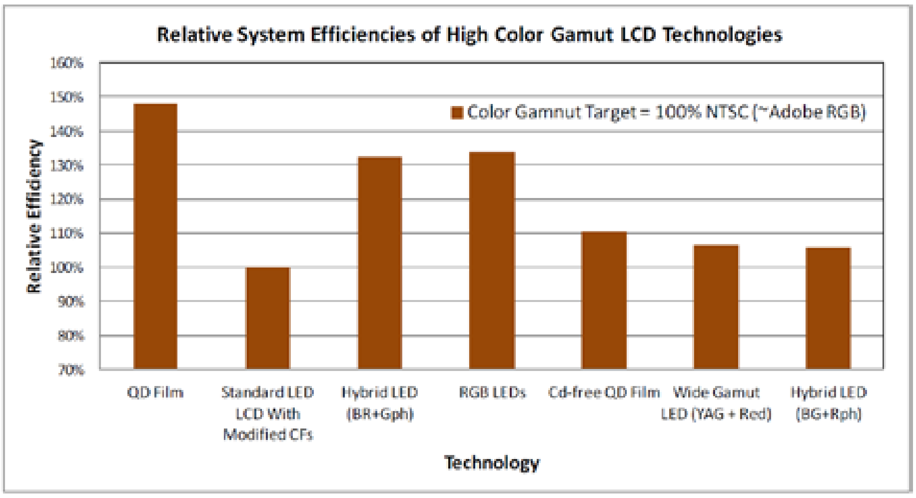
[75] Explained by 3M as *"the quantum efficiency of the dots (how efficiently they convert input photons to output photons)."*

To demonstrate the efficiency of this technology, 3M[76] detail a case study comparing between a 55" LCD TV and a QD film alternative, concluding that QD films result in an average power savings of 46% over existing LCD technologies. Furthermore, a comparison of the relative efficiency[77] modelling of various technology alternatives was included as in Figure 7-8 below.

Figure 7-8: Summary of Relative Efficiency Modelling for Colour Gamut Targets of 70% and 100% NTSC




*Note that the relative efficiencies are normalized as a reference to the standard LED-LCD at 100%.*




*Again, the relative efficiencies are normalized as a reference to the standard LED- LCD at 100%. Also note that this theoretical modelling analysis was performed for illustrative purposes only, currently in practice, only QD film and RGB LED technologies can achieve 100% NTSC colour gamut in LCDs.*
*Source: 3M (2013a)*

[76] Quoted by 3M (2013a) as: Quantum Dot Enhancement Film Cadmium Emissions Analysis, SourceOne, Inc., http://www.sourceone-energy.com/

[77] This reference to efficiency is understood by the consultants to relate to the efficiency of converting light into colour, to achieve the specified colour gamut.

In a later communication 3M[78] explain:

> *"In the context of the diagrams shown, the term efficiency refers to the ratio of electrical power into a display, to the light output from the display. The efficiency value shown in these figures is directly related to energy use. A higher efficiency translates to lower energy use. As an example, for the same light out from a display at ~70% NTSC colour gamut (the first diagram shown) a "Standard LED LCD with Modified CFs" system is approximately 12% less efficient and would therefore consume approximately 12% more energy than the "QD Film solution", assuming all other conditions are equal. The difference in efficiency increases for larger colour gamuts. This is important as the industry is moving to the next generation technical broadcasting TV standards such as Rec. 2020 for ultra high definition (UHD) TV. For the same light out from a display at 100% NTSC colour gamut (the second diagram shown) a "Standard LED LCD with Modified CFs" system would consume approximately 48% more energy than the "QD Film" solution."*

3m[79] estimate that typically 147 kg of cadmium will be placed on the EU market annually by this application (i.e., QD on-surface applications). Table 7-2 outlines the calculations used to develop this estimation. Using the same numbers it is estimated that 565 kg of cadmium will be placed on the global market annually (i.e., the EU has a 26% share of global sales).

Table 7-2: 3M estimation of Cd placed on the EU market through QD applications addressed in Ex. Re. 2013-5. Source: 3M (2013a)

| Application | Global Annual LCD Area (1) ($m^2$) | EU Share of LCD Area (2) ($m^2$) | % Using QD Film(3) | LCD Area Using QD Film in EU ($m^2$) | Typical Cd Content per LCD Screen Area ($g/m^2$) | Total EU Cadmium (kg) |
|---|---|---|---|---|---|---|
| TV | 157,333,925 | 26% | 2% | 818,136 | 0.05 | 41 |
| Monitor | 29,365,561 | 26% | 3% | 190,876 | 0.05 | 10 |
| Notebook/Ultrabook | 22,819,763 | 26% | 7% | 415,320 | 0.05 | 21 |
| Tablets | 12,174,293 | 26% | 60% | 1,899,190 | 0.03 | 57 |
| Small displays (phones, etc.) | 12,000,660 | 26% | 20% | 624,034 | 0.03 | 19 |
| | | | | | ***Total*** | ***147*** |

1. Based on forecasts from iSuppli in the Q4 2011 LCD Market Tracker Database and the Q4 2011 Small & Medium Display Market Tracker Database
2. Estimated based on EU's share of global GDP
3. Estimates for the potential use of QD film for the various segments

### 7.3.3 Roadmap for Substitution

Both applicants provide some information as to the time needed before a substitute (assumed to be in the form of a Cd free QD substitute) is assumed to become available in products in the market:

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[78] 3M (2014d), Response to 4th round of clarification questions, submitted per email on 17.03.2014

[79] Op. cit. 3M (2013a)

QDVision[80] state that:

> "*The best alternative to cadmium in down-conversion materials for LEDs in display and lighting solutions at this time appears to be the III-V semiconductor down-conversion materials. QD Vision initiated a research effort into this space in 2006... III-V semiconductors (e.g. Indium Phosphide) do not contain cadmium, nor do they contain any of the other RoHS-regulated substances. Since 2006, QD Vision has devoted a considerable amount of funding and effort to creating cadmium-free alternatives... QD Vision continue to believe that such alternatives will indeed be viable one day, however, our increased effort has also lead to an increased understanding of the practical technical difficulties of implementing such a material substitution. Our own research has not yet provided a III-V (Indium Phosphide) semiconductor material which demonstrates performance properties (e.g. efficiency at operating temperature, colour saturation, colour tuning, and stability) that match those of the current II-VI colour converting materials that contain cadmium.*"

QD Vision further explains the various steps that need to be undertaken and estimate how much time this would require. The information has been compiled in Table 7-3.

Table 7-3: Compilation of tasks to be performed and cumulative man-hours needed for completion, based on information provided in QD Vision (2013a)

| Stage No. | Tasks | Estimated man hours needed |
|---|---|---|
| 1 | Increase in efficiency, approaching market acceptable quantum yields (>90% at operating temperatures); decrease in colour bandwidth (<40nm FWHM), and increase in colour tuneability and reliability. | 10,000 |
| 2 | All technical requirements including reliability might be met for first applications into displays (estimated 90% probability of success at this time). | 25,000 |
| 3 | Design-in and qualification of developed materials. | Time not indicated |
| 4 | Manufacturing ramp with supply chain; initial low volume market introduction. | |
| 5 | Market ramp. | |

3M[81] provides an estimation that the replacement of Cd in commercial applications is to require a minimum of 7 years (by 2021). They explain that the only potential high colour quality substitute that does not have significantly higher energy consumption is Cd-free QD films. 3M estimates that Cd-free QD research (based on InP) shall reach the current colour quality and energy consumption performance with prototypes

[80] Op. cit. QD Vision (2013a)

[81] Op. cit. 3M (2013a)

becoming available by 2019. Thus they expect full-scale commercialisation by July 2021.

### 7.3.4 Environmental Arguments

QD Vision[82] has submitted two independent expert statements on LCA (life cycle analysis). QD vision summarises, that the Linnunmaa document concludes that even in the worst case, this exemption renewal could not create any non-negligible environmental effects, while in the best case it may provide large net benefits in terms of reduction in energy usage, carbon dioxide emission, and cadmium waste and air emissions. The ERA Technology (Consultancy) LCA document includes a technology-by-technology comparison, and concludes that II-VI down-conversion technology has an overall less negative environmental and health impact, compared to other available products and technologies.

The Linnunmaa document[83] provides some quantitative information as to general Cd emissions in the EU, originating from various sources. The document also analyses the possibilities for emissions from the Cd in the appliances at various stages of the life cycle, though this is done mainly on a qualitative basis and is thus not further detailed here. A comparison is made between displays using LED backlighting with Cd QDs and displays using LEDs with rare earth metal down-conversion material, with the main difference regarding the energy efficiency of the various components. It is noted that the applicant has estimated that a reduction of energy consumption of up to 20% is possible with Cd QDs, where the display is operated with identical brightness, in comparison to the other technology, however this estimation is not further explained. A further comparison is made between Cd QD based lighting and fluorescent lighting on a qualitative basis. The document shortly mentions the probability of reducing Cd emissions related to electricity production from coal; however this reduction is not quantified.

