Study to update the information on the use of cadmium in quantum dot applications for displays and lighting under Directive 2011/65/EU – Draft Report

Under contract No 090202/2022/878143/ETU/ENV.B.3

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Disclaimer

Oeko-Institut has taken due care in the preparation of this report to ensure that all facts and analysis presented are as accurate as possible within the scope of the project. However, no guarantee is provided in respect of the information presented, and Oeko-Institut is not responsible for decisions or actions taken based on the content of this report.

EUROPEAN COMMISSION

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Table of Contents

List of Figures

List of Tables

1 Executive summary – English

With contract No. 090202/2022/878143/ETU/ENV.B., Oeko-Institut e.V. has been requested by DG Environment of the European Commission to provide technical and scientific support in a review of cadmium (Cd) quantum dot (QD) applications. Such applications were subject of an assessment of exemptions performed as Pack 15 Task 5 "Assessing three exemption requests for the use of cadmium in quantum dot applications in displays and lighting", finalised in 2020 and published in January 2021 (European Commission. Directorate General for Environment. et al. 2021). A decision of the Commission on the fate of these exemptions is still pending. Oeko-Institut has been requested to review the current state of scientific and technical progress of Cd QDs in lighting and display applications. This review should include the comparative status of possible Cd-free substitutes for such applications, to consider if exemptions for Cd in these applications are still justified under the RoHS 2 regime.

1.1 Background and objectives

The RoHS 2 Directive 2011/65/EU entered into force on 21 July 2011 and led to the repeal of Directive 2002/95/EC on 3 January 2013. The Directive can be considered to have provided for two regimes under which exemptions could be considered, RoHS 1 (the former Directive 2002/95/EC) and RoHS 2 (the current Directive 2011/65/EU).

- The scope covered by the Directive is now broader as it covers all electrical and electronic equipment (EEE; as referred to in Articles 2(1) and 3(1));
- The former list of exemptions has been transformed into Annex III and may be valid for all product categories according to the limitations listed in Article 5(2) of the Directive. Annex IV has been added and lists exemptions specific to categories 8 and 9;
- The RoHS 2 Directive includes the provision that applications for exemptions must be made in accordance with Annex V. However, even if several points are already listed therein, Article 5(8) provides that a harmonised format, as well as comprehensive guidance – taking the situation of SMEs into account – shall be adopted by the Commission; and
- The procedure and criteria for the adaptation to scientific and technical progress have changed and now include some additional conditions and points to be considered. These are detailed below.

The Directive currently in force details the various criteria for the adaptation of its Annexes to scientific and technical progress. Article 5(1)(a) details the various criteria and issues that must be considered for justifying the addition of an exemption to Annexes III and IV:

- The first criterion may be seen as a threshold criterion and cross-refers to the REACH Regulation (1907/2006/EC). An exemption may only be granted if it does not weaken the environmental and health protection afforded by REACH;

- Furthermore, a request for exemption must be found justifiable according to one of the following three conditions:
  - Substitution is scientifically or technically impracticable, meaning that a substitute material, or a substitute for the application in which the restricted substance is used, is yet to be discovered, developed and, in some cases, approved for use in the specific application;
  - The reliability of a substitute is not ensured, meaning that the probability that EEE using the substitute will perform the required function without failure for a period of time comparable to that of the application in which the original substance is included, is lower than for the application itself;
  - The negative environmental, health and consumer safety impacts of substitution outweigh the benefits thereof.
- Once one of these conditions is fulfilled, the evaluation of exemptions, including an assessment of the duration needed, shall consider the availability of substitutes and the socio-economic impact of substitution, as well as adverse impacts on innovation, and life cycle analysis concerning the overall impacts of the exemption; and
- A new aspect is that all exemptions now need to have an expiry date and that they can only be renewed upon submission of a new application.

In September 2017 and April 2018, the Commission received three requests for exemptions related to cadmium in quantum dots. The Commission commissioned Oeko-Institut e.V. and Fraunhofer IZM to evaluate the exemption requests and the final technical evaluation report was published in January 2021 (European Commission. Directorate General for Environment. et al. 2021). The Commission appraised the conclusions of the report, held further exchanges with stakeholders to clarify open points and consulted the Member State's delegated experts. It became clear that additional information is required before deciding about the exemption requests, considering the dynamic market of the lighting and display technologies where Cd QDs are used, and the market readiness of possible substitutes for such applications.

Against this background, the consultant carried out a review of the scientific and technical progress related to Cd QD technologies and their applications, both in steady state lighting (SSL) and in displays.

1.2 Key findings – Overview of the results of the review

The exemption requests covered in this project and the names of the applicants concerned, as well as the final recommendations and proposed expiry dates are summarised in the table below (Table 1-1). All three requests were evaluated in the past and the current recommendations (differing from those specified in the past) have been concluded after a review of the existing data available for the evaluation of these requests. The main findings of his review can be summarised as follows:

For lighting:

Only the on-chip configuration is relevant for lighting applications and thus only it has been considered:

- Whereas QD on-chip lighting applications with >100 ppm Cd showed an advantage of at least 20% lower energy performance in the past review, current data suggests that this advantage has decreased to around 10%. Though it can be followed that development of such applications was halted due to the delay in the decision on the exemption, alternatives have developed in the last years and show better performance. Based on this current data, it is not clear that the increase in energy performance would still set-off the additional amount of Cd that would need to be placed on the market for its realisation. An exemption is thus not recommended in this case.

For displays:

On *edge applications* have become obsolete and have not been considered in relation to the exemptions at hand;

For *on-surface applications*, it can be understood that the market availability of Cd free alternatives has increased (indium phosphide based as well as Cd QD applications applying <100 ppm Cd and thus not needing an exemption. Such alternatives have reached parity in terms of their technical performance (colour, energy) to Cd QD based applications. Statements were also not made by stakeholders involved in this review in favour of an exemption for such applications. Against the available data, the exemption is no longer considered to be justified for such applications.

The term *on-chip* as a QD configuration is somewhat ambiguous in the display context, and thus how it is interpreted can have a significant impact on the amounts of Cd used in QD display applications. Some manufacturers refer to this term when QD material is contained "in a layer close to the package" and others when it is contained "in the LED package". Cd QDs are market ready in the "in the LED package" configuration and could be applied into displays within a relatively short time, but would need an exemption to allow use, as their concentration in the homogenous material is higher than currently allowed for displays.

In LCD applications, the use of CD QD "in the LED package" configurations could support a general reduction in the amount of Cd and thus an exemption could be justified based on the third criterion, seeing that it would allow providing similar technical performance with significantly lower amounts of Cd than those that can be placed on the market without an exemption (e.g., with <100 ppm Cd).

For micro-displays, it can be understood that only CD QD "in the LED package" configurations would allow placing on the market of such applications, whereas Cd free alternatives are still in development (e.g., first and second criteria apply).

An exemption could be granted, provided that the wording specified in the table below is applied, limiting both the concentration of Cd in the homogenous material, while also limiting the absolute Cd amount per display: this would avoid that the exemption is misused for placing CD QD applications that result in higher amounts of Cd on the market. The reader is referred to the main sections of this report (see Sections 5 through 8) for more details on the evaluation results.

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

Ex. Req. No.	Requested exemption wording	Applicant/s	Revised Recommendations (2022)	Expiry date and scope
Request 2018-1	"Cadmium (<1000 ppm) in luminescent material for on-chip application on LED semiconductor chips for use in lighting applications of at least CRI 80" requested to be valid for 5 years	*LE*	*"Cadmium in downshifting semiconductor nanocrystal quantum dots directly deposited on LED semiconductor chips for use in display and projection applications (< 5 µg Cd per mm^2 of light emitting LED chip surface) with a maximum amount per device of 1 mg"*	*31.11.2027*
Annex III, Ex. 39a	"Cadmium in down-shifting semiconductor nanocrystal quantum dots directly depos-ited on LED chips for use in display and projection applications (< 5 µg Cd per mm^2 of light emitting LED chip surface)" re-quested to be valid for 5 years	*Osram*		
Annex III, Ex. 39a	"Cadmium selenide in downshifting cadmium-based semiconductor nano-crystal quantum dots for use in display lighting applications (<0.1 µg per mm^2 of display screen area)" requested to be valid until October 31, 2021	Najing	Denied	

Note: As in the RoHS legal text, commas are used as a decimal separator for exemption formulations appearing in this table, in contrast to the decimal point used throughout the rest of the report as a separator.

2 Executive summary: French - Note de synthèse : Français

Avec le contrat n° 090202/2022/878143/ETU/ENV.B., Oeko-Institut e.V. a été chargé par la DG Environnement de la Commission européenne afin d'apporter son concours technique et scientifique dans le cadre d'un examen des applications de points quantiques (QD) au cadmium (Cd). Ces applications ont fait l'objet d'une évaluation des exemptions réalisée en tant que Pack 15 Task 5 "Assessing three exemption requests for the use of cadmium in quantum dot applications in displays and lighting", finalisée en 2020 et publiée en janvier 2021 (Commission européenne. Direction générale de l'environnement. et al. 2021). Une décision de la Commission sur le sort de ces exemptions est toujours en attente. Il a été demandé à Oeko-Institut d'examiner l'état actuel des progrès scientifiques et techniques des Cd QD dans les applications d'éclairage et d'affichage. Cet examen devrait inclure le statut comparatif des éventuels substituts sans Cd pour ces applications, afin de déterminer si les exemptions pour le Cd dans ces applications sont toujours justifiées dans le cadre du régime RoHS 2.

2.1 Contexte et objectifs

La directive RoHS 2 2011/65/EU est entrée en vigueur le 21 juillet 2011, ce qui a entraîné l'abrogation de la directive 2002/95/CE le 3 janvier 2013. Il est possible de considérer que la directive a prévu deux régimes qui ont permis de prendre en compte les exemptions, à savoir le régime RoHS 1 (l'ancienne directive 2002/95/CE) et le régime RoHS 2 (la directive actuelle 2011/65/UE).

- Le champ d'application couvert par la directive est désormais plus large sachant qu'il englobe l'intégralité des équipements électriques et électroniques (EEE ; tel que mentionné dans les articles 2(1) et 3(1));
- L'ancienne liste d'exemptions a été transformée en annexe III et peut être valable pour toutes les catégories de produits conformément aux limitations énumérées à l'article 5, paragraphe 2, de la directive. L'annexe IV a été ajoutée et liste les exemptions spécifiques aux catégories 8 et 9 ;
- La directive RoHS 2 inclut la disposition selon laquelle les demandes de dérogation doivent être faites conformément à l'annexe V. Toutefois, même si plusieurs points y sont déjà énumérés, l'article 5, paragraphe 8, prévoit qu'un format harmonisé, ainsi que des orientations complètes - tenant compte de la situation des PME - seront adoptés par la Commission ; et
- La procédure et les critères d'adaptation au progrès scientifique et technique ont changé et comprennent désormais des conditions et des points supplémentaires à prendre en considération. Ceux-ci sont détaillés ci-dessous.

La directive actuellement en vigueur détaille les différents critères d'adaptation de ses annexes au progrès scientifique et technique. L'article 5(1)a), énumère les différents critères et questions qui doivent être considérés pour justifier l'ajout d'une exemption aux annexes III et IV :

- Le premier critère peut être considéré comme un critère de seuil et renvoie au règlement REACH (1907/2006/CE). Une exemption peut uniquement être accordée si elle ne fragilise pas la protection environnementale et sanitaire offerte par le règlement REACH;
- En outre, une demande d'exemption doit être jugée justifiable selon l'une des trois conditions suivantes :
  - La substitution est scientifiquement ou techniquement irréalisable, ce qui signifie qu'un matériau de substitution, ou un substitut pour l'application dans laquelle la substance soumise à restriction est utilisée, doit encore être découvert, développé et, dans certains cas, approuvé pour une utilisation dans l'application spécifique ;
  - La fiabilité d'un substitut n'est pas assurée, ce qui signifie que la probabilité que les EEE utilisant le substitut remplissent la fonction requise sans défaillance pendant une période comparable à celle de l'application dans laquelle la substance originale est incluse, est inférieure à celle de l'application elle-même ;
  - Les incidences négatives de la substitution sur l'environnement, la santé et la sécurité des consommateurs l'emportent sur ses avantages.
- Dès lors que l'une de ces conditions est remplie, l'évaluation des exemptions, estimation de la durée nécessaire, devra tenir compte de la disponibilité des substituts et de l'impact socio-économique de la substitution, ainsi que des effets néfastes sur l'innovation et une analyse du cycle de vie concernant les impacts globaux de l'exemption; et
- Le fait que toutes les exemptions doivent désormais présenter une date d'expiration et qu'elles peuvent uniquement être renouvelées après soumission d'une nouvelle demande, constitue un aspect inédit.

En septembre 2017 et avril 2018, la Commission a reçu trois demandes d'exemption liées au cadmium dans les points quantiques. La Commission a chargé Oeko-Institut e.V. et Fraunhofer IZM d'évaluer les demandes d'exemption et le rapport final d'évaluation technique a été publié en janvier 2021 (Commission européenne. Direction générale de l'environnement. et al. 2021). La Commission a apprécié les conclusions du rapport, a eu des échanges supplémentaires avec les parties prenantes pour clarifier les points ouverts et a consulté les experts délégués de l'État membre. Il est apparu clairement que des informations supplémentaires étaient nécessaires avant de prendre une décision sur les demandes d'exemption, compte tenu du dynamisme du marché des technologies d'éclairage et d'affichage où les Cd QD sont utilisés, et de l'état de préparation du marché des substituts possibles pour ces applications.

Dans ce contexte, le consultant a procédé à un examen des progrès scientifiques et techniques liés aux technologies Cd QD et à leurs applications, tant dans l'éclairage à état stable (SSL) que dans les écrans.

2.2 Les principales conclusions - Aperçu des résultats de l'examen

Les demandes d'exemption couvertes par ce projet et les demandeurs concernés, ainsi que les recommandations finales et les dates d'expiration proposées sont résumées dans le tableau ci-dessous (tableau 1-1). Les trois demandes ont été évaluées dans le passé et les recommandations actuelles (qui diffèrent de celles spécifiées dans le passé) ont été conclues après un examen des données existantes disponibles pour l'évaluation de ces demandes. Les principales conclusions de cet examen peuvent être résumées comme suit :

Pour l'éclairage :

Seule la configuration sur puce est pertinente pour les applications d'éclairage et donc seule celle-ci a été prise en compte :

- Alors que les applications d'éclairage à base de QD sur puce avec >100 ppm Cd présentaient un avantage d'au moins 20% de performance énergétique inférieure dans l'examen précédent, les données actuelles suggèrent que cet avantage a diminué à environ 10%. Bien que l'on puisse penser que le développement de ces applications a été arrêté en raison du retard dans la décision sur l'exemption, des alternatives ont été développées au cours des dernières années et montrent de meilleures performances. Sur la base de ces données actuelles, il n'est pas certain que l'augmentation de la performance énergétique compenserait encore la quantité supplémentaire de Cd qui devrait être mise sur le marché pour sa réalisation. Une exemption n'est donc pas recommandée dans ce cas.