As a public version of the ERA[84] document was not provided, its contents are not addressed in detail. However the consultants have received permission to cite the following statement, relating to the savings in Cd emissions that are enabled through the use of Cd QDs in displays:

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[82] Op. cit. QD Vision (2013a)

[83] Linnunmaa (2012), Expert statement on LCA of Cd vs. non-Cd options for colour conversion in displays and lighting systems, prepared for QD Vision, available under http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/A11_Linnunmaa_Expert_Statement_on_LCA.pdf

[84] ERA (2012), Review of RoHS exemption request for cadmium in QD lighting and displays – short LCA, submitted by QD Vision with original application for Ex. Re. 2013-2, pg. 6.

*"Combustion of coal and oil emit Cd, Hg, Pb, As etc. Emissions from electricity generation are published by the European Environment Agency*[85] *and the total EU electricity generated each year is also published by the EU*[86]*. From this data it is possible to calculate that avoiding generation of 1kWh electricity prevents the emission of 3.8Lg Cd.*

***Lighting**: QD Vision estimate that QD lighting consume 0.2W less than other types of lamp so during 50,000 hours in use will save 11.5 kW. Therefore a QD lamp that contains 0.003mg Cd will avoid emission of 0.044mg Cd.*

***Displays**: QD Vision estimate that QD displays consume 16.8W/h less than other types of display so during 30,000 hours in use will save 504 kWh. Therefore a QD display that contains only 1.5mg Cd will avoid emission of 1.9mg Cd."*

QD Vision further provided a socio-economic analysis[87] in which they state that the use of cadmium in II-VI colour converting material in displays can reduce the energy consumption of a TV by approximately 20%. The document estimates that the economic benefits associated with this energy saving are to be around 3 billion euro between 2014-2019, should the requested exemption be granted.

In the preparation of this document, an actual risk of exposure to Cadmium by workers during the recycling activities was assessed using the CHEmical Safety Assessment and Reporting tool (CHESAR) of the European Chemicals Agency (ECHA) and the Advanced REACH Tool (ART) model for estimating inhalation exposure. It is stated that the assessment of the hazards of Cd and the exposure during recycling activities of LCD televisions shows that the risk is controlled, meaning that no effect on the **health of the workers** involved is to be anticipated when taking into account the operational conditions and risk management measures, and the occupational exposure limit of 4 μg Cd/$m^3$ as recommended by the Scientific Committee (SCOEL).

As for **environmental impacts**, the document states that savings in $CO_2$ emissions are expected in light of the reduction in energy consumption. To demonstrate this, an example is given of a TV using QD technology: "*Coal represents 26% of the total EU production of electricity and 1 kg of coal can generate 3kWh. By using a TV with QD it is possible to save 504kWh. It means that, by using one TV with QD optic, it is possible to save 43.7 kg*[88] *of coal over the lifetime of the television. The content of*

[85] http://www.eea.europa.eu/publications/eu-emission-inventory-report-1990-2010

[86] http://epp.eurostat.ec.europa.eu/statistics_explained/index.php?title=File:Electricity_Statistics,_2011_(in_GWh).png&filetimestamp

=20121128151011

[87] QD Vision (2013b), Socio-Economic Analysis - *Request for a Renewal of Exemption 39 under Directive 2011/65/EU (RoHS II) – Public Version*, submitted during the stakeholder consultation on 06.11.2013, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20131106_QDVision_Socio-Economic_Analysis_exemption_39_Public.pdf

[88] Calculation provided in QD Vision (2013b): (504kWh * 0.26) /3kWh/kg

*carbon in coal normally ranges from 60% to 80%[89]. The estimated reduction in $CO_2$ emissions over 2014-2019[90] has been estimated at 7,095,167 tonnes*." Savings for the environment are quantified using the Social Cost of Carbon (SCC) methodology along with the monetary saving for consumers in light of reduced energy bills and amount to 65,165,348 euro and 2,858,720,924 euro respectively.

3M[91] provide some further information in this regard, quoting:

> "*A case study of 55" LCD TVs has concluded that QD films result in an average power savings of 46% over existing LCD technologies.[92] This study also concluded that while the QD film itself contains approximately 39.7 mg of Cadmium per 55" display, the power savings from the QD film results in 149 mg of avoided Cadmium emissions from power plants, which in turn results in 110 mg of net environmental Cadmium avoided per 55" display during a 5.7 year operating lifetime (50,000 hours in use) or 35 mg avoided during a 2.9 year operating lifetime (25,000 hours in use). The EU televisions ecodesign study found that televisions in the EU are used on average 4 hours per day so 50,000 hours is equivalent to a lifetime of 34 years and 25,000 hours is equivalent to 17 years. Furthermore, the cadmium in the QD-LCD can be recovered safely by recycling whereas the cadmium and other toxic metal emissions from power generation contaminate the environment, enter the food chain, etc.*"

3M[93] elaborate on Cd emissions related to electricity generation, explaining that electricity consumption is said to be most significant in the use phase, as demonstrated by the life cycle assessment carried out during the televisions eco-design preparatory study, DG TREN Lot 5 (see http://www.ecotelevision.org/). Cd emissions related to energy production (and consumption) are however related to the energy source, with both the burning of coal and oil emitting Cd emissions. It is explained that coal can contain up to 300 grams per tonne, though most combustion emissions are abated through the use of scrubbers. 3M state that in the UK, in 2009, Cd emissions were still 180 kg, whereas data published for the EU[94] shows that in 2010, ~12 tonnes of cadmium, ~180 tonnes of lead and ~30 tonnes of mercury were emitted from EU energy generation and distribution. 3M then state that:

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[89] Quoted in QD Vision (2013b) as: Energy Information Administration, Quarterly Coal Report (EIA, 1994).

[90] Explained in QD Vision (2013b): Assuming that the carbon content in coal is 70%.

[91] Op. cit. 3M (2013a)

[92] Quoted in 3M (2013a) as: Quantum Dot Enhancement Film Cadmium Emissions Analysis, SourceOne, Inc., http://www.sourceone-energy.com/

[93] Op. cit. 3M (2013a)

[94] Quoted by 3M (2013a) as: http://www.eea.europa.eu/publications/eu-emission-inventory-report-1990-2010

*"One source has calculated that for a 55 inch LCD-LED television using QD film, the emissions of cadmium from electricity generation are reduced by 110mg per year as compared to a similar performing standard LED-LCD television without QD film, but this uses data for electricity generated in the USA. Comparable data on cadmium emissions per kWh electricity generated in USA and in Europe exists but the accuracy is uncertain. Emissions will be different due to the different mix of generation sources and emission scrubber efficiencies."*

Both 3M and QD Vision were asked to provide further information to clarify the calculations made concerning Cd savings that Cd QD applications enable in light of the significant energy savings associated with the product during the use phase. The data has been compiled into a table format to allow better understanding and comparison of the assumptions made and the information used by each applicant. This information appears in Table 7-6 in Section 7.6.5, followed by its review.

## 7.4 Availability of Alternatives

### 7.4.1 Possible Substance Alternatives

The applicants as well as contributing stakeholders have provided information concerning the existence of possible substance alternatives, namely cadmium-free QD technology.

In this regard QD Vision[95] state that:

*"the most direct alternative would be cadmium-free quantum dots (CFQDs) which have been proposed and researched by many, including our company. To date, however, these materials do not have sufficient properties (narrowband emission, efficiency, stability under operating conditions) to be a viable technical alternative in the marketplace [see for example Kim et al., Appl. Phys. Lett. 101, 073107(2012); doi: 10.1063/1.4745844; Anc et al., JSS 2 (2) R3071-R3082 (2013) OR Annex 8; AND Yang et al., Adv. Mater. 2012, 24, 4180–4185 – Annex 12]."*

As for possible substitutes, it is further explained that:

*"Light emission requires a material with an optically allowed excited state transition. Inorganic materials are to date the only material class that has the reliability to withstand LED operating conditions. Inorganic phosphors are currently in use, but do not have the desirable narrowband emissive properties (in most cases they are three times worse) that lead to LCD displays that can achieve the television colour standards (known as NTSC 1953), nor the optimized lighting efficacy…*

*…group IV semiconductors such as Silicon don't generally emit light. To date, III-V semiconductors cannot be made into sufficiently efficient nor narrowband down-conversion materials, and hence do not have any net*

[95] Op. cit. QD Vision (2013a)

*beneficial properties over conventional phosphor materials. Similarly, the non-cadmium II-VI semiconductors (e.g. ZnS, ZnSe, ZnTe) are better suited for efficient emission outside of the visible spectrum, or have not been shown to be stable enough for commercial use."*

In contrast, Nanoco-Dow, one of the contributing stakeholders, provides information concerning a possible Cd free QD substance. Dow Electronic Materials and Nanoco Technologies are working together towards the development and implementation of a Cd free QD technology for display as well as lighting applications. The Nanoco-Dow Cd-free QD material (herein after CFQD™) is said to be a unique, alloyed semiconductor matrix including both indium and phosphor, but different from InP QDs in composition and thus also in its properties. To summarize the information they have provided:[96]

- CFQD™ cadmium-free quantum dots are not made from indium phosphide. Although containing indium, they are made from a unique, alloyed semiconductor matrix with quite different properties.
- Their optical emission performance currently meets the requirements for commercial LCD screens, in terms of enhanced screen colour range and lifetime (at least 30,000 hours).
- The alloyed matrix of elements in CFQD™ quantum dots ensures that both the semiconductor band gap and the strength of the bonding interactions within the nanoparticles can be manipulated, reducing the strength of the quantum confinement effects and thus the range of wavelengths (i.e., the FWHM) emitted by a given size distribution of quantum dots. As a result, a given size distribution of CFQD™ quantum dots exhibits a significantly narrower wavelength distribution than that exhibited by the same size distribution of indium phosphide quantum dots.

Nonoco-Dow[97] provide further information concerning the performance of CFQD™ in on-chip and on-surface geometries. Though the on-chip technology does not exhibit the minimum reliability requirements at present, Nanoco-Dow provide results to show that CFQD™ can be used instead of cadmium QDs to significantly improve the colour gamut with respect to that of a rare-earth phosphor colour-converted TV. They state that:

- In *on-chip* experimentation the colour gamut was increased from 67% to 92% of the area of the United States National Television Systems Committee (NTSC) 1953 colour triangle.
- As for *on-surface geometries*, Nanoco-Dow state that "*CFQD™ have been incorporated into a film displaying 97% NTSC 1953 area (89% NTSC 1953 overlap)... The colour gamut is comparable to that displayed by the commercially available cadmium quantum dot LED TV. Although the colour*

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[96] Op. cit. Nanoco-Dow (2013a)

[97] Op. cit. Nanoco-Dow (2013a)

*gamut of this TV is reported as 100% of the NTSC 1953 standard, our internal measurements found that the maximum overlap with the NTSC 1953 colour triangle was just 91%...*".

- Regarding the use of CFQD™ in *lighting applications*, it is stated that "colour-converted LEDs were prepared... using Nanoco's CFQD™ cadmium-free quantum dot material... Though the luminous efficacy was slightly lower than that for traditional LEDs with a similar CCT (correlated colour temperature), the CRI (colour-rendering index) for the CFQD™ LEDs was comparable or higher.

As for product availability on the market, Nanoco-Dow[98] explains that:

> "*Small-scale manufacture is currently undertaken in the UK and larger scale manufacture is scheduled to be online by mid-2014. A pilot launch of the first TVs using CFQD™ cadmium-free quantum dots is planned for the first half of 2014, with full commercial production expected within the following 12 months... We envisage that CFQD™ quantum dot-containing colour-converted LED lighting (SSL) will be available by the end of 2015.*"

### 7.4.2 Possible Design Alternatives

The applicants as well as contributing stakeholders have provided information regarding a number of substitutes, including:

- Compact Fluorescent (CFL) bulbs;
- Traditional LED LCDs with More Absorptive Colour Filters;
- RGB LEDs;
- Hybrid LEDs;
- OLED technology;
- Plasma technology.

Table 7-4 details some of the aspects mentioned regarding these possible alternatives by the different stakeholders. The various sources can be viewed for more detailed information.

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[98] Op. cit. Nanoco-Dow (2013a)

Table 7-4: Comparison of Key Qualities and Performance of Possible Alternative Technologies

| Technology | RoHS compliance | Energy efficiency | Colour performance | Additional comments |
|---|---|---|---|---|
| **CFLs**[99] | Contain Hg (1mg vs ~20ug in comparison with CdQDs*) **not clear what geometry and product category would be covered with the ~20ug estimation* | CFLs are also less than half as efficient as today's LED bulbs, and thus even less efficient in comparison with Cd QD technologies | - | Where Hg is used in vapour state, emissions can occur during use in case of breakage |
| **Traditional LEDs with more absorptive colours**[100] | | The lower light transmission through the filters leads to higher device energy consumption – inefficiency is said to increase with high colour gamut targets. | Colour gamut target of ~70% NTSC leads to system efficiency reduction above 12%. Colour gamut target of ~100% NTSC, leads to system efficiency reduction above 45% | Highly absorptive colour filters are explained to be difficult to manufacture and are not scalable to all LCD applications (less suitable for smaller displays) |
| **RGB LEDs**[101] | | Approximately 19% less efficient for a 70% NTSC colour gamut target and approximately 14% less efficient for a 100% NTSC target | | Relevant for larger sized LCDs (typically notebooks and larger). Temperature and age stability are also mentioned to be problematic areas. |
| **Hybrid LEDs** | Currently not used in LCD backlight and so could only be relevant as an alternative in the future. | | | |

[99] Op. cit. QD Vision (2013a)

[100] Op. cit. 3M (2013a)

[101] Op. cit. 3M (2013a)

| Technology | RoHS compliance | Energy efficiency | Colour performance | Additional comments |
|---|---|---|---|---|
| **OLED**[102] | | The energy consumption of an OLED display is estimated to be significantly higher than quantum dot film LCDs. This view is also supported by the stakeholders Touch Display[103] and Nanoco-Dow[104] for the products currently available on the market. However, Nanoco-Dow explain energy efficiency is linked with the image produced (predominant white/ black colour) being 3 times higher than that of a CdQD LCD (white) or consuming very little energy (black) | Ability to produce a high colour gamut area, even above 100% NTSC. | OLEDs directly convert electricity to light and can be patterned into red, green & blue addressable sub-pixels. BLU's and colour filters are thus not needed. Used mainly for small-size screens of smart phones, etc. - manufacture of larger size displays considered technically challenging at present |
| **Plasma**[105] | | Consume significantly more power than do LCD displays for the same luminance (~ 2-4 times as much power) | | Relatively thick and heavy and thus currently only available in sizes of ~ 40" (102cm) diagonal & above |

*Note: Reference to source applies to information provided for technology, as long as no further source is given.*

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[102] Op. cit. 3M (2013a)

[103] Touch Display Research (2013), Contribution by Touch Display Research Inc. to stakeholder consultation, submitted 21.09.2013, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20130921_Colegrove_stakeholder_contribution_Re_2_5_OLED_TVs_are_high_power-final.pdf and http://touchdisplayresearch.com/?page_id=447

[104] Nanoco-Dow (2013b), Contribution made concerning Ex. Re. 2013-5 – answers to RoHS Consultation Questionaire, submitted by Nanoco Technologies Limited & Dow Electronic Materials on 06.11.2013, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-5/20131106_Nonoco_Dow_Contribution_Ex_2013-5_Response_to_RoHS_Questionnaire.pdf

[105] 3M (2013a) quote the following sources regarding this statement: http://en.wikipedia.org/wiki/Plasma_display ; http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=TV ; and http://www.displaymate.com/shootout.html#series1

## 7.5 Stakeholders' Contributions

During the stakeholder consultation, various stakeholders contributed information. As most contributions have been made regarding both exemption requests, the main aspects are detailed shortly below and regard both requests unless otherwise stated. Furthermore, both applicants submitted contributions in support of the other request. As most of the supporting information is reflected in the information provided in the sections above, such information is not further detailed below.

**Touch Display Research Inc.**[106] has submitted a contribution with some data as to the performance of OLED displays. In short it is explained that, at present, the OLED TVs which are currently on the market consume considerably more power than the equivalent LCDs. It is stressed, however that it should not be concluded from this statement that OLEDs won't succeed once further developed.

**Nanoco Technologies Limited and Dow Electronic Materials** have made a few contributions, objecting to both requests and providing information as to Cd free QDs as well as general information to QD technology and to possible lighting alternatives for displays. The key aspects are conveyed in the various sections above.

**Merck**[107] provides a contribution, explaining that they also manufacture displays and develop various materials and applications for display lighting. They claim worldwide recognition as a leading company for developing high end materials for future and current display technologies, working among others on a complete portfolio of materials for OLED displays. To clarify that the exemption is relevant for more than just the two applicants, they state that many other companies are developing applications similar to the CdQD applications described in the requests and that further product launches are expected soon. The use of quantum materials is said to be the only way at present to provide "*high-performance colour LCDs, which offer low power consumption compared to standard LCDs (approximately by a factor of two). Displays can be made with a power consumption which is by a factor of three less than the current OLED displays in the market with a comparable colour performance...this situation will not change at least until 2020*." Merck support both of the requests.

**Nanosys Inc.** Have submitted a letter of support and later also took part in a targeted stakeholder consultation in light of their being a technology partner of 3M. Parts of the information they have contributed are quoted above, and also reflected in the information provided in the above sections. Thus the key issue are not further detailed here.