Pour les écrans :

Les *applications sur la tranche* (English: on-edge) sont devenues obsolètes et n'ont pas été prises en compte dans le cadre des exemptions actuelles ;

Pour *les applications en surface* (English: on-surface), on peut comprendre que la disponibilité sur le marché d'alternatives sans Cd a augmenté (applications à base de phosphure d'indium ainsi que de Cd QD appliquant <100 ppm de Cd et ne nécessitant donc pas d'exemption. Ces alternatives ont atteint la parité en termes de performances techniques (couleur, énergie) avec les applications à base de Cd QD. Les parties prenantes impliquées dans cette révision n'ont pas non plus fait de déclarations en faveur d'une exemption pour ces applications. Compte tenu des données disponibles, l'exemption n'est plus considérée comme justifiée pour ces applications.

Le terme « *sur puce*» (English: on-chip) en tant que configuration QD est quelque peu ambigu dans le contexte de l'affichage, et donc la façon dont il est interprété peut avoir un impact significatif sur les quantités de Cd utilisées dans les applications d'affichage QD. Certains fabricants font référence à ce terme lorsque le matériau QD est contenu « dans une couche proche du boîtier » et d'autres lorsqu'il est contenu « dans le boîtier de la LED ». Les QD de Cd sont prêts à être commercialisés dans la configuration « dans le paquet de LED » et pourraient être appliqués dans des écrans dans un délai relativement court, mais il faudrait une exemption pour permettre leur utilisation, car leur concentration dans le matériau homogène est plus élevée que celle actuellement autorisée pour les écrans.

Dans les applications LCD, l'utilisation de configurations CD QD « dans le paquet de LED » pourrait permettre une réduction générale de la quantité de Cd et donc une exemption pourrait être justifiée sur la base du troisième critère, étant donné qu'elle permettrait de fournir des performances techniques similaires avec des quantités de Cd nettement inférieures à celles qui peuvent être mises sur le marché sans exemption (par exemple, avec <100 ppm de Cd).

Pour les micro-écrans, on peut comprendre que seules les configurations CD QD « dans le boîtier de la LED » permettraient la mise sur le marché de telles applications, alors que les alternatives sans Cd sont encore en développement (par exemple, le premier et deuxième critère s'appliquent).

Une exemption pourrait être accordée, à condition que la formulation spécifiée dans le tableau ci-dessous soit appliquée, limitant à la fois la concentration de Cd dans le matériau homogène, tout en limitant également la quantité absolue de Cd par écran : cela éviterait que l'exemption soit utilisée abusivement pour mettre sur le marché des applications CD QD qui entraînent des quantités plus élevées de Cd. Le lecteur est invité à se reporter aux sections principales de ce rapport (voir les sections 5 à 8) pour plus de détails sur les résultats de l'évaluation.

Tableau 2-1: Récapitulatif des demandes d'exemption, des recommandations associées et des dates d'expiration.

Traduction en français fournie par souci de commodité. En cas de contradictions entre la traduction française et la version originale anglaise, cette dernière fait foi.

<table>
<tr><th>Demande ex. nº.</th><th>Termes de l'exemption demandée</th><th>Demandeur</th><th>Recommandations révisées (2022)</th><th>Date d'expiration et champ d'application</th></tr>
<tr><td>Demande 2018-1</td><td>« Cadmium (<1000 ppm) dans les matériaux luminescents pour une application sur puce sur des puces semi-conductrices LED pour une utilisation dans des applications d'éclairage d'au moins 80 IRC » demandé à être valide pour 5 ans.</td><td>LE</td><td rowspan="2">« Cadmium dans des points quantiques de nanocristaux semi-conducteurs à déplacement vers le bas directement déposés sur des puces semi-conductrices à LED pour une utilisation dans des applications d'affichage et de projection (< 5 µg Cd par mm² de surface de puce LED émettant de la lumière) avec une quantité maximale par dispositif de 1 mg. »</td><td>31.11.2027</td></tr>
<tr><td>Annex III, Ex. 39a</td><td>« Cadmium dans les points quantiques de nanocristaux semi-conducteurs à décalage vers le bas directement déposé sur des puces LED pour une utilisation dans des applications d'affichage et de projection (< 5 µg Cd par mm² de surface de puce LED émettant de la lumière) » demandé à être valide pour 5 ans.</td><td>Osram</td><td></td></tr>
</table>

Demande ex. nº.	Termes de l'exemption demandée	Demandeur	Recommandations révisées (2022)	Date d'expiration et champ d'application
Annex III, Ex. 39a	« Séléniure de cadmium dans des points quantiques nanocristallins semi-conducteurs à base de cadmium en descente pour une utilisation dans des applications d'éclairage d'affichage (<0,1 µg par mm^2 de surface d'écran d'affichage) » demandé à être valide jusqu'au 31 octobre 2021.	Najing	Refusée	

Note: Comme dans le texte juridique de la directive RoHS, les virgules sont utilisées comme séparateur décimal pour les formulations d'exemption figurant dans ce tableau, contrairement au point décimal utilisé dans le reste du rapport comme séparateur.

3 Introduction

Acronyms and definitions

BT.2020	Recommendations BT.2020, also Rec.2020. A standard defined by the International Telecommunication Union.
Cd	Cadmium
CRI	Colour Rendering Index (measure of whiteness of a light source from 1 to 100, sunlight being 100)
DoE	*US Department of Energy*
DCI-P3	Digital Cinema Initiatives - Protocol 3
FWHM	full width half maximum
LE	LightingEurope (industrial association)
LED	Light emitting diode
HMF	Heavy Metal Free
KSF	Potassium Fluorosilicate (narrow red producing phosphor)
LCD	Liquid crystal display
NBP	Narrow band phosphor
Nit	Candela per square metre
OLED	Organic LED
QD	Quantum dots
QDCC	Quantum Dot Colour Conversion
QDEF	Quantum Dot Enhancement Filter (on-surface technology in white backlight displays)
RoHS	Directive 2011/65/EU on the Restriction of Hazardous Substances in Electrical and Electronic Equipment
SSL	Solid state lighting
WEEE	Waste Electrical and Electronic Equipment

3.1 Project scope and methodology

The objective of this study is to support the Commission in its obligation to perform an evaluation of requests for RoHS exemptions and to decide whether to approve the exemptions requested for quantum dot applications in 2017 and 2018. This is to be performed through an in-depth assessment of quantum dot applications and an update of the information presented in the assessment Pack 15 Task 5 "Assessing three exemption requests for the use of cadmium in quantum dot applications in displays and lighting" under the Directive 2011/65/EU ('RoHS'), hereafter referred to as "the previous study". The objective of the requested study is thus understood to be to assess the use of cadmium in solid state lighting (SSL) and display applications to provide the Commission with clear technical and scientific evidence as to whether the requested exemptions are justified in line with the criteria stipulated in the RoHS Directive for exemptions. Furthermore, a targeted stakeholder consultation is to be performed.

The assessment covers technical aspects mentioned in the study request specifications. In this respect, for these requests the assessment should, among others:

- Update the analysis presented in the previous study, as regards the alternative technologies to quantum dots and their applications which are currently available on the market, and assess their environmental, health and consumer safety benefits; technical as well as economic information on the current market availability of quantum dots should also be included.
- Give additional information on the current LED market, in view of the availability of cadmium free quantum dots with comparable performance as the requested cadmium quantum dots.
- Evaluate the end-of-life stage of display and lighting applications; and
- Investigate whether the energy efficiency of cadmium containing quantum dot applications would outweigh the negative impacts caused by substitution.

A targeted stakeholder consultation was also performed as part of the study as is detailed in Section 4.

In case that the consultants differ from the previous recommendation of the technical report, the consultants are to provide a clear evaluation and explanation why the respective applications are justified or not justified in line with the requirements in the RoHS Directive. A wording for a possible exemption should be proposed and explained in this case. This is addressed in Section 8.

The review is focused on technologies of relevance to three requests for exemption submitted to the European Commission in the past and reviewed in 2020. An overview of the exemption requests assessed in the previous report is given in Table 3-1 below.

Table 3-1: Overview of the exemption requested, associated recommendation and expiry date

Ex. Req. No.	Requested exemption wording	Applicant/s	Recommendations of 2020	Expiry date and scope
Request 2018-1	"Cadmium (<1000 ppm) in luminescent material for on-chip application on LED semiconductor chips for use in lighting applications of at least CRI 80" requested to be valid for 5 years	*LE*	*"Cadmium in downshifting semiconductor nanocrystal quantum dots* *I. directly deposited on LED semiconductor chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface)* *II. directly deposited on LED semiconductor chips for use in lighting applications of at least CRI 90 (< 1.000 ppm in the luminescent material)* *provided that applications comply with entry 72 of Annex XVII of Regulation 1907/2006."*	5 years
Annex III, Ex. 39a	"Cadmium in downshifting semiconductor nanocrystal quantum dots directly deposited on LED chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface)" requested to be valid for 5 years	*Osram*		
Annex III, Ex. 39a	"Cadmium selenide in downshifting cadmium-based semiconductor nanocrystal quantum dots for use in display lighting applications (<0.1 µg per mm² of display screen area)" requested to be valid until October 31, 2021	Najing	Denied	

Note: As in the RoHS legal text, commas are used as a decimal separator for exemption formulations appearing in this table, in contrast to the decimal point used throughout the rest of the report as a separator

Most of the study duration was devoted to the exchange with stakeholders. This was mainly done through correspondence. As part of the consultation, a virtual meeting was held with the stakeholder Nanosys on the 28 September 2022.

Inputs of stakeholders have been summarised in the sections below. Each section summarises stakeholder information and data and presents first conclusions. The various aspects have been evaluated according to the relevant criteria laid down in Article 5 (1) of the RoHS 2 Directive, as shown in the section on background and objecttives on page 9.

Final conclusions and recommendation are then provided at the end of the report.

3.2 Project set-up

The tasks were assigned to Oeko-Institut by the Commission on 29 August 2022, with a study duration of 40 days. Due to requests of stakeholders for more time to prepare their contributions, the study timeline was extended until 11 September 2022 at which time this report was submitted in its final draft version.

The overall study has been managed by Yifaat Baron.

3.3 General note: Declaration

In the following sections, explanations and arguments have been adopted from the documents provided by the stakeholders as far as required and reasonable in the context of the evaluation at hand. Formulations were only altered or completed in cases where it was necessary to maintain the readability and comprehensibility of the text. Stakeholder views referred to are based exclusively on information provided by applicants and stakeholders, unless otherwise stated.

4 Targeted Stakeholder Consultation

In agreement with the European Commission, no open online consultation was carried out as part of this study, but only targeted consultation. This was related to the short time frame of the study, furthermore the stakeholders were known to both the EU Commission and the consultant from previous assessments.

To allow involvement of additional stakeholders who were not initially involved in the previous assessments, the specific project website was used to inform stakeholders of the launch of the study and to request those interested in expressing their views to contact the consultants. In addition, stakeholders who had provided contributions to the previous assessment were also contacted directly, requesting a contribution be made and including a questionnaire providing some background information on the study and focussing questions.

Table 4-1 below specifies the various stakeholders who were contacted and sent questions related to this study in alphabetic order. Not all stakeholders contacted directly (i.e., those involved in the prior assessment) responded to the request for new information and data, however all contacted parties are listed below. Some organisations, that had not been involved in the past, responded to the RoHS Exemptions website study notification and submitted data and information; the names of such organisations are also listed in the table below. Furthermore, in some areas, additional stakeholders were contacted and asked to provide data, such as companies involved in the waste management of relevant EEE. Such companies are also listed below, regardless of whether they provided information or not. Stakeholders who provided data that was specified as public are named in the study sections where their information and data is reproduced and/or discussed.

Table 4-1: Stakeholders contacted on the consultant's initiative during the study

Stakeholder (organisation)	Type of stakeholder
Balcan	Recycling company and manufacturer of recycling systems for LED lighting applications
Blubox	Lamp and display recycling, CH
Current Chemicals	Chemical/material manufacturer
DEPA	Danish MS delegated expert
DuPont	Material manufacturer
EERA	Association of recyclers
EuRIC	Association of recyclers
General Electric	Manufacturer of EEE
HiQ-Nano	Nano material manufacturer
KEMI	Sweden MS delegated expert
Lighting Europe	Applicant, Lighting association
Merck	Material manufacturer
Najing	Applicant, manufacturer of EEE
Nanoco	Manufacturer of QD
Nanosys Inc.	Manufacturer of QD
Norwegian environmental Agency	Norway delegated expert
OSRAM	Applicant, manufacturer of lighting applications
Relight	Waste treatment of lamps, Italy
Remondis Electrorecylcling	WEEE recycler in Lünen, Germany
Samsung	Display and lighting manufacturer

Note: Own compilation

Most of the information submitted by stakeholders was classified as public. Such documents submitted by stakeholders were published on the project website[1] and on the EU CIRCABC website[2]. In a few cases stakeholders submitted data classified as confidential. Such data has not been taken into consideration on the following report and in its conclusion.

[1] See: https://rohs.exemptions.oeko.info/substance-review-2018/2019-consultation-4-1

[2] See the EU CIRCABC website: https://circabc.europa.eu/ui/welcome (Browse categories > European Commission > Environment > RoHS Evaluations, at top left, click on "Library" > Reports).

5 Types of configurations of QD

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

From prior evaluations, the consultants are aware that there are three different strategies or configurations in which QDs can be applied, on-edge, on-surface and on-chip.

5.1 On-edge technology

On-edge technology has QDs incorporated into a remote component situated near the LED chips. This can be done for instance in an adjacent capillary. On-edge technologies allow a compromise between the risk of thermal degradation and the respective QD material requirements. This configuration was addressed in past evaluations but was not initially mentioned by the applicants in the current review. It is understood to be obsolete.

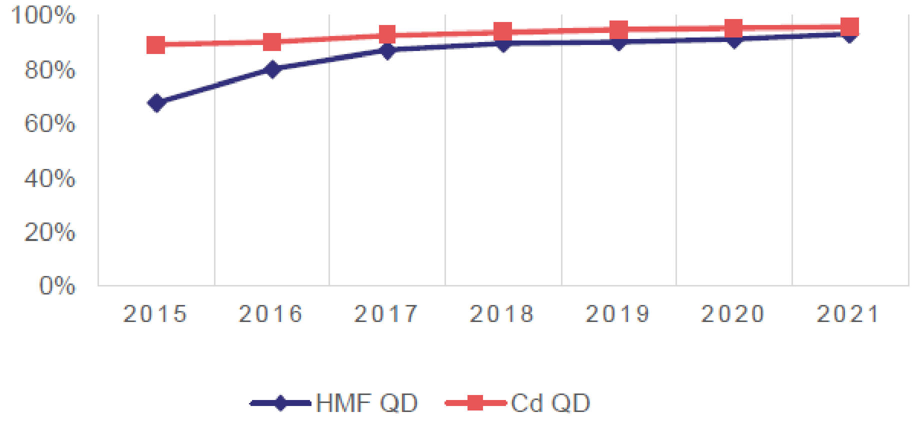
5.2 On-surface technology

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 operates at near room temperatures, so that the thermal degradation risk is not an obstacle for practical application. On-surface technologies using quantum dots for colour conversion are also known as QD-films or quantum dot enhancement films (QD-EHF). Najing addressed such configurations in their request, referring only to display applications. On-surface technology is still the standard for white backlight displays on the market. "*Due to its lower cost of implementation and easy integration into existing LCD technology, we believe the QD-enabled white backlight implementation will remain one of the major implementations for years to come*." (Nanosys Inc. 2022).