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[106] Op. cit. Touch Display Research (2013)

[107] Merck (2013), contribution submitted by Merck in the stakeholder Consultation, regarding exemption requests 2013-2 and 2013-5, submitted on the 07.11.2013 and available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20131107_MERCK_ContributionEx_Re_2013-2_and_2013-5_QD_RoHS.pdf

**Blubox Trading AG**[108] has made a contribution providing information about the technology they represent for integrated plants for recycling of mixed lamps and flat screens. Their contribution is meant to support that products containing the QD Vision technologies they claim can be safely and securely handled at end-of-life by the Blubox technology as required in the various EC rules and regulations. This technology is said to be installed in 3 locations across Europe and is fully contained, does not produce emissions, is safe to operate and almost fully automated and therefor cost-effective. Blubox was asked by QD Vision to conduct a series of tests which included processing the company's components through the Blubox system, to see how effective the handling of the components is. It was concluded that "*The components can be handled safely by the system operators and processed efficiently within the Blubox system. The dismantling of flat screens containing QD Vision's components is not required prior to processing and the potentially hazardous components…(Cd) are separated and accumulated in the fraction of fine particles in very small amounts, which can then be recycled or disposed of safely and securely…".*

**Crytalpex Corporation; Ocean Nano Tech LLC; QLight Nonaotech LTd.; Pacific Light Technologies; Voxtel Inc.; and Navillum Nano Technologies**[109] have submitted a general letter of support. The letter briefly reiterates that the exemptions are relevant for additional stakeholders involved in the development and manufacture of QDs as well as in the implementation of such technologies in lighting and displays. Further reference is made to the advantages afforded by QD technologies in solid state lighting applications in terms of energy efficiency and the respective emission reduction.

**Lighting Europe**[110] has submitted a contribution supporting the two requests. It states that *"…the main focus of the lighting industry is on developing energy efficient lighting with a high quality colour spectrum…",* and *"energy use is the main environmental impact of the product which takes approximately 90% share from the total negative lifecycle impact. The environmental advantage due to energy efficiency outweighs by far the much smaller impact of the materials used in the product. Therefore, LightingEurope strongly supports the use of innovative materials to increase efficiency and improve colour quality of lighting… LightingEurope members*

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108 Blubox Trading AG (2013), Blubox Trading AG Contribution submitted in the Stakeholder Consultation", submitted on 07.11.2013 and available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20131107_Blubox_Contribution_Ex-Re-2013-2_QD_Vision_Letter_110513.pdf

109 Crytalex et al. (2013), Support Letter Sighned and submitted in the Stakeholder Consultation by Crytalpex Corporation; Ocean Nano Tech LLC; QLight Nonaotech LTd.; Pacific Light Technologies; Voxtel Inc.; and Navillum Nano Technologies Concerning Requests 2013-2 and 2013-5, available under: http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/Request_2013-2/20131111_Ex_Re_2013-2_5_6_Support_Letters.pdf

110 Lighting Europe (2013), Lighting Europe Contribution submitted in the Stakeholder Consultation", submitted on 11.11.2013 and available under: 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

*have extensive expertise in the field of phosphor materials and lighting products and our experience is that the use of Cadmium II-VI colour converting materials will lead to improved colour rendering (CRI > 90), luminous efficacy (improvements over 20%) and lower overall system cost for LED lamps and luminaires… For general lighting applications, an alternative to Cadmium II-VI colour converting materials is the current use of AlInGaP red LEDs… Unfortunately, the red LEDs suffer from severe efficiency loss as the temperature increases. This limits the applications for use and increases the total cost as expensive drivers and heat sinks are necessary to correct for these ill-effects. In the display market, the green InGaN LED is insufficient to meet the efficiency requirements. Cost and complexity also negate the practical use of RGB LEDs in comparison to a colour converting material that can provide the same colour output."*

Lighting Europe further raise a few questions regarding the market surveillance and the compatibility of an exemption wording to the capabilities of market surveillance operations:

- They raise concern as to which part of the LED is to be considered as a homogeneous material; and
- As to the experience of market surveillance authorities with regard to testing of LEDs, and complying exemption related allowances.

Lighting Europe further explains that setting a maximum cadmium content level for the exemption may result in additional administrative costs for industry and market surveillance authorities. They believe the environmental advantage of such an allowance to be questionable.

LightingEurope is asking *"whether it would be a better solution not to have limit value. As mentioned above, a threshold would create legal uncertainty due to uncertainties in interpretation of homogeneous material samples and also for variations in measurements of cadmium content using state of the art measuring and mechanical disjointing techniques."*

The **Swedish Ministry of Environment**[111] has submitted short statements for each of the requests. Concerning Ex. Re 2013-2, it states that *"The exemption applies to a use that was not available on the EU market when the previous exemption was approved. According to the description in the request for renewal of the exemption, the referred use is still not applied to any products on the EU market, why an exemption does not seem justified.*" As for Ex. Re. 2013-5, it emphasizes that "*In our opinion, the exemption should be specified more clearly, to avoid that it may be applied to uses in other screens than intended. We suggest that the specification should include a clear technical description of the type of screen referred to in the request*."

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[111] Swedish Ministry of Environment (2013), Contribution to RoHS Stakholder 2013 Consultation 1, submitted 11.11.2013, available under http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_IX/SE_Comments_on_stakeholder_consultation_RoHS_Aug_Nov_2013.pdf

## 7.6 Critical Review

### 7.6.1 REACH Compliance - Relation to the REACH Regulation

Chapter 5.0 of this report lists entry 23 restricting the use of Cd and its compounds in Annex XVII of the REACH Regulation. This entry restricts the use of Cd in mixtures and articles produced from a number of synthetic organic polymers referred to as plastic materials. Mixtures and articles produced from the named plastic materials shall not be placed on the market if the concentration of Cd (expressed as Cd metal) is equal to or greater than 0.01% by weight of the plastic material. Among others this list refers to PET which has been mentioned by 3M as the sheet material used to encapsulate the matrix in which the Cd QDs are present. From the explanations provided by 3M, the Cd in QD film applications is present only within the QDs contained within the matrix material and Cd is thus understood not to be present in the PET sheets in between which it is encapsulated.

In the context of the RoHS Directive, the important factor would be to understand if within the end product component, the two layers can be separated in order to understand if PET and Cd are in the same homogenous material or not. However to the consultants understanding the homogenous definition does not apply to the term used in Article 32 (the plastic material), nor is it generally applied in the REACH context. Thus, in the consultants' understanding, entry 32 of Annex XVII does not apply to the referred uses of Cd in QD films used for solid state lighting and display lighting applications.

Various Cd compounds are also specified for entries 28 – 30, which restrict the placing on the market of these compounds as substances and in mixtures. As the use of Cd in the relevant applications results in its presence in a component present within a product to be placed on the market and not a substance or mixture, these restrictions would not apply.

The consultants conclude that the use of Cd in QD films used for solid state lighting and display lighting applications, would thus not weaken the environmental and health protection afforded by the REACH Regulation. The same holds true for potential substitutes, namely Cd free QDs based on InP, which may apply as a substance alternative, as this substance is currently not specified in the REACH legal text. An exemption could therefore be granted if other criteria of Art. 5(1)(a) apply.

### 7.6.2 Scientific and Technical Practicability of Substitution

#### 7.6.2.1 Elimination

In the consultants view, the information submitted, sufficiently demonstrates that where non-QD alternatives are concerned, there is a trade-off between the ability to achieve high colour performance (i.e., colour gamut) and the final energy efficiency of the product. This is understood to be the reason why application of alternatives with a wider band-width in products, results in either lower colour quality or higher energy consumptions. In some cases, additional obstacles for implementation may exist, the most relevant for substitution being the limited scalability of some of the alternative technologies, to allow covering the full product range. Though the estimations made by the applicants concerning differences above 10% energy efficiency in the comparison of Cd QD technologies with alternatives may be questioned, the information submitted by other stakeholders does not suffice to negate this claim:

- Some of the contributing stakeholders have provided their support to this point in general (e.g., Lighting Europe, Merk – see Section 7.4.2 for further information)
- The contribution of Nonoco-Dow, which do not support the requested exemptions, states that the "*current power consumption for OLED TVs is higher than for LCD TVs because it is not yet fully optimised. As the technology stabilises for mass production, power consumption is expected to improve dramatically, towards that of an LCD*." Though it can be understood that the development and optimisation of OLED technology may provide a sufficient alternative to Cd based QD technology, it also clarifies that the current state of technology is still insufficient in this regard. Touch Display Research Inc. has also referred to this point concerning the OLED used in displays already on the market.

Though OLED technology could further develop and become comparable in terms of both colour and energy efficiency with Cd QD technology, information is lacking as to how long this may take. It can thus not be concluded that OLED provides a practical alternative at present, neither can it be assumed at what time in the near future this may change.

It is further concluded that even if there are some specific applications where the QD advantages are less prominent than suggested, for the majority of the product range, the use of Cd based technology would provide end-products with qualities that are to be considered beneficial in comparison with other displays in terms of colour and energy performance. Based on the information made available CdQD technologies are understood to be at least 10% more efficient than the alternative technologies, in converting light photons into colour photons, in most cases showing a higher efficiency (cf. Figure 7-8 for further detail). This efficiency is understood to translate into energy efficiency, in cases where the same colour performance can be achieved, as with QDs the narrow band spectrum allows for more light photons to be translated into the image. Further information links energy savings with a reduction in Cd emissions, related to the reduction associated with producing energy from coal – this is further discussed in Section 7.6.5 below.

#### 7.6.2.2 Substitution

From the information provided by the applicants as well as some stakeholders, it can be understood that substance alternatives, in the form of Cd-free QDs could in general be applied in displays in the same way that Cd based QDs are applied. Concluding as to the applicability of substance alternatives thus requires:

- Ensuring that alternative QD materials can provide at least comparable properties; and
- Clarifying that they are already available on the market and provide a comparable reliability to Cd based QD technology.

QD Vision[112] state that *“Reliability has been a major impediment to the inclusion of new light emissive materials in electronic equipment in general, and to date the reliability of cadmium-free alternatives is far from sufficient to meet the requirements of consumer electronic and lighting devices. However, given the lack of market acceptable cadmium-free alternatives, there is also a complete lack of publicly available reliability data on such material alternatives”*.

Nanoco-Dow have provided information as to a promising Cd-free QD material that is scheduled to come on to the market shortly, however as long as products are not commercially available, such alternatives could not yet be regarded as an available substitute, nor could the comparable properties and reliability be confirmed.

It should however be noted in this regard, that according to Nonoco-Dow and the applicants, once a Cd-free QD material is established in terms of its colour spectra, performance and reliability under the application conditions, its implementation into end-products is to be very similar to that of the present Cd-QD based products. In this regard, similar products, using the same QD geometry are understood to require the same resources in terms of production. Assuming it provides comparable properties, a RoHS compliant QD Cd free material would thus be understood to have an advantage as products should otherwise also be comparable. Furthermore, even if such products may result in a certain decrease in performance (colour gamut; energy efficiency) as soon as this alternative is viewed to be available, it should be considered if a certain level of lesser performance would be acceptable, to allow the elimination of a RoHS regulated hazardous substance.

### 7.6.3 Cadmium Reduction

The information provided by the applicants has been compared to determine the relative amounts of Cd required for different products, based on the various geometries. Table 7-5 is a compilation of this information to that end. It should be noted that the current Ex. 39 permits the use of 10 µg Cd per $mm^2$. As this allowance does not provide a further limitation on the thickness of the colour converting material, in practice, a range of concentrations may be applied.

[112] Op. cit. QD Vision (2013a)

Table 7-5: Comparative Cd Concentration and Quantities in Various Applications, Based on Applied QD Configuration – Compiled by consultants based on data provided by applicants in Annex 6 to QD Vision (2013a) and in 3M[113] (2014b)

| Product | Required Cd concentration in the homogenous material | | Resulting Cd amount in product | | Comments |
|---|---|---|---|---|---|
| | On Edge (QD Vision) | On Surface (3M) | On Edge (QD Vision) | On Surface (3M) | |
| Large Display | 1200ppm | 90 - 145 ppm yellowish / low efficiency: 600 ppm (Approximate film thickness: 400 µm ) | 1.5mg (1500 µg) | TVs: 8.5-40.4 mg yellowish / low efficiency: 162 mg | TVs: Display sizes from 32" - 60"+ diagonal |
| Medium display | 2000ppm | 150 - 250 ppm (Approximate film thickness: 200 µm ) | 0.2mg (200 µg) | Monitors: 2.4 - 14.1 mg: Notebooks: 0.8 - 4.0 mg: Tablets: 0.07 - 1.4 mg: | Mid-size monitors, laptops, tablets Display size from 10-32" diagonal |
| Small display | 3000 ppm | 205 - 340 ppm (Approximate film thickness: 100 µm ) | 10ug | Mobile phones: 0.07-1.4 mg; | Smart-phones Display size around 3" diagonal |
| Lighting | Wide range of values: several thousand ppm | No information provided - 3M's focus has been on on-surface QD technology for display applications | 20ug | No information provided - 3M's focus has been on on-surface QD technology for display applications | |

The compiled information clarifies the complexity of addressing both on-edge and on-surface configurations with a single threshold limit. Though on-surface configurations use significantly lower concentrations, they result in a larger total Cd quantity in the final product. In contrast, using a quantified threshold would require specifying quantities for a large number of sub-product groups. This may also result in less motivation of industry towards further reductions where such thresholds are already met in specific end-products.

To add to that, as on-edge technologies exhibit an advantage in terms of the total Cd present in the end-product, the applicants were asked as to the ability of this technology to cover the full product range.

113 Op. cit 3M (2014b)

A few limitations have been named in this regard:

- **Lifetime and Reliability** – Though 3M[114] state that"...*In contrast, the on-surface approach has the QDs remote to the LEDs, greatly reducing temperature and flux exposure. Therefore, the on-surface geometry has a significant advantage that results in increased system lifetimes that can be on the order of 4 orders of magnitude*"[115], the more important question here is if a minimum reliability is ensured. As QD Vision (2013a) refers to a *"lifetime of 30,000 operating hours"* for current products using its applied on-edge technology, translating to a 20 year service life if the product is to be used for 4 hours per day.

- **Form Factor and Bezel Size** – The on-edge geometry is not scalable to all display sizes. The fact that a QD element (a glass tube filled with a QD matrix material) has to be inserted into a device between the LEDs and the light guide plate (LGP) simply does not match with the slim, narrow form factors of many smaller LCD devices, particularly those of a 14" diagonal and less. Also some larger edge-lit TV's won't be able to incorporate quantum rails, as bezel design considerations would not allow for the extra space required. [116]

  Though the suggested 14" threshold may not be exact, the various information provided by QD vision in various documents supports that on-edge configurations cannot be applied at present in all displays in light of insufficient space. Though this aspect is not exclusive to the smaller displays, it is also clear that in such displays this is indeed more of an issue than in the larger ones.

- **Direct-Lit LCD Systems** – 3M[117] explain that one of the major drawbacks to the on-edge approach is that it only works in systems that use an edge lighting approach. In this regard QD Vision[118] states that *"Placing the QDs on the edge of a display is only useful if the LEDs are on the edge. Edge-lit design is implemented in essentially all mobile phones, tablets, and notebooks, but one can find some products that are not backlit this way in segments of monitors, all-in-one computers, TVs, and signage. Usually the industry uses the terms 'edge-lit' vs 'direct-lit' to make this distinction...We do anticipate that future developments in QDs will enable more efficient material usage in direct-lit designs than the current generation of on-surface technology. However, we would not characterize those potential future solutions as on-edge technology, but rather something that is much closer to on-chip technologies... On-chip configurations may impact both edge-lit and direct-lit backlighting approaches*

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[114] Op. cit. 3M (2014b),

[115] Quoted in 3M (2014b) as Coe-Sullivan, et al., JSS 2 (2) R3026-R3030 (2013)

[116] Op. cit. 3M (2014b),

[117] Op. cit. 3M (2014b),

[118] QD Vision (2014b), Response to 3rd round of clarification questions, submitted per email on 24.02.2014

*in the future. Again we emphasize that such solutions are not market-ready today."*

It should thus be noted that a possible shift away from the direct-lit approach could have an impact on the application of on-chip developments as well as on that of other technologies used in such displays, including Cd-free QD applications.

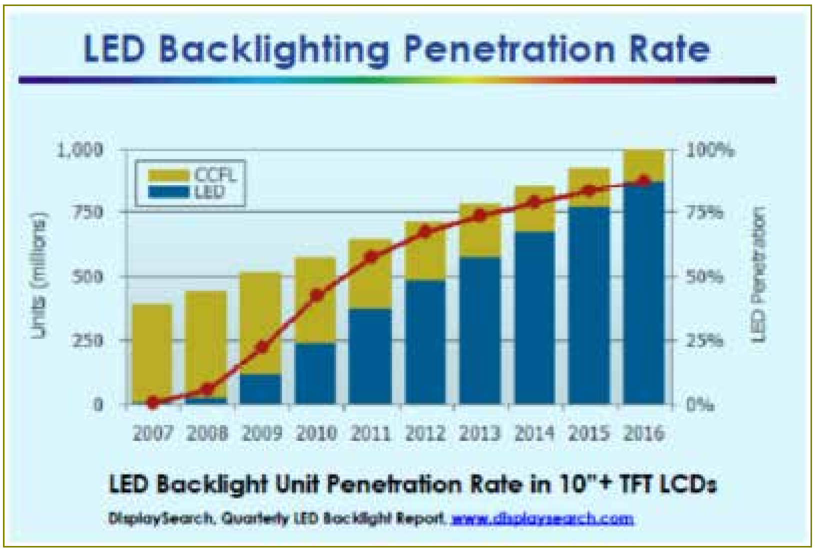
### 7.6.4 Market Aspects

Though it has not been discussed in detail by the various actors, it is understood that the future of the display lighting industry is to be significantly impacted, following the EU COMs ruling if to grant an exemption or not. The range of impacts may also vary as a result of the possible wording that such an exemption may have, and the range of products that would be respectively addressed.

In this context, an important aspect is to understand what part of the display market, the Cd QD technology displays are expected to represent in the coming years.