Najing did not contribute to the stakeholder consultation conducted as part of this study. Najing stated during the former assessment that for on-surface technologies "*the performance of Cd-free quantum dots (based on InP) is expected to reach the current colour quality and energy consumption performance of cadmium quantum dots by 2020. Full commercialization will be achieved by 2022*." (Najing 2019). Indeed, both Cd-based and Cd-free QD are offered by now in this configuration. Different stakeholders are confident that Cd-based quantum dots in on-surface technologies do not require an exemption for the following reasons:

- The market availability of similar or better performing Cd-free alternatives on the **quantum dot level** is given. "HMF-QD [heavy metal free quantum dots] performance improvements at both the materials and device levels have closed the performance gap with Cadmium-containing QDs such that exemptions are no longer required for display or lighting products." (Nanosys Inc. 2022). The internal quantum efficiency (IQE) measures how many of the incoming photons are down converted. An IQE of one means, that every single blue photon that is absorbed will be re-emitted as a red (or green, depending on the material) photon. This measure of the quality of the optical material shows a steady improvement, as shown in Figure 5-1.

Figure 5-1: Internal Quantum Efficiency (%)



Source: Nanosys Inc. (2022)

- On the **device level**, there are four quality measures described by Nanosys, both for Cd QD and HMF QD. The numbers are listed in Table 5-1 below:
  - Colour Gamut is a measure for the colour space that can be reached i.e., how purely can red, green and blue be displayed.
  - Peak luminance measures the brightness and is expressed in candela per square metre (referred to as nit).
  - Colour Volume is a combination of both colour gamut and peak luminance. It is the percentage of colours the TV can display, compared to the number of colours possible within the Rec.2020 gamut with a luminance range from 0 to 10,000 cd/m². ITU-R Recommendations BT.2020, or Rec.2020 or BT2020, are names of a standard defined by the International Telecommunication Union.
  - Power Efficiency was measured for both display types in their most power-intensive setting with high brightness, wide colour gamut, and high dynamic range (HDR).

Table 5-1: Quality measures of on-surface HMF QD and Cd QD

Quantum Dot technology	Colour Gamut BT.2020 standard	Peak Luminance	Colour Volume	Power Efficiency
HMF QD	"Nearly 90%"	>2,000 nits	52%	11.7 nits/watt
Cd QD	"Nearly 90%"	>2,000 nits	48%	6.8 nits/watt

Source: Nanosys Inc. (2022)

The detailed results of this study are listed in Table 5-2, indicating similar or better results for HMF QD than Cd QD across various performance measures. DCI-P3 stands for Digital Cinema Initiatives - Protocol 3 and defines a colour space used in the film industry that is wider in scope than RGB.

Table 5-2: RTINGs TV Performance Data for HMF and Cd QD TVs 2020-2022

Name	QD Type	TV Size	Max Power Consumption (W)	Peak HDR Luminance 10% Window (nits)	Efficiency Nits/Watt	% DCI-P3 coverage (xy)	% BT.2020 coverage (xy)	Colour Volume	RTINGs Picture Quality Score Mixed Usage
TV 1	HMF	65″	183	1786	9.76	89.75%	65.26%	45.20%	8.5
TV 2	HMF	65″	175	2054	11.74	94.42%	71.76%	52.10%	8.6
TV 3	HMF	65″	181	869	4.80	89.65%	65.15%	34.80%	7.7
TV 4	HMF	65″	164	1000	6.10	94.17%	71.29%	35.10%	7.9
TV 5	HMF	55″	179	1609	8.99	95.92%	72.06%	48.30%	8.6
TV 6	Cd	65″	242	505	2.09	94.12%	74.12%	26.40%	7.7
TV 7	Cd	65″	232	969	4.18	92.03%	69.44%	39.70%	8.1
TV 8	Cd	55″	219	986	4.50	91.01%	69.72%	37.30%	7.8
TV 9	Cd	65"	275	1705	6.20	98.56%	77.95%	47.80%	8.6
TV 10	Cd	55"	154	1051	6.82	91.53%	69.61%	34.50%	8.3

Source Nanosys Inc. (2022)

- Regarding Cd-free technology, some stakeholders state that it is not only available on the market, but also dominates it by far. "*Cadmium-free technology has dominated the QD TV market since 2016, with over 90 % of the current market share, attesting to its high performance. It is our understanding that Samsung, the biggest QD TV manufacturer, is solely focussed on Cd-free QD products. In 2022, Samsung also launched 2nd generation 'QD OLED' technology using Cd-free QDs*" (Nanoco Technologies Ltd. 2022).

Furthermore, applicants of two of the exemptions assessed in the Pack 15 study do not provide statements that support an exemption for Cd QD in on-surface applications, even if it is not straightforward to conclude the opposite:

- *On-surface technologies are not in the scope of the exemption requested by LE and Osram: "On Surface / remote films are not the current focus of the exemption request of LightingEurope nor for the exemption renewal request for displays (Exemption 39(a)) issued by OSRAM."* (LightingEurope 2022)
- *On-surface technology is not relevant for lighting applications. None of the three exemption requests refer to on-surface lighting applications. "Conventional LED are available with much better energy efficiency and quality performance. Only on-chip configuration is suitable, only LED in on chip configuration can achieve the high CRI90 energy efficiency*" (Osram GmbH 2022c).

Thus, the consultants conclude that the exemption requested for on-surface technologies by Najing is not relevant anymore.

5.3 On-chip technology

In the case of on-chip technology, the QDs are placed on the LED chip surface, encapsulated within its package. This technology requires the lowest amount of QD material; however, practical application was difficult to accomplish in the past as the QD material undergoes thermal degradation due to the proximity to the light emitting source. This configuration is addressed in the requests of LightingEurope and OSRAM and can be applied in both white solid-state lighting and white backlight display applications. OSRAM (2019) further explained in the past that there are two sub-cases for on-chip applications:

- The dots are used close to the chip, around it, confined by the dimensions of an LED package, or
- the quantum dots are highly concentrated in a thin layer on top of the chip whereas this layer has got similar outer dimensions as the chip i.e., smaller than the package.

In the context of the current review, it has become clear that stakeholders have different understandings of the on-chip configuration.

- OSRAM explains that in their "understanding "on-chip" means that the conversion material is already applied to the chip and being part of the LED before the whole LED is placed into a device" and provide explanations as to how this may affect the amount of Cd that may be used e.g., in display applications (see Appendix A.1.0) (Osram GmbH 2022a).

- Nanosys confirms that they have a similar interpretation, information specified in the following sections suggests that their calculations for Cd in QD display is often based on a larger surface area than that applied by OSRAM. The consultants note that this may be related to the existing CdQD technologies available on the market that are understood to apply QD in on-surface QDs, resulting in significantly large amounts of Cd being applied. In this context Nanosys states that their applications are "*quite similar to "on-chip" LED since the QDs are in close proximity to the pump source.*".

The main reasons to use Cd-QDs are their stability, high internal quantum efficiency and their narrow full width half maximum (FWHM) of less than 30nm. The narrower the peak in the spectrum is, the more precise the colour mixing is and, if present the less light gets lost in the filter. High energy efficiency and colour quality are the aim for both, lighting and display applications. The less the spectrum of the emitted light leans into the infrared, the less invisible heat radiation is wasted.

With the understanding that an exemption is now only relevant for on-chip applications, the rest of the report refers only to such applications, presenting the main findings for On-chip Lighting applications (see section 6) and for On-chip display applications (see section 7) and then culminating in Conclusions and recommendation for both (see section 8).

6 On-chip Lighting applications

For **lighting applications**, the consultants understand from stakeholder input that the configuration is **always on-chip** configuration.

LightingEurope requested an exemption for

> "Cadmium (<1000 ppm) in luminescent material for on-chip application on LED semiconductor chips for use in lighting applications of at least CRI 80"
>
> Valid for 5 years in 2018

The last assessment came to the recommendation to grant an exemption

> *"Cadmium in downshifting semiconductor […] directly deposited on LED semiconductor chips for use in lighting applications of at least CRI 90 (< 1.000 ppm in the luminescent material)*."
>
> Valid for 5 years, recommended in November 2020

Energy savings of 20% were put forward as the main argumentation and regarded as a legitimate reason to grant an exemption, even for products that were not yet available on the market.

6.1 Amount of non-compliant Cd in on-chip lighting applications

If the exemption as requested initially by LE was granted, "*1.65 kg cadmium in 840 Mio pieces of packaged QD LEDs [would be] put on the EU market.*" (LightingEurope 2022).

This estimation is based on a market penetration of 1% and per year. This assumption is regarded as realistic by the consultants, as also supported by a statement of another stakeholder: "*On-chip Cd-QD for solid-state lighting is in the early stages of development with negligible impact on the broader lighting market*." (Nanosys Inc. 2022). Though it is not completely clear what the basis was for this estimation, it is assumed that it represents LEDs with an amount of Cd that is above the RoHS threshold and that could only be placed on the market once an exemption is granted.

According to LightingEurope, the amount of cadmium applied in products based on Cd QD that are not on the market yet (with >0.01% by weight Cd in the homogenous material) ranges between 1.3 and 2.3 microgram per LED (LightingEurope 2022)*:*

- *„2.3 micrograms cadmium per LED (1 Watt) used in residential applications (e.g. LED retrofit bulb),*
- *1.3 microgram cadmium per LED (0.5 Watt) used in the professional market (troffer luminaire for office lighting, 2000 lumen, 64 LED = 84.5 microgram cadmium)*
- *Average cadmium amount of above values per 1 Mio pieces: 1.97 grams*"

Such LED can be understood to have the following concentrations of Cd: "*Best performance in illumination shown to date using Cd QDs in development runs (E2835) using 400 – 800 ppm Cd."* (Osram GmbH 2022c). In this respect it was also stated that "due to the lack of the exemption and the long waiting time and uncertainty, research and development activities [for Cd QD above 100 ppm] are currently reduced" (Osram GmbH 2022c).

An example given by Osram is a standard retrofit bulb with 800 lumen containing 12 LED chips (idib.), in this case that would mean 27.6 micrograms cadmium are applied.

6.2 Market availability of substitutes for and alternatives of Cd-QD in on-chip lighting applications

6.2.1 RoHS conform quantum dots containing <100ppm Cd (reduction)

First RoHS-conform Cd QD-based products have already entered the market. It is unclear how much Cd the LED products with <100 ppm Cd contain. From the statements in the above section, it is understood that the optimum amount of Cd in a non-compliant Cd QD lamp is four to eight times the threshold given by RoHS (Osram GmbH 2022c). Assuming, that the volume of the Cd containing homogenous material is not much larger for RoHS conform LEDs, the consultants conclude that the amount is about five times less than stated above, for example, a lamp with 800 lumens containing 12 LED chips would in this case thus use around 5.5 micrograms cadmium.

Nichia, a Japanese manufacturer of LEDs, also offers RoHS-conform Cd-QD LEDs with high light quality (CRI=90) and high efficiency (200 lm/W) (NICHIA CORPORATION 2022). The Cd contained in such LED is understood not to be considered in the amount referred to above of 1.65 kg Cd. There is no available data as to the amounts of Cd placed on the market through such applications.

6.2.2 Technological substitutes

Alternatives on the **level of colour conversion technology** are based on phosphors such as potassium fluorosilicate (KSF). These technologies have been on the market since 2015 (Current Chemicals, Current Lighting Solutions, LLC 2022).

It is unclear though, under which conditions and in which parameters KSF performs better or worse than Cd QD, since stakeholder input in this regard is contradictory:

- "We believe that KSF Phosphor offers superior performance to that of Cd-QD due to KSF's more narrow emission resulting in lower relative infrared light emission and improved lumen efficacy. It is often difficult to compare the catalogue specifications of LEDs from different manufactures directly, but KSF's ability to improve an LED's performance from 80 CRI to 90 CRI with the same efficacy (Lumens/ Watt) at warmer colour temperatures (CCT) is a clear indication of the capability of the technology." (Current Chemicals, Current Lighting Solutions, LLC 2022)
- "KSF phosphors technically do not reach the energy efficiency of Cd QD [for lighting in the CRI 90 range]." (Osram GmbH 2022c).

As both technologies evolved over the past few years and reference products might be from previous generations, it can be concluded, that KSF and Cd QD are actively competing for best colour performance and energy efficiency in the main market, which "is in the CRI 80 range" (Osram GmbH 2022c). Only in the CRI 90 segment, Osram promises "*highest performance but only with more Cd per LED the highest energy* *efficiency can be achieved".* (Osram GmbH 2022c). As described in the next section, regarding energy efficiency, and as visible in Table 6-2, with a four-fold concentration of Cd, the energy efficiency can be increased by up to 10% by CRI>90. In conclusion, substitution is technically feasible, but with small efficiency disadvantages in the CRI>90 segment.

6.2.3 Substance alternatives: Cd free quantum dots

In the previous assessment, OSRAM (2018) explained that there were no substance alternatives at the time to Cd in QD applications that were stable and long-lasting enough in the high photon flux.

On the quantum dot level, there are indications that there is still no Cd-free solution on the market: *"There are no HMF-QD on-chip LEDs for lighting and Nanosys is aware of only a single on-chip Cd QD LED product currently available for purchase in the EU."* (Nanosys Inc. 2022).

For Cd-free quantum dots, research is studying InP on the level of quantum dots as well as organic dies and perovskite. On the level of colour conversion technology materials based on InP, organic dyes or perovskite, seem not to withstand the physical conditions on-chip. "*InP does not reach acceptable energy efficiency and is not usable due to lack of reliability. Organic dyes are instable as well. Perovskite quantum dots are nicely narrow but instable."* (Osram GmbH 2022c).

Market adoption of Cd-free quantum dots are expected in…

- *"the next five years. For example, Nanosys is working closely with the US Department of Energy (DOE) to develop HMF-QD alternatives for on-chip applications in lighting and display backlights. We have demonstrated HMF-QDs with a breakthrough LT70 lifetime of 5,000 hrs at 5 W/cm2 at 50°C and a quantum yield of 90%. It is technically feasible to use these alternatives for all relevant SSL lighting applications where Cd-QDs are applied."* (Nanosys Inc. 2022).
- *"Likely 4-5 year until technology is mature enough for products. ams-OSRAM is currently running a DOE funded project: 'Cadmium-Free Quantum Dot Building Blocks for Human-Centric Lighting' which will run until end of 2023."* (Osram GmbH 2022c)

6.2.4 Conclusion on market availabilities

It can be concluded that market availability of alternatives on the level of conversion materials is given in the main market by phosphor-based technologies. For CRI>90, phosphors might be less energy efficient, see the following section on Energy efficiency comparison. On the QD material level, substitutes could be available in 2026 or 2027.

Table 6-1: Overview of market availability of substitutes of on-chip Cd QD in lighting

Level	Substitutes	Market Availability
Reduction: RoHS compliant Cd Qd	<100ppm Cd	given
Technological substitute: Colour conversion	KSF	High
Substance alternative: Quantum dot level	InP, perovskite, organic dye	In 4-5 years

Source: Own representation

6.3 Energy efficiency comparison

The data provided in Table 6-2 indicates, that the KSF based lamp has the same energy efficiency as the one based on 100 ppm Cd, but suffers 4.3% less colour quality i.e., a CRI value of 88 compared to 92. Looking at the data in this table further suggests that products with a Cd concentration of 400 ppm have a 10% better efficiency in lumens per watt compared to products with the RoHS maximum allowable concentration of 100 ppm or products based on KSF. The base value can be confirmed by the data sheet of a competitor’s product, Nichia V1H6. The product mentioned in the bottom line is “ready for the market” but requires an exemption.