3M[119] have stated in this regard that they assume *"QDs to penetrate the display market in a similar manner to how other new technology introductions have gone within this industry."* To illustrate this comparison they provide Figure 7-9 to show *"how LED backlight technology is currently completing its penetration into the LCD industry, displacing CCFL*[cold cathode fluorescent] *backlight units. QD penetration into the LED backlit LCD industry in 2013 is best compared to the LED penetration rate (from the graph, above) as of 2007, and so perhaps we are 3-4 years from a 50% penetration rate."*

Figure 7-9: LED Backlight Technology Penetration in the LCD Industry




*Source: 3M (2014a)*

[119] 3M (2014a), Information provided to clarify open issues specified at a targeted stakeholder meeting held on 13.12.2013", submitted by the applicant on 17.01.2014

QD Vision has also provided the diagram above and a similar statement as to the possible penetration of Cd QD display applications on the market.[120]

To summarize, the provided information suggests that the penetration over the next 3-5 years could be in the range of 20-50% of the LCD market. As it is clear that such market penetration would have a significant impact on the use of alternative technologies being implemented in display products, it raises a question as to the severity of this impact on other segments of the lighting industry. As this point has not been raised by stakeholders, data is insufficient to go beyond raising the general concern in this regard.

Concerning CD QD in solid state lighting applications, QD Vision[121] state that "While QD Vision has several active collaborations with companies targeting lighting applications with our materials, we don't view it as likely that 2014 will see new product launches. 2015 and 2016 will likely be when QDs in this application and industry are again ready for introduction, with typical market growth expected thereafter." Further information does not allow concluding as to expected penetration of Cd QD technologies in the solid state lighting market – neither in terms of types of lighting applications, nor in terms of possible trends in market share.

### 7.6.5 Environmental Arguments

Information has been included by applicants as to the various environmental impacts.

Various comparisons of Cd QD technologies with other technologies have been submitted, including quantitative information and qualitative information. However, the detail of submitted data does not allow a full understanding of all aspects. Quantitative information usually regards a specific device, where as it is difficult to deduce from one device to the full range of application (e.g. from a large display to all displays etc.). It can be followed that when comparing devices with comparable colour performance certain benefits occur, especially regarding energy consumption. However, the detail of information does not allow concluding as to the range and significance of such benefits regarding the full product range.

Information was also provided related to the reduced Cd emissions that are enabled through the use of the Cd QD technology, in light of the reduced energy consumption attributed to such products. Both 3M and QD Vision clarify a reduction of Cd emissions to be expected, related to a decrease in manufacture of energy from coal. Coal combustion is explained to be a source of emissions of Cd, Hg, Pb and As, that cannot be completely abated. Both QD vision and 3M provide results of an example calculation of such savings as related to a TV:

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[120] QD Vision (2014a), Response to open issues highlighted during the targeted stakeholder consultation held on 13.12.2013, sent on 17.01.2014

[121] Op. cit. QD Vision (2014a)

- The 3M information refers to a savings of 149 mg Cd over 50,000 hrs of operation in comparison with 39.7 mg of Cd used within the display, i.e, a net benefit of 110 mg of Cd avoided. This is further demonstrated with a lifetime of 25,000 hrs for which the net benefit is estimated to be 25 mg avoided Cd.
- The QD Vision information refers to a savings of 1.9 mg Cd over 30,000 hrs of operation in comparison with 1.5 mg of Cd used within the display i.e., a net benefit of 0.4 mg of Cd avoided

The calculations resulting in these numbers, along with various explanations and references appear in Table 7-6 below.

Table 7-6: Calculation of Cd Savings from Reduced Energy Consumption through Product Use Phase. Compiled by consultants based on data from the following sources: Source One Energy Solutions (2011)[122], QD Vision (2014c)

| QD Vision calculations | | | |
|---|---|---|---|
| | **Unit** | **Value** | **Notes and references** |
| Typical power consumption of 42" TV with QD Optic | W | 67.2 | 20% reduction due to QD benefits |
| Typical power consumption of 42" TV with LED only | W | 84 | RG Phosphor is next best alternative |
| | | | 20% power difference is conservative at NTSC spec |
| Basis | 1 TV | | |
| Lifetime of a TV | hours | 30,000 | Rated lifetime of our components |
| Power consumed by TV with QD optic | W | 67.2 | |
| Power consumed by TV w/o QD optic | W | 84 | |
| Savings with QD optic | W | 16.8 | 84 – 67.2 |
| Total energy saved over lifetime | kW-hr | 504 | (C13*C8)/1000 |
| Cd content in TV Optic | mg | 1.5 | Conservative estimate for either 1H or 2V configuration of 42" TV |
| EU cadmium AIR emissions from | tonnes | 12,228 | http://www.eea.europa.eu//publications/eu-emission- |

| 3M - based on Nanosys calculations for one source report, dated 2011 | | | |
|---|---|---|---|
| | **Unit** | **Value** | **Notes and references** |
| Typical power consumption of 55" TV with QD Optic | W | 129.46 | |
| Typical power consumption of 55" TV - "current models" | W | 239.83 | |
| | | | |
| Basis | 1 TV | | |
| Lifetime of a TV | hours | 50,000 | |
| Power consumed by TV with QD optic | W | 129.46 | |
| Power consumed by TV w/o QD optic | W | 239.83 | |
| Savings with QD optic | W | 110.4 | |
| Total internal energy saved over lifetime | kW-hr | 55185 | |
| Electric T&D losses between the power plan and the TV | rate | 6.14% | Average energy losses across the US - EIA, State Electricity Profiles 2008, DOE/EIA-0348(01)/2 |
| Electric T&D losses between the power plan and the TV - | kW-hr | 338.8359 | Lifetime energy savings* electric T&D losses: |

[122] Source One Energy Solutions (2011), Quantum Dot Enhancement Film Cadmium Emissions Analysis, prepared for Nanosys

| QD Vision calculations | | | |
|---|---|---|---|
| | **Unit** | **Value** | **Notes and references** |
| electricity generation (2010) | | | inventory-report-1990-2010 |
| Electricity generation by EU27 2010 | TWh | 3,181 | http://epp.eurostat.ec.europa.eu/statistics_explained/index.php?title=File:Electricity_Statistics,_2011_(in_GWh).png&filetimestamp=20121128151011 |
| EU Cd emissions per kWh of electricity generation | ug/kWh | 3.8 | C17/C18 |
| Cd saved during display lifetime | mg | 1.9152 | C19*C15/1000 |
| | Note: Savings estimated here across the TV's life time exceed the 1.5mg of Cd in a QD TV | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

| 3M - based on Nanosys calculations for one source report, dated 2011 | | | |
|---|---|---|---|
| | **Unit** | **Value** | **Notes and references** |
| calculated | | | **calculation added by consultant to check results** |
| Total electricity generation savings | kW-hr | 5,857.3 | |
| US - Grams Cd per KWh - emissions factor | g/kWh | 5.56E-05 | |
| US - Coal electricity Cd emissions | µg/kWh | 55.58 | According to the EIAf, over the last three years coal was used to generate 45.88% of the electricity in the United States. |
| US - Coal electricity Cd emissions | mg/kWh | 0.0556 | Unit conversion added by consultant to check results |
| US - Grid electricity Cd emissions | µg/kWh | 25,5 | For US |
| US - Grid electricity Cd emissions | mg/kWh | 0.0255 | Unit conversion added by consultant to check results |
| Cadmium emissions avoided per 55" QDEF TV | mg | 149.38 | Total energy savings* Cd emissions per kWh |
| Cadmium content of 55" QD Enhancement film | mg | 39.70 | |
| NET Savings | mg | 109.68 | |

Though the numbers differ significantly in each case, it can be followed that products that consume less energy may contribute to the environment in light of the benefits derived from a lower demand for electricity. However, the information provided by the applicants does not allow concluding if this benefit would indeed justify the use of Cd in the application for a number of reasons:

- The applicants base their estimations for Cd emissions savings on the operation of the TV for a stated service life of 25,000 to 50,000 hrs. As the 3M information states, the EU ecodesign study found that televisions in the EU are used on average 4 hours per day. Though 3M continue to calculate that the service life of the TV would thus be between 17 and 34 years, the consultants cannot follow this logic. Regardless of the calculation itself, in the current society, it is doubtful if the average private consumer would indeed use the same TV for such long periods, especially if one assumes that image quality, energy efficiency and other parameters shall continue to develop tempting consumers to purchase new appliances. In this sense, it is concluded that only a portion of the related benefit could be considered to accumulate during the actual service time of the product.
- The calculations of Cd savings in both cases are based on the Cd emission factor that is associated with the production of electricity in the EU (3.8 ug/kWh as stated by QD Vision) or in the US (25.5 ug/kWh as explained in the calculation referred to by 3M). The Cd emission factors, for the most part, are the result of the rate of energy produced from coal, estimated to be 26% and over 50% for the EU and the US respectively. However, the factor 2 difference in the share of coal combustion from the energy mix does not suffice to explain the larger difference between the Cd emissions factors used. Cd emissions resulting from energy production depend on a few factors, including:
    - The Cd content of the coal being used (tied to the type and origin of the coal);
    - The retention of Cd in flue gas abatement technologies applied at the power plant (i.e., how much Cd remains in unavoidable emissions) as well as respective emissions that cannot be avoided to air as well as other media; and
    - The share of coal based energy production in the general energy mix.