Table 6-2: Comparison Cd vs. Cd-free LED

Product	Phosphor	Lm/W	Colour Temp	CRI	Flux Range (IF 65mA, 25°C)
Samsung	Standard	184	4000	min 90	31,5 – 33,5 lm
Bridgelux	KSF	204	4000	88	36 lm (typ)
OSRAM Osconiq E2835	Cd QD <100ppm	195-200	4000	92	41.5-40 lm
Nichia V1H6	Cd QD <100 ppm	196	6500	90	36.9 lm
OSRAM CdQD (not marketed)	Cd QD, 400 ppm	223	4009	91.7	39 lm

Source: Osram GmbH (2022c) and NICHIA CORPORATION (2022)

The current data shows that approximately 10% energy efficiency gains can be reached in the CRI>90 segment, if an exemption is granted. This is a smaller energy efficiency gain than the values referred to in the past assessment, that suggested an order of magnitude of 20%. The data is reproduced in Table 6-3 below for comparison and though it differs in scope, it becomes obvious that the capabilities of both Cd QD and Cd-free modules have improved in the last year, reducing the advantage that Cd QDs initially showed in this market segment. It can be understood from OSRAM that further development of the RoHS non-compliant CD QD technologies has been halted, while waiting to see if the exemption is approved (Osram GmbH 2022a). The decrease in the energy efficiency gains could be tied to this, however the modules with >100 ppm Cd also show improvements, though this may also be a result of comparison of different modules (4000 k at present as compared to 3000 K in the

Table 6-3: Comparison of efficacy white (3000k) LEDs: CdQd with RoHS conform and non-conform Cd amounts and other alternatives: reproduced from 2020 RoHS assessment report

Colour temperature: 3000 K	Efficacy [lm/W]	Rel. Efficacy [%]	CRI
Commercial no Cd LED, Osram (Duris-5 based)	154.2	96.5%	93
Commercial no CD LED, competitor (Samsung)	157.6	98.6%	94
Commercial <100 ppm Cd LED (OSCONIQ S3030 Osram) – *can be POM without an exemption*	159.85	100%	93
Commercial-ready >1000 ppm Cd LED, Osram – requires an exemption	193.7	121.2%	90

Source: cited in (European Commission. Directorate General for Environment. et al. 2021) as "reproduced with modifications from (OSRAM 2020)"

6.4 Evaluating End-of-Life Stage

Lighting applications are collected separately from other waste streams due to the existence of mercury containing lamps in the market. It is assumed that in practice all sorts of lamps enter the same waste stream, regardless of whether LED, mercury vapor or glow wire. "*The current estimate for LED lamps coming through the UK waste stream with other lamps is approx. 5%. These are usually mixed with traditional lamps*." (Balcan Engineering Ltd 16.09.22). Lighting Europe estimates this number to be 10% on EU level (LightingEurope 2022). The consultants are not aware of the volume of lamps in general (and LED lamps in particular) that do not enter the separate waste stream but that are disposed of with municipal waste or that are "lost in the environment".

As lamps collected separately are mainly comprised of discharge lamps, they usually contain mercury and thus in this stream, all the lamps are treated as hazardous waste. Waste operators are capable of handling LEDs and the amount of Cd they might contain. "*Our lamp recycling system allows us to process LED with other lamps without separating them. The design of our system means LED's do not damage it*." (Balcan Engineering Ltd 16.09.22). During the waste treatment, "*it is not a practical or commercially viable option to try and separate the LED chip containing Cd-QD from the rest of the lamp*" (Balcan Engineering Ltd 16.09.22). Instead, the main material fractions of the lamps get separated.

In the future, it is expected that the LED fraction will increase and eventually can be collected and treated separately. Therefore, Balcan developed, produces, and operates a machine that is called LED lamp recycler. "*Our processor shreds the components prior to separation of the main fractions. Fractions are aluminium, ferrous, plastic and glass (where present)*. *The Balcan system operates under negative pressure to control dust emissions. Our system is also fitted with a suitable carbon filter to control mercury emissions from post processing tradition lamp components. As cadmium is similar chemically to mercury any cadmium vapours generated through the recycling process will be controlled so none should exhaust to atmosphere. Cd is not separately collected during this process as it is not practical to do so. The term LED recycling refers to recycling the lamp or fitting, but not the actual chip*. *Cd-QD is purely diluted within the output fractions unless it is displaced during the shredding process and taken off with the filtration system.*" (idib.)

It is not clear in which fraction the Cd will remain in the above technology. The statements on cadmium vapor control can be followed when Cd is released from the LED modules. However, in most cases it is expected that the module will be left unharmed after the shredder operations, meaning that it would be included in one of the resulting fractions. Advanced shredding usually results in pieces in the order of 1 cm in diameter, but LED packages have the size of a few millimetres and would probably not be separated. The package often contains a heat-diffusing ceramic casing and a matrix above the diode to fixate the phosphors. The light-emitting part of the chip is a semiconducting crystal made of semi-metals, in most cases containing silicon (Si) and gallium (Ga). It is unclear in which fraction the LED package will end up. When the LED module is still attached to a larger material part after shredding, such pieces may be sorted to the various material fractions during sorting, and then sent to further processing e.g., such as ferrous, non-ferrous or plastic fraction. In such cases it is assumed that the Cd would be controlled through standard emissions controls, i.e., in smelting or incineration processes. Where this is not the case, it could be that due to the ceramics that the modules and their constituents end up in the mineral fraction.

Marwede et al. (2012) explain that LEDs contain high amounts of critical raw materials (e.g., gallium, rare earth elements) and that it could be relevant to ensure their recovery from such applications in the future. Should an exemption for Cd QD applications be granted, increasing the amount of Cd in mixed WEEE fractions/lamp fractions/display fractions in the coming years, the question was raised whether this could create an obstacle to better extraction of rare earths in the future. In this respect, according to Balcan, if the exemption was granted for lighting applications and Cd concentrations in LED lamps went up, this would not affect the recovery of rare earth metals. "*Having spoken to one of the RE [i.e. recycling] recovery companies, the cadmium in the [LED] chips will not affect the recovery of the rare earth metals. However, there would have to be a further treatment processes for the effluent to ensure that if there is any cadmium that is dissolved, this is recovered."* (Balcan Engineering Ltd 16.09.22). This statement seems to be based on a misunderstanding as Cd QD are made of CdSe, which is non-solvable in water. It can be concluded that recyclers do not have processes established that are capable of extracting and recycling Cd from LED chips.

LE argues, that the concentration of Cd would in any case be rather low, and that therefore risks of emissions are not expected. "*Assuming a weight of 60 grams per lamp the concentration of cadmium would be below 0.3 parts per million (ppm) and therefore far below any critical concentrations in waste management"* (LightingEurope 2022).

6.5 Other environmental impacts of Cd in on-chip lighting applications

LE argues, that Cd-QD LEDs are an alternative to the even more hazardous mercury containing lamps. "C*admium Quantum Dot LED based lamps and luminaires can substantially contribute to the transition of lighting from mercury-containing lamps to mercury-free solutions*" (LightingEurope 2022). This argumentation is in contradiction to the description of Cd-QD applications, as mercury vapor lamps have a CRI of about 50, whereas Cd-QD technology is only needed for CRI above 90. "*Our estimation for lighting is that CRI 90 is only a small portion of the LED market. Due to higher costs, CRI 90 is only used in high quality lamps and luminaires where the improved Colour Rendering Index is desired and required."* (LightingEurope 2022).

Therefore, it is considered by the consultant that mercury containing lamps can be substituted by available Cd-free alternatives. Looking at the dynamic development of the LED market, the consultant would not expect that the phase-out of discharge lamps would be significantly affected should an exemption not be granted for the use of Cd QD in lighting applications: The part of the lighting applications with a CRI of 90 is considered to be small, some alternatives are already available (e.g., with a 10% lower energy performance) and the dynamic development of this sector can be expected to increase their availability.

7 On-chip display applications

Osram had requested an exemption with a similar wording to the in 2019 expired exemption 39a in Annex III:

> "Cadmium in downshifting semiconductor nanocrystal quantum dots directly deposited on LED chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface), requested to be valid for 5 years"

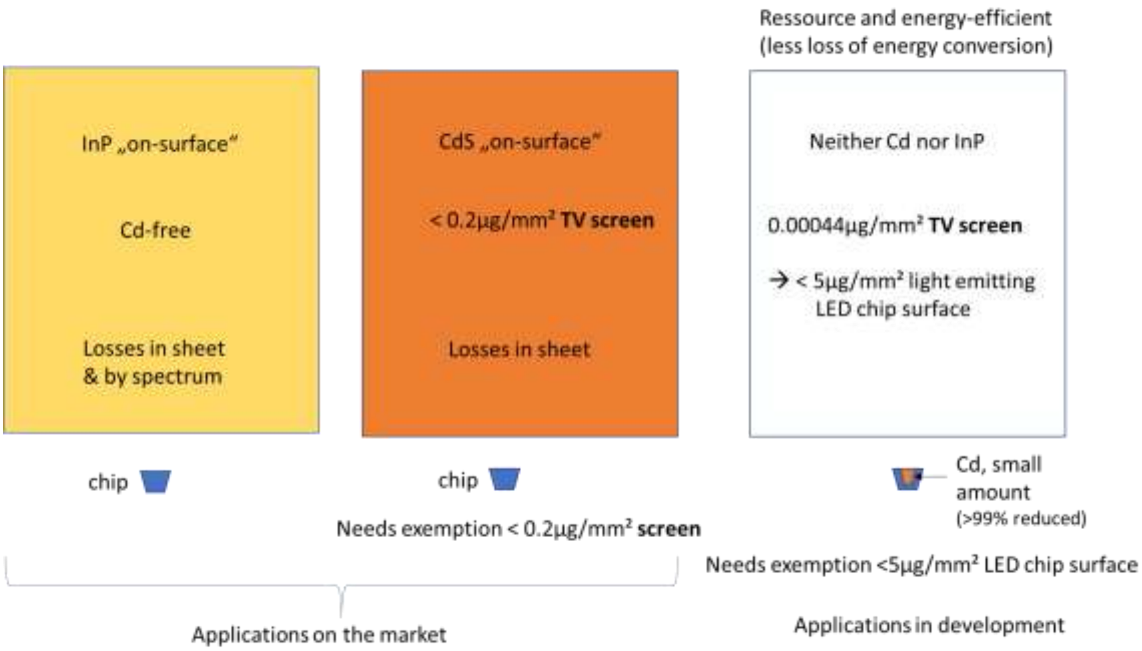
The last assessment came to the recommendation to grant an exemption for:

> *"Cadmium in downshifting semiconductor nanocrystal quantum dots directly deposited on LED semiconductor chips:*
>
> *I. directly deposited on LED semiconductor chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface)*
>
> *II. […]*
>
> *provided that applications comply with entry 72 of Annex XVII of Regulation 1907/2006."*

This was justified by the energy efficiency gains of Cd-QD on-chip technology compared to on-surface and the technical impracticability of substitutes.

As of yet, it has not been possible to place Cd-free quantum dot on-chip white LEDs for backlight displays on the European market. The statements of Nanosys indicating the opposite can be understood in the context of a different definition of on-chip. Osram still awaits an exemption for on-chip QD to bring Cd-based QD on the market for on-chip white backlight display applications. "*For displays OSRAM also only focusses on the development of LED with on-chip configuration.*" (Osram GmbH 2022c). The consultants understand that different to on-chip Cd-QD for lighting, display applications are not yet market ready but under development. Although higher in Cd concentration than on-surface technologies, these applications require 99% less Cd per device. *"CdQD 'on chip' would be a 'nearly zero'-Cadmium solution with a Cd reduction from 40 mg* [on-surface] *to 200-400µg* [on-chip] *per 55" TV screen.*" (Osram GmbH 2022b). While reducing the total amount of Cd is an honourable effort, RoHS limits are described as concentration values in homogenous materials. Thus, under RoHS, on-surface homogeneous materials may seem to have a better performance when looking at the concentration limit alone, however this results in much higher total amounts of Cd per EEE. The following Figure 7-1 compares the amount of Cd for three common possibilities of generating white backlight for displays with quantum dots: InP QD on-surface, CdS QD on-surface and Cd QD on-chip.

Figure 7-1: Comparing the amount of Cd for on-chip and on-surface applications



Source: Osram GmbH (2022c)

Notes: "Losses in sheet" are understood to refer to the on-surface conversion metrics and the resulting loss of energy. "Losses by spectrum" refers to the slightly wider colour spectrum into the red and infrared of InP compared to CdS, which is filtered out by the pixel.

The consultants understand that the proportions of chip to filter matrix were not intended to be close to reality. Still, a factor of approximately 100 times less Cd is required for the on-chip configuration compared to the on-surface configuration. Due to the small distance to the light source, the physical conditions on-chip are challenging. "*In such a configuration the blue photon flux required to generate the desired white backlight is at least 100 X higher than the on-surface solution (where the QD film is placed at a distance from the light source and after the diffuser film)*" (Nanosys Inc. 2022).

This new energy and resource efficient technology would make a whole new type of display application accessible. "*OSRAM's development focus are* [micro or] *µ displays with on chip QD technology which would not be possible otherwise in the intended small and energy efficient applications.*" (Osram GmbH 2022b).

Other research found in the literature is still ongoing on the fabrication of Cd-free quantum dots for backlight display applications. *"All-inorganic $CsPbX_3$ perovskite nanocrystals (PeNCs) are being investigated intensively as a promising optoelectronic material. However, the issues of its intrinsic instability and toxicity restrict their commercial applications."* (Chen et al. 2021). Those alternative technologies are called environmentally friendly as they are Cd-free. Instead, many materials under research contain lead (Pb) and phosphides. "*The hazard results indicate that there is no clear alternative either, with each novel nanomaterial or organic substance having different negative [environmental] aspects.*" (Bechu et al. 2022). For the evaluation under RoHS, especially the threshold of lead (0.1%) and cadmium (0.01%) concentrations need to be considered for research of new on-chip quantum dot materials.

Direct view technologies, such as quantum dot organic LED (QD OLED) and microLED, might be assigned to on-chip configurations (Nanosys Inc. 2022). For the interested reader, they are described in Appendix A.2.0. It is unclear, whether these technologies are to be classified as "on-surface" or "on-chip". They were brought into the discussion by Nanosys as evidence that there are Cd-free technologies for displays on the market that outperform all existing Cd-based solutions on the market. Whereas Nanosys refers to this configuration as "on-chip", Osram does not. To the consultants understanding, the QD in this case are not inside the LED package, but inside a layer close to the package with the same size and pattern as the packages. Such displays are considered to have a very high performance in terms of colour and image quality: "*In terms of performance, QD-OLEDs have been widely regarded by independent reviewers as the best TV and monitor products ever made. Every QD-OLED product on the market in 2022 uses HMF-QD technology. There should be no doubt that HMF-QD can deliver on-chip performance for direct view display applications today.*" (Nanosys Inc. 2022). According to Nanosys, though all OLED currently on the market using this configuration use heavy metal free QD, prototypes using CD QD have been developed and can be expected to be marketed in the next few years if covered by an exemption. The consultants understand that such applications would make use of QD in proximity to the LED source and not directly in the package, thus meaning that the total amount of Cd per display would be higher than what could be achieved with OSRAMs on-chip configuration as the volume of the homogenous material would be larger. None of the three exemption requests explicitly refer to QD OLED, and it cannot be understood from OSRAMs input that an on-chip Cd QD OLED display is in development for the near future. Thus, it can be understood that QD OLED technology does not require any exemption for Cd but this technology can be used as a reference point for the performance and energy efficiency of on-chip Cd-based QD displays.

7.1 Amount of Cd in on-chip display applications

The exemption 39a that allowed less than 0.2 µg Cd per mm^2 of display screen area was set to expire in October 2019 but is still valid as a renewal request was submitted for which a decision is still pending. Cd-free alternatives are available on the market but still, Cd-based QD continue to enter the EU market. "*According to Nanosys internal market data, approximately 30% of quantum dot displays entering the EU in 2022 will contain some amount of intentionally added Cadmium. These Cadmium-based displays* [contain] *an emerging range of components with less than 100 parts per million (ppm) of Cadmium. Sub-100ppm Cd-QD components are expected to continue shipping into the EU and growing in volume. Most sub-100 ppm Cd components contain at least the same amount of Cadmium by weight as the previous generation of Cd-QD components* [that fell under exemption 39a]. *The reduction in ppm is achieved by increasing the thickness and weight of the homogenous layer. We believe this trend toward "Low Cadmium" display components is the result of a misunderstanding of the intent and spirit of RoHS.* […] *At the highest volumes, HMF-QD component cost is close to Cd-QD. However, at lower volumes, there is a price premium for HMF-QD components. This price premium, though small in terms of absolute dollar amount, has been making a* *difference in the extremely price-sensitive consumer electronics market*." (Nanosys Inc. 2022)

The following Table 7-1 lists the various technologies and their Cd concentration in the homogeneous layer as well as the total amount per 65" TV screen. As different stakeholders have differing definitions of on-chip, the numbers in the on-chip column differ a lot from the ones provided in Figure 7-1. With the numbers provided by Osram GmbH, Cd concentration per display surface are 0.00044 µg/mm^2. A 65" TV has an area of appr. 1.16 Mio mm^2, which results in a total amount of 0.5 mg Cd per 65" TV. "*In a 55 inch TV set (…)*[3] *less than 0.5 mg Cd (0.2-0.4 mg), would be needed on chip*" (Osram GmbH 2022c). This is more than two orders of magnitude less than stated below! Osram explains this discrepancy by assuming "*they take the full display screen area as it is the case for "on-surface" technology. This is certainly wrong in our understanding. The clue with the use of µLEDs is the fact that one has a very tiny chip or pixel of each colour (3 sub-pixels) for each full pixel (fig. 3). Furthermore, only red and green pixels are covered with quantum dots*." (Osram GmbH 2022a). Also see section 5 for the definitions.

Table 7-1: Cd QD Concentration in Homogeneous Layer for different applications

	On-surface QD Diffuser Plate	On-surface QD Film	QD for OLED Displays[4]	QD microLED Displays	On-Chip QD Lighting	Electro-luminescent QD Displays
Homogenous Layer Thickness	500 – 1000 µm	50 – 100 µm	7 – 10 µm	2 – 5 µm	300 – 500 µm	~0.03 µm
QD Weight % Concentration	0.06 – 0.12%	0.3 – 0.6%	20 – 30%	20 – 30%	0.025 – 0.1%	>80%
Cd ppm	30 – 55	85 – 280	6000-60,000 Green-Red	6000-60,000 Green-Red	60 – 240	24,000 – 200,000
Cd µg/mm²	<0.1	<0.05	0.3 – 0.5	0.15 – 0.25	4 – 16[5]	~0.005
Cd per 65" TV	<117mg	58mg	350 – 580 mg	175 – 290 mg	~116mg	5.8mg

Source: Nanosys Inc. (2022)

The ambiguous definitions and assumptions about on-chip are clearly visible between stakeholders. In the case that an exemption is granted for Cd QD in on-chip applications in displays, this ambiguity would need to be clarified and the exemption formulated in a way that would only benefit applications that use Cd but that result in a significant decrease in the total amount used per display:

3 The consultants left out "0,2-0,4", as it is understood to be the amount of Cd in mg with decimal comma.

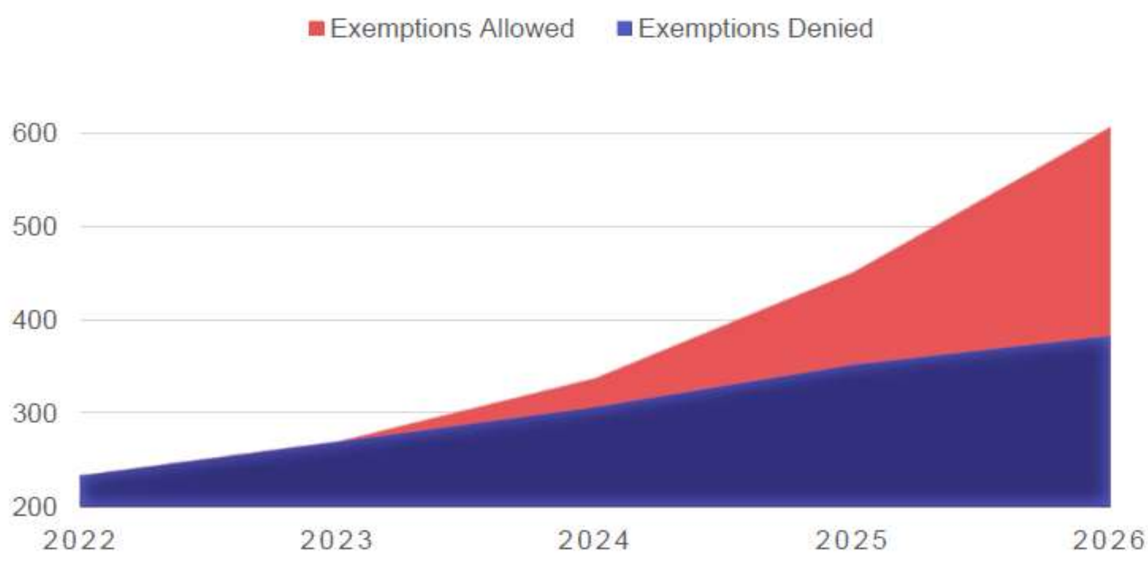
4 See Appendix A.2.0 for technical explanation of Cd in OLED and the different understanding of on-chip, als addressed under Appendix A.1.0.

5 Due to different definitions of on-chip, the amount of Cd is controversial. Compare Figure 7-1.

Nanosys warns that the amount of Cd entering the EU market would rise even more if the exemption for on-chip Cd QD in display applications was granted. "*If the requested exemptions (i.e. 5 µg /mm² [per light emitting LED chip surface] for on-chip) are adopted, Nanosys believes that the amount of Cadmium entering the EU will increase significantly. […] Establishing an exemption for Cadmium in direct view displays now will only encourage the continued development of Cadmium QD for these future applications. […] For example, we expect that a brand will enter the market in 2025 with a Cadmium QD-based version of QD-OLED. Proof of concept demonstrations of a Cd-QD-OLED display have been shown at display industry events already.*" (Nanosys Inc. 2022). Furthermore, Nanosys points out, that the amount of Cd shipped into the EU by display applications is already rising. There is a "*current trend towards increased Cadmium content by weight with lower Cadmium ppm levels through component optimization*. *Some vendors of film and diffuser plate implementations have developed thicker, bulkier solutions using Cd-containing QDs which have less than 100 ppm concentration. However, as noted elsewhere in this report, these on-surface QD films may contain as much as 100 mg of Cd per square meter of display area*!" (Nanosys Inc. 2022).

Nanosys provides a graphical presentation of "two scenarios for the expected amount of Cd entering the EU market annually for the period from 2022 – 2026." It estimates an additional amount of more than 200 kg Cd in 2026 entering the EU, if the exemption is granted as is shown in Figure 7-2 below.

Figure 7-2: Scenarios for the expected amount of Cd annually entering the EU



Source: Nanosys Inc. (2022)

In contrast, Osram argues that an exemption would enable a shift from on-surface to on-chip configurations for white backlight displays and thus the total amount of Cd would decrease by a factor of 100 per device. "*For on-chip technology a high concentration of quantum dots on the chip is required, however, the overall amount of dots is much less than compared to on-surface solutions. This reduces the total amount of* *hazardous substances such as Cd or InP in on surface applications by > 99%. In a 55 inch TV set less than 0.5 mg Cd, would be needed on chip compared to ca. 30 mg InP or 40 mg Cd on surface."* (Osram GmbH 2022c). For transmissive technologies, Osram provided the following estimate (Table 7-2) comparing substance amounts for an amount of 10 Mio TV sets. This number is higher than a realistic market penetration in Europe. The number of globally shipped TVs with QD technology was about 15 Mio (Nanosys Inc. 2022).

Therefore, Osram proposes an exemption with 5 µg/mm² light emitting chip surface in the on-chip configuration for display applications. A "*certain amount of Cd is needed per light emitting area and not per screen size. Estimated theoretical minimum is 2 µg / mm² for 99 % conversion assuming all Cd is active in optical absorption, realistically 2-5 µg are required*" (Osram GmbH 2022c). Equivalently, the amount per device might be limited to between 0.5 to 1 mg. Table 7-2 lists the comparison of the amount of Cd under the two scenarios, with and without exemption.

Table 7-2: Comparison of substance amount, with/without exemption

Model	Configuration	Amount per screen	Mio Units 55" TV sets	kg Cd	
LCD-NBP	On-chip, could be replaced by QD	< 0.5 mg	10	< 5kg	Suggested exemption with 5µg/mm² light emitting chip surface required
LCD-QDEF	On-surface	30 mg InP or 40 mg Cd	10	300 kg InP or 400kg Cd	Covered by existing exemption [<100ppm]

Source: Osram GmbH (2022c)

Comments: QDEF: Quantum Dot Enhancement Filter (i.e., on-surface configuration), NBP: Narrow band phosphor

Additionally, new types of augmented reality micro-displays would be made possible by the exemption. According to Osram GmbH, they would bring less than 1.3 kg Cd into the EU market. The details of estimated amount of Cd are listed in Table 7-3.

Table 7-3: Estimation of the amount of Cd by augmented reality micro displays

Augmented Reality		World market 2027 *	
Display size	0.2”-0.3” diagonal	28 mio. pieces / a	**μ displays**
Screen size	~25 mm²	25%	**EU share**
1-2 displays per glasses	~37 mm² average	5.18 kg Cd	**World market**
Cd/mm²	5 µg	1.295 kg Cd	**EU market**
Cd/glasses	185 µg		

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

Altogether, Osram estimates a saving of almost 400 kg/a of Cd if the exemption for on-chip configuration is granted.

This contradiction can be explained by the different understanding of ‘on-chip’ and the scope of the exemption. Nanosys refer to both, QD-OLED and microLED as on-chip (Nanosys Inc. 2022), however it can be understood that in both cases the QD material is not confined in the LED package but rather in a layer close to the package which has the same size and pattern as the package. Osram’s on-chip quantum dots are confined inside the LED package. Their surface or volume is thus understood to be smaller than the configuration that Nanosys refers to and thus to require significantly lower amounts of Cd. This technology can either be used as a white light source for transmissive backlight display applications instead of on-surface or as single-coloured subpixels in microLED direct view display applications. Products for the latter application are not developed yet, as they require an exemption, but “*could be realized within reasonable time.*” (Osram GmbH 2022b).

Both stakeholder contributions imply that the current limit of 100 ppm allowing for Cd intentionally entering the market is unfortunate for different reasons. It motivates research into Cd-based instead of Cd-free solutions and encumbers the market entrance of a technology that requires a much smaller total amount of Cd in a high concentration.

The consultants conclude that both statements might be true at the same time, while the assumption that 10 Mio devices switch to on-chip resulting in 300 kg savings seems too optimistic and not realistic. The numbers will be lower. While there might be a moderate increase in Cd entering the EU without an exemption, if QD OLED[6] and microLED applications are not explicitly excluded from a possible future exemption, there might be a significant increase of Cd, as QD OLED and microLED work with both, Cd and HMF QD. As a minimum, it would be relevant to limit the absolute amount of Cd applicable per display, as a means of ensuring that Cd can only be applied in the on-chip configurations that use the smallest amount of Cd possible.

[6] Though it can be understood that current OLED on the market are Cd free, it is also understood (Nanosys Inc. (2022)) that CdQD OLED prototypes already exist.

7.2 Displays with microLED and Displays with nanoLED

These new developments are partly in the scope of the assessment of the exemption request and added for completeness so as to give an understanding for where research and development are heading with Cd-based quantum dot technologies. If granted, the exemption will be used for microLED technology that was already mentioned in the previous assessment.

MicroLED technologies have entered the market in 2022. An exemption for Cd QD would give this technology a strong push.

- *"Micro LED display applications*[7] *require a thin film conversion layer that can only be realized using QDs. Cd QD are currently the only QDs that are stable enough to satisfy the requirements. Proof of principle for full conversion has been demonstrated in very thin layers (< 3µm, internal development project). This is an enabling and key technology for small (< 10µm) Micro LED application for next generation display applications."* (Osram GmbH 2022c).
- *"Direct view emissive microLED displays are beginning to enter the market at the extreme high end of the premium segment in TVs. These microLED TVs use a combination of 24.9 million native red, green, and blue emitting microLED. Nanosys believes mass market consumer microLED displays may become possible in the next five years with the help of on-chip Quantum Dot Colour Conversion (QDCC) technology. Cadmium and heavy metal free quantum dots (HMF-QDs) are currently being evaluated by the industry for on-chip colour conversion in direct view microLED displays. Every public QDCC display demonstration at Display Week 2022 used Cadmium quantum dots*." (Nanosys Inc. 2022).

On the other hand, it might be possible in the future to realize this technology without Cd by adopting experiences from QD OLED to microLED:

- *"HMF-QDCC materials for on-chip applications are ready today and are already shipping into the market in QD-OLED products. The blue photon flux required for a direct view microLED display is much lower than the flux required by an LED backlight implementation. This makes it possible to use HMF-QD in direct view emissive displays, even at current performance levels*." (Nanosys Inc. 2022).

NanoLED are a completely different and new technology that has not been mentioned neither in the exemption request nor in the previous assessment but is also based on quantum dots. In nanoLEDs, quantum dots are used directly as the light source for each subpixel. Instead of being excited to a higher energy state by blue light, they are excited by electrons. Thus, also based on quantum dots, this technology cannot be attributed to any of the configurations (on-chip, on-surface, on-edge). This technology is also a form of direct view but differs to the above mentioned in that it does not include any LED anymore and subpixels can be dimmed and turned off individually. "*NanoLED is the future of Quantum Dots. NanoLED displays are like OLED devices in that the Quantum Dots convert electricity directly into photons. HMF-QD NanoLED technology is making rapid progress towards commercialization but remains in the research and development*

[7] It is noted that throughout the document there is reference to both micro displays, understood to be displays of very small size, as referred here, and to micro-LED (referred to in second bullet and later on). The latter refers to the size of the LED, which can be used both in micro displays but also in larger ones.

phase. At the 2022 SID DisplayWeek show, Nanosys demonstrated record-setting HMF-QD external quantum efficiency (EQE) of greater than 16% for blue, 17.5% for green, and 21% for red. For context, commercial blue OLED EQE today is only about 7%. Work still needs to be done to improve the lifetime of NanoLED materials, but progress has been rapid. Red and green NanoLEDs are approaching commercial reliability levels today. Demonstrations of NanoLED products have been shown at the SID Display Week tradeshow in 2022. BOE featured a 55" 8K TV using Cd-based QDs at their booth, while Sharp privately showed a smartphone-sized 6.1" NanoLED display using HMF-QDs. NanoLED displays may be commercialized in the next three to five years." (Nanosys Inc. 2022). Electroluminescent QD as nanoLEDs might become a RoHS-conform substitution for microLED applications in the next few years.