  Therefore conclusions on Cd savings tied to Cd emissions from electricity production are complex and do not generally allow deducing the significance of environmental benefits.
- Another aspect of concern is the dependence of this estimation on a certain energy mix relevant for the EU. It is assumed that this mix shall not remain unchanged over the next 20 years or even over the next 10 years. This is further supported by information that both applicants provide to show that Cd emissions from electricity production have substantially decreased in the EU in the last decades. It is thus concluded that the estimations would need to assume a certain change in the energy mix over time which would likewise mean that annual benefits would change over time.

- Ø It can be followed that from the alternative technologies, some are more efficient than others. A benefit related to lower energy consumption could also be calculated for other technologies and it is understood that some would also allow a certain degree of Cd savings. In this sense it remains unclear what portion of the Cd savings could only be achieved through the Cd based technology and what portion could be achieved through other technologies.

In general, though the consultants can follow that benefits, in terms of emission reductions and benefits derived from lower energy consumption during use, might be possible for the Cd QD technologies, the provided information from both sources does not allow quantifying the degree of this benefit, nor comparing it with the respective benefit that is relevant for other display technologies.

### 7.6.6 Legal Aspects

A number of stakeholders, as well as one of the applicants, have provided information concerning the applicability of the current exemption 39 (which QD Vision have requested to be renewed) to the various applications for which an exemption is being discussed. The current Ex. 39 reads:

> *"CADMIUM in colour converting II-VI LEDs (< 10 µg Cd per $mm^2$ of light-emitting area) for use in solid state illumination or display systems*
> *Expires on 1 July 2014"*

The current Ex. 13(b) has also been cited in this regard and is formulated in Annex III of RoHS as:

> *Ex. 13(b): "Cadmium and lead in filter glasses and glasses used for reflectance standards"*

A main concern that has been raised regards the applicability of these exemptions to the use of Cd in products already available on the EU market. In this context, it should be noted that the legal aspects of how stakeholders choose to interpret the various exemption wordings, and what products are as a result placed on the market, is beyond the mandate of the consultants. Though the consultants aim at providing a wording formulation that is clear and that limits use only to areas where this is understood not to be avoidable, what is later done in practice falls beyond the scope of this project. The importance of this issue thus regards the various considerations tied to the formulation of an exemption, should it be decided to grant a new exemption or to extend and or adjust the current one.

Furthermore, the possibility that the scope of Ex. 13(b) includes the use of Cd in QD applications has been raised, the main concern being that it provides no limitation for the use of Cd and could thus be interpreted by manufacturers as permission to use more Cd in QD applications as compared to the allowances prescribed in Ex. 39. Though it may be argued, how the Ex. 13(b) wording formulation is to be understood, the fact remains that this exemption existed in the RoHS 1 legal text with an even wider scope, at the time that the request leading to the current Ex. 39 was submitted and evaluated. The original formulation "Ex. 13: *Lead and cadmium in optical and* *filter glass*" still existed in the RoHS 1 consolidated version[123] of 26.02.2010 (as well as before) in which the original Ex. 39 makes its first appearance and the current narrower scope was only updated at a later time. It is thus understood that neither 3M nor the evaluating consultant assumed at the time that the applications mentioned were covered by an existing exemption, as a new exemption would otherwise not be needed. Though it could be that the existing formulation was not taken under consideration in the course of the review, the fact that a specific exemption was granted should clarify that the areas of application in which such materials were permitted for use fall under the scope of Ex. 39 and would thus not fall under the scope of other exemptions. As the scope of Ex 13(b) is narrower in relation to the earlier Ex. 13, the same logic should apply concerning the scope of the current Ex. 13(b), thus also not to be understood to cover Cd QD applications in displays and lighting.

A further area of concern, raised by Lighting Europe, regards the capability of market surveillance operations to sample the related homogeneous material, and to conclude unambiguously from measurement results if the Ex. is misused or not. This could also be relevant in the understanding of what component is understood to be the homogenous material in the various Cd QD applications. Regarding the first questions, in Annex 6 to their original application, QD Vision[124] mention *"direct elemental analysis (ICP-MS) of prototype products after dissolution in HF[*hydrogen fluoride]*"* as the method used to establish the actual quantities of Cd in prototype applications. Nanoco-Dow[125], in their original contribution, have referred to "...analysis of the resin by inductively coupled plasma mass spectrometry (ICP-MS)", which is understood to be the same method used by QD Vision. The US EPA refers to a detection threshold of 0.0001 mg/l for Cd in ICP analysis[126]. The consultants thus understand an analysis method to be available.

### 7.6.7 Possible Wording Formulation of an Exemption

Under certain assumptions, the EU COM may see an exemption as relevant. This section thus shortly discusses how such an exemption could be formulated.

As has been explained shortly above, specifying a threshold that would address both on–edge and on-surface configurations is a complex task. Prescribing a concentration would give preference to on-surface configurations, though these generally result in more Cd per end product. Prescribing a quantity limit would need to be compatible for a range of products, as within a product group, quantities depend not only on size but also on other provided properties such as colour spectra (e.g., white light versus warm yellow light). This shall require addressing a number of product groups and shall

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[123] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2002L0095:20100226:EN:PDF

[124] Op. cit. QD Vision (2013a-1)

[125] Op. Cit. Nanoco-Dow (2013a)

[126] See "U.S. EPA's Methods and Minimum Detection Limits - List taken from the 2007 version of 40 CFR 141.23 to 141.25" at http://www.epa.gov/ogwdw000/ccr/pdfs/list_ccr_mdl_and_methods.pdf, last viewed 17.2.2013

result in a "split-exemption". Such a split could make future reviews of an exemption more complex, as has occurred in the case of the CFL exemptions. It should also be said in this regard, that at present a quantity threshold is preferable for on-edge applications, and could also result in a shift away from the backlight approach in displays in general. It is unclear if this shift is beneficial in the long term, despite its appeal in the Cd amount context in the short term.

The consultants understand the industry to be moving towards a reduction in the total amounts of Cd that need be applied in end-products. Both applicants have attested to their own research into Cd-free QD alternatives and it is also clear that research is still underway in the hope of delivering an on-chip geometry, providing the minimum reliability requirements of possible end-products. The application of Cd QD in displays has made its first day-view on the market (currently in a number of TV's and in a number of tablet applications) and is further expected to mature and develop with time. As with any technology, it can be assumed that this will lead to higher efficiencies, probably also in terms of the amounts of Cd that are to be applied. To further promote this direction, the consultants feel that if an exemption is to be granted, at present, it would be preferable to provide a simple formulation, allowing more room for development of the market in the near future.

The wordings listed in Table 7-7 have been mentioned in the context of these requests for exemption:

Table 7-7: Possible wordings proposed for Ex. Re. 2013-2 and Ex. Re. 2013-5

| No. | Proposed by | Wording |
|---|---|---|
| 1 | Original Ex. 39 wording | *CADMIUM in colour converting II-VI LEDs (< 10 µg Cd per mm² of light-emitting area) for use in solid state illumination or display systems* |
| 2 | QD Vision – proposed change | Cadmium in II-VI colour converting material (< 10 µg Cd per mm² of light-emitting area) for LEDs for use in solid state illumination or display systems |
| 3 | 3M – request for new exemption | *Cadmium in LCD Quantum Dot Light Control Films and Components* |
| 4 | Lighting Europe – proposed merge of requests | Cadmium in light control materials used for lighting- and display devices |

As has been raised by some of the actors, the initial formulation of Ex. 39 (No. 1 in Table 7-7) is ambiguous and open to interpretation as to how Cd may be used in colour converting II-VI LEDs (i.e., it remains unclear if this formulation indeed covers the three possible configurations or if it regards only the direct use of Cd Qds in a layer applied directly to the LED as is the case in on-chip configurations). The No. 2 suggestion is also ambiguous, as *"colour converting materials for LEDs"* could still be interpreted to mean materials to be used in the LED component, where as in some cases the configuration makes use of the material in the proximity of the LED. The No. 3 suggestion only addresses on-surface configurations, though clearly, where other configurations can be used, this would result in the use of less Cd per product.

The No. 4 suggestion on the other hand allows the use of Cadmium in all light control materials. The main concern in this regard, is that the exemption could be used for an application that is not defined as a quantum dot application, consequently resulting in an extreme increase of Cd. This formulation would thus not serve the purpose of limiting the use of the exemption to a clear and limited area of application.

The consultants contacted both applicants to clarify the significance of various terms to the formulation of a possible exemption.