It is understood that microLED is strongly dependent on an exemption for short term market entry. Differently, nanoLED technology is not dependent on an exemption for Cd i.e., concentrations are below 100 ppm, but an exemption, if granted, might have an impact on further developments.

7.3 Market availability of substitutes for and alternatives of Cd CD on-chip display applications

7.3.1 QD based display technologies:

"Nanosys' internal market research estimates that HMF-QD currently makes up approximately 70% of all QD displays shipped both globally and in the EU. Many leading brands including Samsung, LG, Sony, HP, and Dell have successfully adopted a "zero-Cadmium" policy for their display products." (Nanosys Inc. 2022). The number of 70% of all QD displays being Cd-free compares to 90% of QD TV displays being cadmium-free as cited above from Nanoco.

On the device technology level, heavy metal free **QD OLED** technology might be seen as an alternative to Cd QD-based LCD and microLED technology. "*QD-OLED is a new type of display, introduced by Samsung Display Corporation in late 2021 and launched into the market by Samsung Electronics, Sony, Dell and MSI in TV and monitor products during the first half of 2022. The Samsung S95B QD-OLED TV received a 9.1 mixed usage score from RTINGS.com and is currently the highest scoring TV on the website. In terms of raw picture quality performance, this set delivers over 1,000 nits of peak luminance, more than 86% coverage of BT.2020, and 51.7% BT.2020 colour volume coverage. Every QD-OLED product on the market in 2022 uses HMF-QD technology."* (Nanosys Inc. 2022). The consultants understand, that QD OLED is neither seen as on-chip nor as an alternative to on-chip quantum dots for transmissive and microLED based display applications by Osram, that initially requested the exemption. And yet, Cd QD OLED prototypes have been mentioned by Nanoys and could be placed on the market if an exemption is granted that would cover their use in this application.

For **microLED** technologies, first products entered the market in 2022 "*at the extreme high end of the premium segment in TVs, in many cases costing over $80,000*." (Nanosys Inc. 2022). "*Micro LED display applications require a thin film conversion layer that can only be realized using QDs. Cd QD are currently only QDs that are stable enough to satisfy the requirements. Proof of principle for full conversion has been demonstrated* *in very thin layers (<3µm, internal development project). This is an enabling and key technology for small (<10µm) Micro LED application for next generation display applications.*" (Osram GmbH 2022c). Mass market production will probably become possible: "*in the next five years with the help of on-chip Quantum Dot Colour Conversion (QDCC) technology*" (Nanosys Inc. 2022). On the **QD substance level** both, HMF QD and Cd QD are studied. Cd-based solutions seem to have better chances: "*Cadmium and HMF-QDs are currently being evaluated by the industry for on-chip colour conversion in direct view microLED displays. In fact, at the Society for Information Display's recent Display Week 2022 tradeshow held in San Jose, California, there were several demonstrations of microLED displays using QDCC. Every public QDCC display demonstration at Display Week 2022 used Cadmium quantum dots.*" (Nanosys Inc. 2022)

NanoLED technology is still in the development phase and not market ready:

- "*Rapid progress in the development of future […] NanoLED technologies for direct view displays are well positioned to use HMF-QD*." (Nanosys Inc. 2022)
- "*HMF-QD NanoLED technology is making rapid progress towards commercialization but remains in the research and development phase. At the 2022 SID DisplayWeek show, Nanosys demonstrated record-setting HMF-QD external quantum efficiency (EQE) of greater than 16% for blue, 17.5% for green, and 21% for red. For context, commercial blue OLED EQE today is only about 7%. Work still needs to be done to improve the lifetime of NanoLED materials, but progress has been rapid. Red and green NanoLEDs are approaching commercial reliability levels today*." (Nanosys Inc. 2022)

For NanoLED, on the QD substance level both, HMF QD and RoHS compliant Cd QD are still in the race: "*Demonstrations of NanoLED products have been shown at the SID Display Week tradeshow in 2022. BOE featured a 55" 8K TV using Cd-based QDs at their booth, while Sharp privately showed a smartphone-sized 6.1" NanoLED display using HMF-QDs*." (Nanosys Inc. 2022) Commercialisation may start "*in the next three to five years.*" (Nanosys Inc. 2022)

Still on the QD substance level, **Cd with <100 ppm** seems to be impracticable for on-chip colour conversion technologies (i.e., excluding NanoLED). Two stakeholders are of the opinion that the market does not offer any on-chip solutions for Cd-free or RoHS compliant QD. Both stakeholder contributions even question the physical possibility of RoHS compliant QD:

- "*'On-chip' QD configurations are not currently available on the market in trans-missive displays such as LCDs in either Cd-QD or HMF-QD formulations. The brightness (photon flux) required for on-chip QD integrated into blue mini-LEDs in LCD backlights is prohibited by both Cd and HMF-QD's current reliability limitations.*" (Nanosys Inc. 2022).
- "*Market not developed for displays [based on on-chip QD]. RoHS compliant [on-chip] Cd QD LED are not possible due to the different distribution of Cd in the luminescent material. This means for Cd QD we need more than 100 ppm in homogenous material, up to 5 µg per mm² light emitting area.*" (Osram GmbH 2022c).

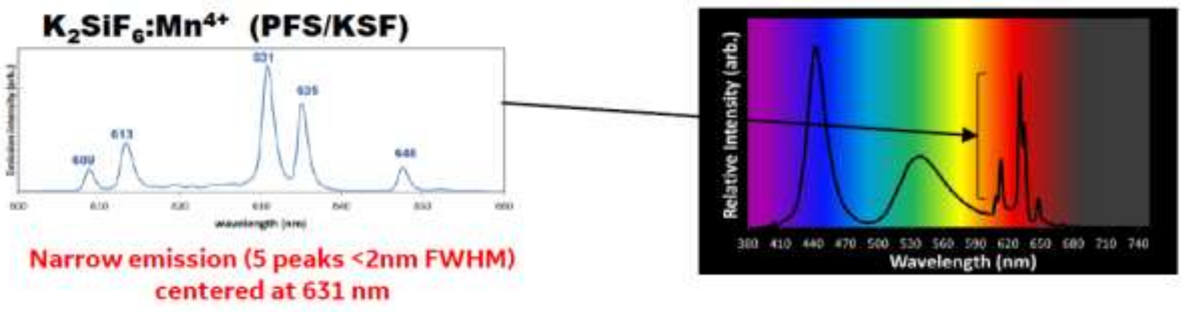
On the QD substance level**, research** is mainly studying materials based on indium phosphide (InP) and lead:

- *"While InP-based Quantum Dots caught up in efficiency during the last years their band widths did not improve in similar ways. With this improvement they are used in on-surface configurations. For on-chip configuration they lack tremendously in lifetime as seen in internal experiments but from other groups as well*" (Osram GmbH 2022c)
- *„In addition to indium-based materials such as InP, we are aware that research into perovskite-based QDs has accelerated in recent years, with significant progress being made in this area. While the most technologically advanced of such perovskite QDs contain Pb, it is our understanding that manufacturers are working to develop display products with a Pb content well within the RoHS limit."* (Nanoco Technologies Ltd. 2022)

7.3.2 Other technologies that do not use QD: colour conversion technologies

Another alternative on the colour conversion technology level is based on phosphors. Potassium fluorosilicates exhibit a very specific optical signature "*providing 5 extremely narrow peaks in the red region."* (General Electrics 2022). This is shown in Figure 7-3.

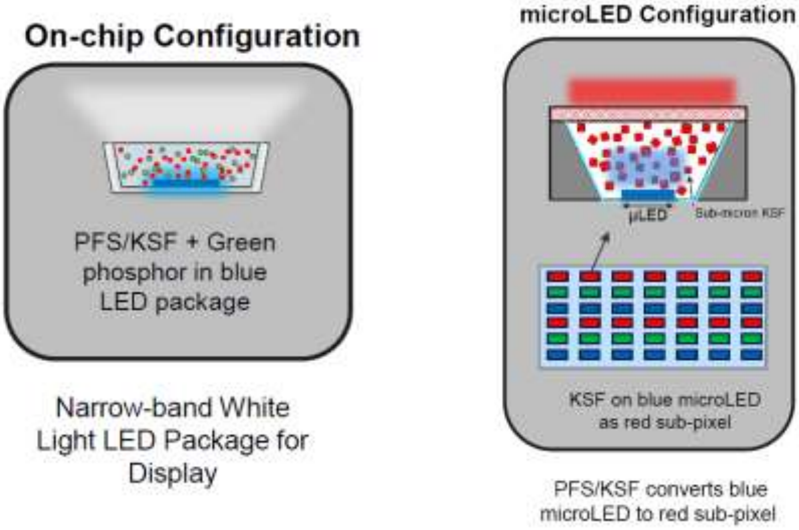
Figure 7-3: Spectrum produced from a blue LED with green phosphor and GE's red KSF phosphor



Source: General Electrics (2022)

It is understood that KSF-based solutions can be implemented on-chip for **white backlight display** applications as well as in **microLED** beside its well-known application in **on-surface configurations**. For both on-chip configurations, the conversion matrix is confined by the size of the LED package and directly placed on the LED chip. Schematic drawings are shown in Figure 7-4. "*KSF phosphor is typically packaged directly on top of the LED chip without an additional encapsulation layer for protection from atmosphere. It has been designed to withstand 10s of thousands of hours under the extreme conditions on chip without degrading and without encapsulation layer. GE has developed multiple size options of KSF to meet market needs. All these products use the same fundamental material, potassium fluorosilicate with manganese, K2(SiF6):Mn4+, and all have quantum efficiencies well above 90%, approaching unity."* (General Electrics 2022).

Figure 7-4: Schematic drawing of KSF on-chip for white backlight and microLED



Source: General Electrics (2022)

The following shows a comparison of KSF with red InP QD and red Cd QD under various quality measures. It indicates, that KSF is on a par with QD technologies. "*KSF is used in displays that reach 100 % DCI-P3 colour gamut, which is the current standard for wide colour gamut displays. KSF has a response time on the order of milliseconds, and this has not prevented adoption in display technology. Liquid crystal switching speeds are typically the slowest component of a display which are on the order of ~10 ms, which is slower than the response time of KSF. In fact, KSF is implemented in some of the fastest response time displays such as gaming laptops and monitors with refresh rates of up to 300 Hz (3.3 ms), including the Dell G7 laptop, Alienware m17 laptop, and HP OMEN 15 laptop."* (General Electrics 2022).

Table 7-4: Comparison of properties for KSF and QD

Property	KSF phosphor	Red InP QD	Red Cd-based QD
Color gamut	5 peaks <2nm each	FWHM >40nm commercially	FWHM 25-30nm commercially
Max % EQE	IQE > 90%, EQE >70%	EQE <40%	EQE>50%
Reliability to air	No encapsulation necessary in commercial products	Encapsulation required	Encapsulation required
Reliability to moisture	No encapsulation necessary in commercial products	Encapsulation required	Encapsulation required
high temperature quenching	no loss at 100 °C	>20% loss at 100 °C	>5% loss at 100 °C
High temp. curing degradation	<2% at 150 °C for 30 min.	>20% at 80 °C for 20 min.	Unknown
Reliability to high blue flux	Commercialized on chip	Not commercial on chip	Commercialized for lighting
Passivation film required (O_2/H_2O)	no	Yes	Yes
Self-absorption	no	Yes, all QD colors	Yes, but less than InP QD
Scatterance	RI = 1.4 so provides some scattering at typical sizes	Must add scattering agent	Must add scattering agent
Photoluminescence decay time	LCD like response time	Faster in microLED with no LCD	Faster in microLED with no LCD
Absorption	Requires >2x QD thickness	Higher abs. coefficient	Higher abs. coefficient

Source: General Electrics (2022)

According to GE, this technology is well placed on the market with 50 billion KSF on chip LEDs sold into display technology. "*LEDs containing KSF red phosphor on-chip have been commercially available and widely used in displays since 2014*" (General Electrics 2022). Just for special display applications where millisecond reaction times are required, on-chip QD colour conversion technologies in micro-LEDs cannot be replaced by KSF yet.

7.3.3 Conclusion on the market availabilities

In summary, for different technology levels, the situation of substitutes is quite different. The results are listed in Table 7-5.

Table 7-5: Overview of market availability of substitutes of Cd QD in displays

Level	Substitutes	Market Availability
Cd Reduction in Cd QD: on-chip	RoHS compliant Cd QD (<100 ppm Cd)	Not available on the market
Design changes: not on-chip	HMF QD OLED	High
Design changes: no colour conversion	HMF-QD NanoLED	In 3-5 years
Component substitute: Colour conversion	KSF phosphors	High
Material substitute: Quantum dot level	InP- and perovskite-based RoHS-compliant QDs	Not available on the market, research status
Material substitute: Quantum dot level	HMF QD MicroLED	In 4-5 years

Source: own representation

7.4 Energy Efficiency Comparison

QD Substrate level:

The development of the internal quantum efficiency cited in section 5.1 is understood to be valid also for on-chip quantum dots. "*Here we can see that both QD formulations have improved and are now approaching or above 95% IQE. Cd-QD maintains a slight edge in IQE, however, this advantage does not necessarily translate to an advantage in full device performance." (Nanosys Inc. 2022)*

Device technology level:

The energy efficiency of display devices has many dependencies that vary according to design choices of the manufacturer. The display technology (LCD vs. OLED) has the biggest impact on energy use of display products. *"Display size is the second most impactful factor in determining a display's energy consumption. Larger displays consume more power. Resolution can have a significant impact on display power consumption. For example, 8K TVs can consume up to 90% or 100% more power compared to 4K TVs with 25% of the number of pixels*." (Nanosys Inc. 2022)

For on-surface displays, Nanosys conducted a study at the RTINGS website. Nanosys "*pulled publicly available data from the review site RTINGS.com on a selection of five HMF-QD LCD displays compared to five similar Cd-QD LCD displays. Each of the ten TVs we looked at was placed on the market in 2020 through 2022 and is still available to purchase in the retail channel.*" (Nanosys Inc. 2022). The results shown in Table 5-1 and Table 5-2 indicate that for on-surface, using Cd QD does not give an advantage in energy efficiency compared to heavy metal free QD. It is understood that these results do not allow any conclusions for the energy efficiency of on-chip Cd QD in transmissive (e.g. LCD) displays. In the context of LCD displays, Osram argues that Cd QD on-chip light sources have the potential to reduce the colour filtering losses of classical LCD displays. "*Used for TV screens higher resource efficiency can be realized, as no converter materials are required. The main energy loss in displays is the use of filters to extract colours of high purity. The light that doesn't pass the filters is thrown away. Therefore, a strong lever to enhance the display efficiency is to use narrow spectra, i.e. pure colours as provided by Quantum Dots. Quality of light and energy efficiency are expected to be improved.*" (Osram GmbH 2022c)

In summary, it is difficult to say how much energy efficiency will be gained by an exemption on the device technology level. A direct comparison of best performing Cd QD and KSF is also lacking, as the former is understood to be still in the development phase. As KSF is found to be more energy efficient than on-surface Cd QD by General Electrics, the potential saving by on-chip Cd QD might not be significant.

7.5 Evaluating End-of-Life Stage

The end-of-life processes and waste streams of Cd-containing displays could not be evaluated during this study. In the past, displays were dismantled in an effort to remove among others backlighting units containing mercury (legal requirement) as well as other components. Such display are still expected to be in the waste EEE fraction collected for treatment and thus facilities will probably have appropriate emission control technologies in place. In displays where LEDs provide the backlight function, it is not clear whether the LED modules are removed or not. In case of removal, it is conceivable that they would be collected and treated separately, avoiding uncontrolled shredding or breakage of the modules and subsequently uncontrolled Cd emissions. Where not removed, the modules would end up being sent to shredder. As the modules are comprised of plastic their pieces would be directed to that fraction. Where modules are broken during shredding, some Cd may be released, but as explained above, it is probable that where display recycling facilities are (still) equipped to deal with mercury vapours that they would also have relevant emission reduction systems in place for Cd. The accumulation in future circular systems should be kept in mind for future revisions but is not a concern to current waste treatment. The concentration in the current waste stream is "equivalent to cadmium limits for chocolate" (LightingEurope 2022). Balcan indicates that LED chips might get separated or even recycled in the far future. "*Currently I am not aware of any company operating a rare earth recovery system specifically for RE from lamps. However, there are two companies who have the technology to do so.*" (Balcan Engineering Ltd 16.09.22).

LE argues that Cd concentrations would be rather low, even if the exemption was granted. "*The cadmium content coming from LEDs in a 55-inch TV screen is calculated to be < 1 mg. Assuming a weight of 20 kg per TV set a concentration of clearly below 0.05 ppm cadmium in the waste stream*." (LightingEurope 2022) this statement is understood to refer to the case of on-chip configuration as presented by OSRAM, in which the display contains very small amounts of Cd. In contrast, in the on-surface configuration where displays are still allowed on the market (and where it is reported that displays using <100 ppm Cd are placed on the market), much larger amounts of Cd may be contained per unit.

Consequently, as there are already devices on the market that contain hundred times more Cd per device in on-surface technologies than needed for on-chip, the consultants assume that waste treatment would not be affected by an exemption for on-chip configurations limited to devices containing only small amounts of Cd as those referred to by LightingEurope (Osram GmbH 2022c).

7.6 Other environmental impacts

Updated insights about the toxicity of the red phosphor were contributed by GE: "*KSF phosphor does not contain any RoHS restricted elements or compounds, and the composition is potassium fluorosilicate with manganese. The base compound has a sister compound, sodium hexafluorosilicate, that is widely used as a fluoridation compound in water treatment. The two compounds have similar hazard profiles according to their SDS3*." (General Electrics 2022). The statement in the contribution[8] for the former assessment by Nanosys about its toxicity in landfills was called "inaccurate or misleading" by GE.

[8] See https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/4th_Consultation/Contributions/contribution_Nanosys_RoHS15_InP_Stakeholder_Response_20191106.pdf

7.7 Conclusions for on-chip display applications

The different interpretations of "on-chip" make the data a bit difficult to navigate. The consultants understand that the configurations referred by Nanosys, where QDs are applied "in a layer close to the package" would likely require higher amounts of Cd per display than possible with the OSRAM interpretation of on-chip, where the QDs are placed directly "in the LED package".

In all cases it can be understood that displays with the OSRAM on-chip configuration with QDs "in the LED package" are not yet on the market – this is the case for standard LCDs, OLED, MicroLED and NanoLED[9]. The case, however, for Cd QD applied "in a layer close to the package" differs depending on the type of displays:

- For standard LCDs such QDs are still allowed, though for the most part Nanosys contends that heavy metal free QDs are the dominant technology aside from Cd QD with >100 ppm Cd. Nonetheless, Cd QD with <100 ppm Cd do not need an exemption and would result in more Cd entering the market than in the case that Cd is applied in an "in the LED package" configuration. An exemption limiting the total amount of Cd per display in this case may not necessarily lead to applications with less than 100 ppm Cd being abandoned, but it would at least set the scene for a shift of manufacturers using Cd in this direction and is expected to potentially lead to a reduction of Cd.
- For OLED, all QD based display on the market apply heavy metal free QDs, though prototypes using Cd QD "in a layer close to the package" are expected to be market ready within 2-3 years. Here an exemption that would allow the use of Cd in OLED applications would penalise manufacturers that have opted to develop the alternatives and could harm the existing market dominance of heavy metal free QD.
- For MicroLED and NanoLED, developments with Cd QD "in a layer close to the package" can be expected to be underway, though detailed information on this has not been made available. Though it has been assumed that they would show a higher energy efficiency, this could not be supported with quantifications. Only in the case of micro-displays, does provided data suggest that high efficiency would be possible with very small amounts of Cd.

When comparing configurations where the QD is "in a layer close to the package", the heavy metal free QDs show a dominance in displays already on the market and it has not been shown that Cd counterparts would exceed this performance (neither Osram nor other stakeholders provide any data for such applications). Should an exemption be granted for Cd QD, it should be limited to their application "in the LED package". As this term could still be interpreted differently, a limitation of the absolute amount of Cd per display was discussed with OSRAM (see section 8).

[9] It is noted that there are differences between micro-LEDs and micro LED displays, see footnote 7 in this respect.

8 Conclusions and recommendation

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.

For the exemptions at hand, conclusions differ in relation to lighting and display applications, and are thus presented in two respective sub-sections. Some additional aspects are realised in a final sub-section.

8.1 Lighting

Even in the CRI>90 segment, RoHS compliant alternatives (on the colour conversion and the quantum dot level) exist and are available on the market i.e., KSF and <100 ppm Cd QD. The environmental impacts are mostly represented by the placing on the market of an annual Cd amount of approximately less than 2 kg versus 10% energy efficiency gains in 1% of LED lighting applications, if the exemption is granted. Health and consumer safety impacts are not expected by the substitution. A side effect of an exemption might be that QD technology would push the energy efficiency targets further also for phosphor-based technologies.

In conclusion, elimination of Cd for on-chip lighting with CRI>90 is practicable by LED using Cd QD with less than 100 ppm (compliant with RoHS) as well as by Cd free alternatives. Such alternatives are considered reliable as they are already placed on the market. Comparing the negative environmental impacts of 100 ppm Cd QD LED vs. 400-800 ppm CD QD LED (where OSRAM expect the optimum of energy efficiency to be achieved), reveals that the <100 ppm LEDs exhibit 10% higher energy consumption while at the same time they require between 1/4 to 1/8 of the amount of Cd per module. In the last assessment, it was argued that 20% would just be enough to outweigh trace amounts of Cd. However, at present, this advantage is no longer maintained.

The impacts of both, energy efficiency and the extra amount of Cd are relatively small but cannot be directly compared. In the context of the assessment above, the consultants conclude that negative impacts of RoHS-conform solutions rather hold balance with, rather than outweigh benefits of an increased amount of Cd.

The consultants thus recommend denying the request for Cd in QD applied in solid state lighting.

8.2 Displays

On the device and colour conversion technology levels, RoHS compliant alternatives exist, e.g. both in the form of HMF-QD display and other conversion technologies as in the form of Cd Qd with <100 ppm Cd and HMF-QD. In on-surface applications, HMF-QD are understood to be the prevalent technology and an exemption has not been argued for by any of the stakeholders in the context of this study. In the previous assessment, Najing requested a renewal of the exemption for on-surface Cd QD until 31 October 2021. As Najing did not follow the invitation to contribute a stakeholder statement, the consultants conclude that the request is obsolete. This may also have to do with the fact that nowadays many on-surface CD QD display applications apply <100 ppm Cd in the homogenous material.

For on-chip applications, there is ambiguity as to what this term means (see Sections 5.3 and 7.1 as well as Appendix A.1.0).

As portrayed by Nanosys, HMF QD are available on the market with applicability in microLED and nanoLED approaching within the next five years. Also, KSF phosphors as a component substitute are already available on the market for most applications with sub-micron KSF for microLED (General Electrics 2022). Technical obstacles for sub-micron KSF are thicker fil architectures due to lower absorbance (ibid.). Nano-KSF is still under development. The case of micro displays is the only one where at the level of quantum dot substance portrayed by OSRAM alternatives (e.g., InP- and perovskite-based QD's) are still in the research phase, whereas Cd QD could be applied quickly if an exemption is granted. Micro displays use microLEDs, but the latter are also used for larger displays.

The environmental impacts are dominated by the amount of Cd and potential energy savings. Both are found to be ambiguous. If the higher concentration but much lower total amount of Cd for on-chip compared to on-surface is allowed, the amount of Cd might be significantly reduced in displays on the European market.

How the amount of Cd will develop under an exemption or without, strongly depends on the assumptions of the technology and the scope of the exemption. The amount of Cd entering the EU might saturate or even decrease, if the following conditions are valid for an exemption:

- only on-chip "in the LED package" should be allowed
- QD OLED is not regarded as on-chip "in the LED package" (out of scope) and for this application there is already a market dominance for heavy metal free QD,
- Quantification of potential energy savings and technical performance were not made available for both, OLED as also for new applications not yet on the market (e.g., micro-LED displays and nano LED), so the superiority of Cd QD could not be confirmed, nor the opposite,
- Enabling Cd QD on-chip "in the LED package" would require max. 5 µg/mm^2 light emitting LED chip surface: The suggested amount by the applicant, theoretical minimum is 2 µg/mm^2, realistically 5 µg/mm^2.
- To avoid that an exemption with the above threshold results in an increase in the amount of Cd placed on the EU market (and potentially also to generate a

reduction of current amounts) a max. of 1 mg per device/ display application should be specified. By this limit it is also granted, that technologies other than on-chip (e.g., OLED) do not benefit from the exemption. The applicant Osram promises a decrease of the amount of Cd by 99% per display compared to existing 100 ppm on-surface displays. Only if this is ensured, the exemption will enable environmental benefits.

- For micro-displays (not to be confused with microLED, which are also used in other displays), the second criterion is met as the other alternatives are lacking in reliability.
- max. 4-5 years: HMF QD microLED and HMF QD nanoLED are approaching the market.

Looking at the ambiguities related to the on-chip configuration and the amounts of Cd that are applied per display area, OSRAM was asked to clarify its understanding of this term and how a possible exemption could be formulated to avoid that the amounts of Cd in EEE placed on the market increases as suspected by Nanosys. OSRAM contends that "*there seems to be a discrepancy in the understanding of "on chip" technology. We do not share most of the interpretations but we do have to acknowledge, that misunderstandings might be possible leading to higher Cd content […] We agree that the only way to achieve more clarity is to limit the amount of Cadmium per "device"*."(Osram GmbH 2022a). OSRAM thus provided the following formulation proposal that limits both the amount of Cd per surface as well as absolutely in relation to the display:

"Cadmium in downshifting semiconductor nanocrystal quantum dots

I. directly deposited on LED semiconductor chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface) with a maximum amount per device of
a. 1 mg for Liquid Crystal Displays (LCD)
*b. 10 mg for display and projection devices with self-emissive display technology (e.g OLED, µLED; no LCD) up to a resolution less than < 8K (e.g. 4K: 2160 * 3840) pixel*
*c. 20 mg for display and projection devices with self-emissive display technology (e.g OLED, µLED; no LCD) and a resolution of 8K (4320 * 7680 pixel) and higher.*

II. directly deposited on LED semiconductor chips for use in lighting applications of at least CRI 90 (< 1.000 ppm in the luminescent material)

provided that applications comply with entry 72 of Annex XVII of Regulation 1907/2006." (Osram GmbH 2022a)

OSRAMs justification is that the "*Above exemptions can lead to increase of energy efficiency of displays as well as of quality of displays. Displays with direct transmission need more Cd as much more Micro LEDs are required. But the overall energy efficiency increases dramatically compared to LCD displays where most of the energy is lost by the filtering*". (Osram GmbH 2022a)

The energy and resource efficiency are likely to increase under these conditions. On the other hand, this exemption will enable a new form of microLED displays e.g., for glasses.

The effects on waste streams and the environment, if more devices that are not treated and seen as EEE become WEEE, is still unknown.

Looking at the formulation proposed by OSRAM and reproduced above, the consultants can follow the proposal of item I.a, for which data has been provided as to Cd amounts in support of the on-chip configuration as interpreted by OSRAM and would recommend an exemption in this case based on the Article 5(1)(a) criteria for both LCD applications as also for micro display applications:

- For LCDs, where Cd QD can be applied on surface at <100 ppm levels, an exemption for Cd QD on-chip "in the LED package" could result in a decrease in the total amounts of Cd placed on the market, but could only be achieved if the amount of Cd per display is limited as well as the concentration per homogenous material. In this case, though there are alternatives on the market that are reliable, the application of Cd QD on-chip "in the LED package" could decrease the total amount of Cd on the market which can be seen as a positive environmental impact as compared to Cd-based alternatives already on the market without any exemption (e.g. third criteria).
- For micro displays, alternatives are not on the market and also not in progressed stages of development: the size of these displays suggests that here only QD on-chip "in the LED package" could be applied, and for this configuration alternatives currently show lacking reliability. Looking at the absolute Cd amounts calculated by OSRAM (e.g., 185 µg per glasses application), suggests that here too the, the 1 mg limit would be more than sufficient.

As for items I.b and I.c, it is plausible that when applied according to OSRAMs interpretations, that here too large reductions of Cd would be possible, also resulting in a reduction in energy consumption and in an increase in display quality. However, such devices are still understood to be in development, and it is not completely clear how they would compare with HMF alternatives that are expected to be developed in the coming years. Data has not been provided to allow understanding the technical capabilities, whereas here, heavy metal free applications of QD are further advanced in development. Though this could still be consulted with the various stakeholders, this would extend beyond the study timeline and could no longer be accommodated in this report. Here the recommendations are thus inconclusive.

Due to research and market activity, we recommended max. 4-5 years. This gives manufacturers a chance to develop alternatives for micro-displays and to try reducing the total amount of Cd for other displays. If the latter effect does not show to be significant in practice, the exemption should not be renewed after five years.

In conclusion, the consultants recommend granting an exemption with the following wording and a duration of 5 years:

"Cadmium in downshifting semiconductor nanocrystal quantum dots

> *directly deposited on LED semiconductor chips for use in display and projection applications (< 5 µg Cd per mm² of light emitting LED chip surface) with a maximum amount per device of: 1 mg"* *valid until 31.11.2027*

It could also be considered to include items b and c in the exemption, however the data collected so far does not allow a conclusion as to the justification of these exemptions.

8.3 Additional aspects:

The consultants understand that the purpose of the RoHS is protection of human health and the environment including the end-of-life stage of products. It is thus questionable whether intentionally adding hazardous substances just below the threshold into products for the EU market and pursuing research to do so is in accordance with the purpose of RoHS. In order to avoid the risk of undermining the fundamental protection goals of the RoHS Directive, the consultants therefore recommend adapting the pollutant-related threshold values to the modern manufacturing possibilities of nano-technologies.