QD Vision[127] have proposed the following formulation: *"Cadmium in components for lighting and display applications containing downshifting cadmium based semiconductor nanocrystal quantum dots, where for display applications the cadmium per display screen area is limited to less than 20 ug/cm²"*, noting that *"the term "downshifting" as being the most specific and scientifically accurate term of art to describe the process of absorbing high energy photons and emitting somewhat lower energy photons. The term "down-conversion" is used in the scientific literature sometimes to describe processes wherein one photon is absorbed and two photons are emitted (not the case in the QDs considered in this consultation), and hence could cause some confusion. The term "colour converting" to our knowledge is not well-defined in the scientific literature, and hence has the potential to cause confusion with, for example, simple absorptive filter materials."*

3M propose[128] the formulation "*Cadmium in light control materials used for lighting and display devices*" explaining that "*The term "light control materials" would include both on-surface film (QD Film) and on-edge structure applications. An alternative acceptable term for "light control materials" would be "light converting materials". The term "light converting materials" also describes both on-surface and on-edge structure applications.*" In reference to a practical threshold for the use of Cd, they further explain that "*The lowest maximum concentration value appropriate for the on surface film application is 0.2 µg Cd per $mm^2$ (accordingly, a maximum would be expressed as <0.2 µg Cd per $mm^2$ of light emitting or light converting area in light control films for use in display systems)...For on-surface applications, it is essential that concentrations be stated in unit area, for example: "µg Cd per $mm^2$ of light emitting or light converting area*"

In the consultant's understanding, the threshold of 0.2 µg Cd per $mm^2$ (or *20 ug/cm²)* is acceptable by both applicants. As this threshold is a substantial reduction as compared to the current 10 µg/mm2, it would in any case be recommended that should an exemption be granted, this threshold be adopted. The wording that QD Vision propose is understood to address the various uses of cadmium in QD Dots for which the exemptions have been requested more precisely – "*downshifting cadmium based semiconductor nanocrystal quantum dots*" – and would thus allow limiting the scope of a possible exemption to the use of Cd in specific materials used for specific applications. The consultants see a further limitation of the use to components for use in the lighting of displays as beneficial.

[127] Op. Cit. QD Vision (2014b)

[128] 3M (2014c), Response to 3rd round of clarification questions, submitted per email on 24.02.2014

As is explained below, the consultants would not recommend at present that an exemption be granted allowing the use of the discussed technologies in solid state lighting.

The following formulation is thus assumed to cover the various applications in display lighting and should be considered should an exemption be considered:

> *Cadmium in components for 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*

Both applicants have been consulted as to the suggested wording to ensure that the Cd threshold still allows manufacturing display applications with both on-surface as well as on-edge QD configurations.

QD Vision[129] have raised a few points concerning the various adjustments made to earlier proposals, which in the consultants opinion are worth noting to enable better understanding of the new proposal:

- *"Specifying display applications as 'display lighting applications' – we would interpret this as inclusive of all formats of display backlight units, whether direct or edge-lit, and hence inclusive of our applications.*
- *Changing units to ug/mm2 from ug/cm2 – we assume it is desirable to utilize the same units as the original exemption 39, and hence this change is also not meant to change scope, but rather make the exemption changes easier to understand. The unit conversion is correct, and hence there is no change of scope and our applications remain covered by the proposed new language."*

It should be noted that further stakeholders were not consulted as to the applicability of this formulation, and more specifically of the threshold. From the information made available through the consultation process and by the applicants, it is understood that though other manufacturers may be active in the development of Cd Qd applications for display lighting, none of these have matured into actual products available on the market at present. Furthermore, as it is understood from both applicants that the proposed threshold is sufficient to allow development of the various configurations, other manufacturers would be expected to develop further applications complying with this threshold.

It is apparent that the application of QDs in display lighting is developing, both in the direction of further reductions that may be possible through on-chip configurations and through the possible application of Cd-free QDs. In the consultants view the availability of the exemption is thus to be reconsidered in the short term to ensure that the reduction of Cd is still motivated and/or that the use of Cd QDs is indeed still unavoidable. The duration of the exemption should be sufficient to provide the applicants with sufficient time to: research and prepare a comprehensive strategy for the reduction of Cd quantities/ its substitution, in the relevant applications, as well as to submit an application for exemption renewal should this remain relevant (at least

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[129] Op. cit. QD Vision (2014c)

18 months before expiration). To accommodate the applicants with sufficient time in this regard, the consultants recommend a duration of 3 years.

### 7.6.8 Conclusions

Article 5(1)(a) provides that an exemption can be justified if at least one of the following criteria is fulfilled:

- their **elimination or substitution** via design changes or materials and components which do not require any of the materials or substances listed in Annex II is scientifically or technically impracticable;
- the **reliability** of substitutes is not ensured;
- the total negative **environmental, health and consumer safety impacts** caused by substitution are likely to outweigh the total environmental, health and consumer safety benefits thereof.

Concerning elimination, it is understood that various alternatives exist, many of these already in use in display and lighting applications currently on the market. However, most of these alternatives are said not to provide comparable colour gamut performance as is possible with Cd QD products, or otherwise to result in significantly higher energy consumption. Though the colour aspect could be seen as an aesthetic aspect, the applicants have provided quantifications of this quality that allow it to be addressed on a comparative and thus technical basis. In this sense, if the colour gamut aspect is to be understood to suffice, alternatives could be understood to provide performance inferior to that of the Cd QD applications, thus meaning that elimination is not possible on the grounds that substitutes are not practical as the colour gamut provided would be significantly inferior to that of the discussed applications. The only alternative that is understood to provide comparable colour performance (e.g., OLED) is said at present to exhibit substantially higher energy consumption in comparison with that of the technologies at hand, and would thus be understood to be impractical on this level. As for substitution, the current research into alternatives relevant as a substitute in quantum dots used in lighting applications has not sufficiently matured in terms of implementation in products which are currently available on the market. Though the information provided by Nanoco-Dow is promising in terms of the launch of first products on the market in the coming year, as long as such a counter product is not available, a comparison would not be allowed. As a forecast is always liable to change, it remains to be seen at what time such alternatives shall become available in products on the market. At that time, concluding as to the comparable reliability shall also become possible. It should however be noted that if such products are indeed to come onto the market in the coming months, in light of the time needed for the final stages of granting an exemption, it could be that the fulfilment of this criterion shall change.

If to return to the alternatives relevant for elimination, the applicants, as well as a number of the stakeholders claim that CdQDs used in displays provide better performance in terms of energy efficiency when in operation. The low range of energy efficiency cited is above 10%, rising considerably in the comparison with most of the alternative technologies or in relation to the display size. In this regard, it is understood that the negative environmental impacts tied with the available alternatives would be higher than the positive ones in terms of energy consumption, though the range of difference is not clear. As other environmental aspects could change this balance (e.g. consumption of energy, raw materials and water in production), it cannot be concluded if and to what degree the third criterion is fulfilled. However in light of the colour gamut aspect highlighted above, the consultants understand at least one of the criterions to be fulfilled.

As for possible impacts on the lighting industry in light of significant penetration of Cd-QD technologies into the relevant product market range, applicant information suggests a penetration of 20–50% over the next 5 years. As data is lacking to confirm this estimation as well as to conclude as to the impact that this may have on the rest of the lighting industry, the consultants could not further conclude as to this aspect. That said, in light of the presence of Cd, a RoHS regulated substance in the relevant product, the swift penetration of the various CFL applications is to be kept in mind in this regard. An example of a product providing energy saving benefits as well as low costs, CFLs quickly dominated the lighting market in various areas. This aspect is understood to have provided industry with a strong market related argument concerning the applicability of substitution with Hg-free products, as is at least in part represented in the numerous exemptions listed in Annex III of the RoHS Directive to date.

Concerning Cd QD applications in solid state lighting applications, it should be emphasized that little information has been provided by the applicants in reference to such applications. Even more-so in terms of understanding how possible lighting applications may compare with other alternatives, for which the market provides a wide range of solutions. If in display lighting applications, colour gamut is understood to be a significant parameter for image quality, in lighting applications, other parameters are also of importance. The consultants do not feel that the provided information allows a comprehensive understanding of the various aspects, nor of the lighting areas for which applications are to be manufactured with Cd QD technology (consumer products, industrial lighting, long-life lamps etc.). Furthermore, it is understood that such products are only expected to become available on the market in the future, thus meaning that it is still difficult to state what part of the market range would be covered and what actual properties the Cd QD technology could provide that are not already provided with other technologies. In some cases, it would be relevant to shed light on the benefits of a new application in comparison with similar applications on the market (i.e., demonstrate to what degree such benefits justify the use of a RoHS regulated substance). However, the current information suggests that the use of Cd QDs in lighting applications is still in development and would not allow a sufficient comparison – either in light of the development which is still forthcoming or in light of the confidentiality tied to products still not on the market[130].

[130] As the RoHS exemption evaluation process is a transparent one, confidential information may not be used to support argumentation, either in support or in oposition of a request.

## 7.7 Recommendation

Concerning the use of Cd QDs in solid state lighting, the information provided does not allow a conclusion that such an exemption would be justified at present. The consultants therefore recommend not granting an exemption for Cd in QD applications to be used in solid state lighting. It should however be noted that such an exemption may be regarded as relevant within the next few years. This recommendation is thus made in light of the current limitations to clarifying the necessity of such an exemption and is not to be understood as the consultants support or objection to future requests.

For the application of Cd QDs in displays, the consultants recommend granting an exemption with the following wording:

> *Cadmium in components for 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/mm$^2$*
>
> *To expire 01.07.2017*

This exemption is recommended for a shorter period than that applied for, in light of the understanding that applications resulting in reduction of Cd quantities as well as Cd free substitutes are in final stages of research.

## 7.8 References Exemption Request 2013-2 and 2013-5


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