The pace of innovation is very high in the field of lighting applications and screens, with new technologies and devices entering the market every 2-3 years. Allowing for an in-expensive and environmentally detrimental technology might reduce innovation pressure und thus the development of environmentally beneficial technology. The latest series of applications suggests that cadmium products are not only being further developed but that new products containing cadmium and lead are being researched for the market with concentrations that circumvent the RoHS restrictions. This is possible in the field of nanotechnology, where the concentration limits described by RoHS can be met, even though the hazardous material is placed into the product intentionally. Concentration limits may be reached also by enlarging the mass of the homogeneous material, thus wasting material with the purpose of circumventing RoHS. This is contrary to the purpose of the RoHS Directive and of exemptions, which are to allow companies time to develop restricted substance-free alternatives to existing products and not to continue to develop new and improved products reliant on highly toxic materials such as cadmium, without presenting evidence that they are developing cadmium-free alternatives instead. Stakeholders state that new applications will be made possible and enter the market if a higher concentration of Cd is allowed, also for displays.

Compared to phosphor solutions, Cd QD exhibit energy savings of up to 10% per lighting device while also improving light quality (the parallel case for displays is not clear). This might have a beneficial effect for the environment if we assume that increased energy efficiency directly translates to energy savings and therefore decreased resource extraction from and pollution to the environment. That assumption neglects rebound and macro-economic effects. Thus, energy efficiency is not the primary intent of RoHS, but rather "environmental benefits". Furthermore, energy efficiency of consumer products is already addressed by other legal acts e.g., Eco-design directive. But energy consumption on the application level is strongly dependent on other factors as well that might, depending on the case, by far outweigh the effect of hazardous substances. Screen size of TVs and their resolution is a placative example.

The phase down of hazardous substances and the reduction of the overall energy demand in the EU must not be played against each other. Only those technologies supporting both, the aims of RoHS and other legal acts e.g., in the context of the Green New Deal, should be allowed on the European market. Thus, the consultants recommend the Commission to create a legal frame, in which there is no trade-off necessary between the phase-out of hazardous substances and the environmental impacts thereof. Especially for new products and technologies that are about to enter the EU market, a clear signal can be sent to market and research.

A final aspect to consider is the still ongoing development of the "essential use" concept of the European Commission.

It is not clear how the essential use principal will be applied, nor starting when it could be implemented and whether it would apply to the case of Cd in QDs. However, looking at the dynamic development of both the lighting and display sectors, the question comes to mind whether these applications are essential and whether a RoHS exemption would be in line with the future intentions of the European Commission.

9 References

Balcan Engineering Ltd (16.09.22): Response to Stakeholder contribution to the RoHS Cd QD Review 2022. eMail with Oeko-Institut e.V., 16.09.22.

Bechu, A.; Ghoshal, S.; Moores, A.; Basu, N. (2022): Are Substitutes to Cd-Based Quantum Dots in Displays More Sustainable, Effective, and Cost Competitive? An Alternatives Assessment Approach. In: *ACS Sustainable Chem. Eng.* 10 (7), pp. 2294–2307. DOI: 10.1021/acssuschemeng.1c04909.

Chen, Y.; Liang, X.; Liu, J.; Chen, S.; Xiang, W. (2021): Environmentally Friendly and Ultrastable Narrow-Band Emitter: CsPbX 3 @SEBS Flexible Film for Light-Emitting Diode Displays. In: *ACS Sustainable Chem. Eng.* 9 (30), pp. 10291–10298. DOI: 10.1021/acssuschemeng.1c02981.

Current Chemicals, Current Lighting Solutions, LLC (2022): New RoHS CD QD Follow-up Study has started. eMail with Oeko-Institut e.V., 7 Oct 2022.

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

General Electrics (2022): New RoHS CD QD Follow-up Study has started. eMail with Oeko-Institut e.V., 7 Oct 2022.

LightingEurope (2022): Contribution Questionair, 30 Sep 2022.

Marwede, M.; Chancerel, P.; Deubzer, O.; Jordan, R.; Nissen, N. F.; Lang, K. (2012): Mass flows of selected target materials in LED products. Conference Paper Electronics Goes Green 2012+ (EGG), 2012, last accessed on 12 Sep 2022.

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

Nanoco Technologies Ltd. (2022): Stakehodler contributions to RoHS Cd QD Review 2022. eMail with Oeko-Institut e.V., 23 Sep 2022.

Nanosys Inc. (2022): New RoHS CD QD Follow-up Study has started. eMail with Oeko-Institut e.V., 4 Oct 2022.

NICHIA CORPORATION (2022): H6 Series Lighting. Online available at https://led-ld.nichia.co.jp/en/product/lighting_h6.html, last updated on 13 Oct 2022, last accessed on 13 Oct 2022.

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

OSRAM (2019): Feedback to the 1st Oeko Clarification Questionnaire on the OSRAM Exemption Renewal Request for the use of Cadmium in Quantum Dot LEDs for Display applications, Renewal Request to renew Exemption 39(a) under Annex III of the RoHS Directive 2011/65/EU: Cadmium selenide in downshifting cadmium-based semi-conductor nanocrystal quantum dots for use in display lighting applications (< 0,2 µg Cd per mm2 of display screen area), 13 Mar 2019. Online available at https://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_15/3rd_Consultation/clarification_OSRAM_Ex_39a_appl_1_RoHS15_20190313.pdf.

Osram GmbH (2022a): RE: Stakeholder contribution. eMail with Oeko-Institut e.V., 31 Oct 2022.

Osram GmbH (2022b): Stakehodler contributions to RoHS Cd QD Review 2022 - clarification questions. eMail with Oeko-Institut e.V., 5 Oct 2022.

Osram GmbH (2022c): Stakehodler contributions to RoHS Cd QD Review 2022. eMail with Oeko-Institut e.V., 30 Sep 2022.

A.1.0 Appendix 1: Explanation of OSRAM as to definition of on-chip and how the interpretation of this term affects the amount of Cd that can be applied per display application

This section is from (Osram GmbH 2022). It is noted that it is easier to follow in the context of the differing information provided by Nanosys and OSRAM as to the potential content of Cd in QD QD display on-chip applications.

<u>Definition for "on-chip" configuration and for "homogenous material</u>

In our understanding "on-chip" means that the conversion material is already applied to the chip and being part of the LED before the whole LED is placed into a device.

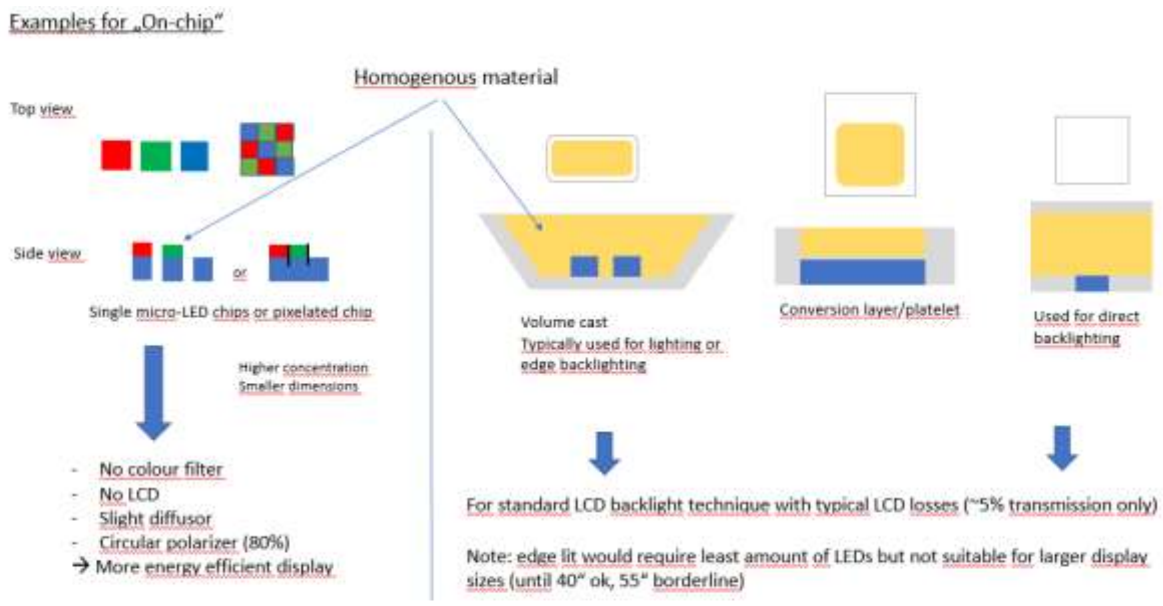


Figure 1: Several package types for conversion

For the exemption for display and projection we calculated the amount of Cd that will be needed for full conversion in a highly concentrated layer as depicted in Figure 1 with the idea of a usage for augmented and virtual reality. For lighting we use different packages with a kind of cast in different configurations. There, we don't have full conversion, i.d. less amount of converter material, lower concentrations but higher volume. These and similar devices can be used for LCD backlighting as well, right side in fig. 1.

The total amount of Cd in such devices needed for LCD display is lower as there is no full conversion. The calculation 5µg/mm² chip surface will take the total amount of Cd within one package and the total chip surface (blue part in pictures). The calculation with <1mg Cd per 55" TV was done with such kind of devices. For larger TVs the amount will increase.

The homogenous material will be the red, green, or yellow part in fig.1, see also enlarged in fig.2.

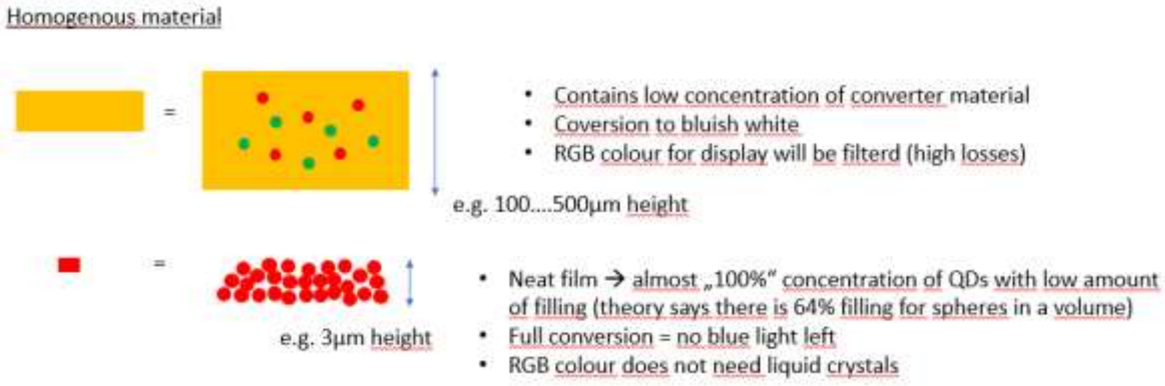


Figure 2: Explanation for homogenous material

As µLEDs can be used as well for TV screens, we did the calculation for this as well. Especially, as the numbers Nanosys provided are astonishingly high.

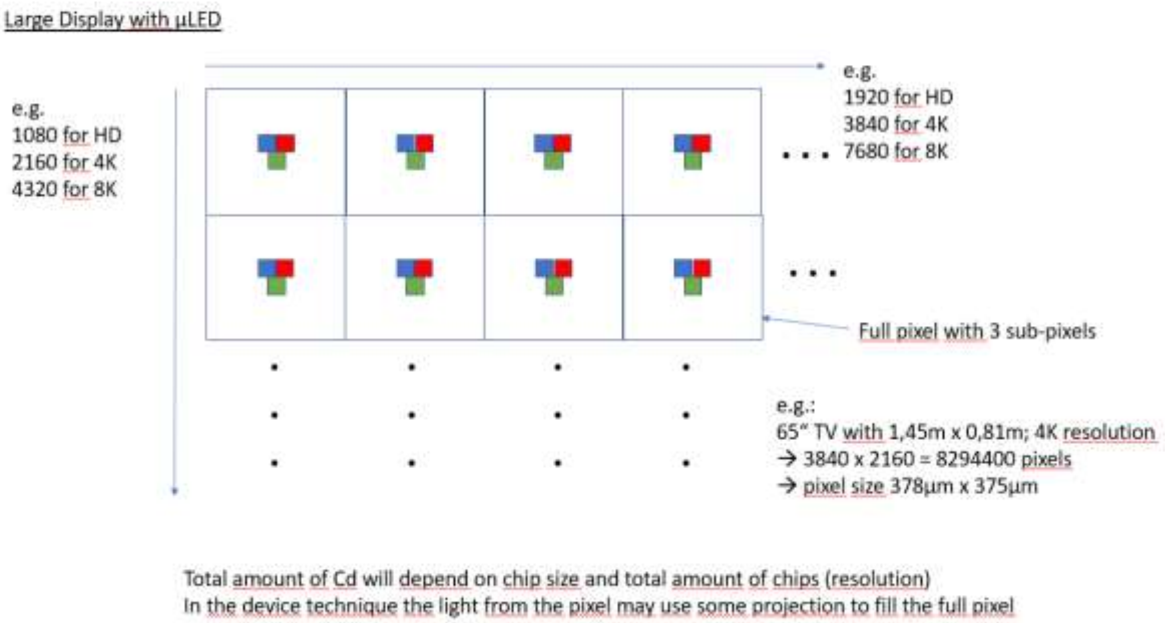


Figure 3: schematic drawing of µLEDs for display application.

We (OSRAM) realized that they (NANOSYS) did some assumptions to come up with 0,15-0,25µg/mm² without specifying the area which is below the amount of 5µg/mm² per chip area (top surface of the blue part in fig.1) that we found. However, to come to *the total amount they take the full display screen area as it is the case for "on-surface" technology. This is certainly wrong in our understanding. The clue with the use of µLEDs is the fact that one has a very tiny chip or pixel of each colour (3 sub-pixels) for each full pixel (fig. 3). Furthermore, only red and green pixels are covered with quantum dots.*

Full conversion LEDs will need a higher amount of Cd compared to the LEDs for LCD technique but they are self-emissive. Inefficient LCD technique is obsolete here enabling the chance for much more energy-efficient devices (table 1, details for µLED in table 2). LCD devices have losses in transmission of ~ 95% whereas self-emissive displays have a transmission of 80%, i.e. 20% loss. The amount of Cd in µLED converted displays is dependent on the chip size and the amount of chips, the latter determining the resolution (table 2).

Table 1: Comparison between LCD and µLED

Comparison of LCD and µLED display technique

	LCD technology	µLED technology
component	e.g. 	
Degree of conversion	Bluish white	Full conversion red and green
Light emitting surface	Top surface of blue chip (e.g. 0,45mm²)	Top surface of blue chips for red & green converted light (≤ 10µm edge)
Required amount of Cd	e.g. <1mg for 55"	10 (< 8K) - 20mg (≥ 8K)
Energy aspect	LCD transmission 2-7%	Transmission through polarization filter ~ 80%

Table 2: Calculated amount of Cadmium for different resolutions

Self-emissive µ-LED display

µ-LED	HD 1920x1080	4K 3840x2160		8K 7680x4320		
Total amount of screen pixels	2073600	8294400		33177600		
sub-pixel edge size	10µm	10µm	5µm	7.5µm	5µm	2µm
Total light emitting chip area (RGB)	622,08 mm²	2488,32mm²	622,08 mm²	5598,72mm²	2488,32mm²	398,1312 mm²
Converted chip area (RG)	414,72 mm²	1658,88 mm²	414,72 mm²	3732,48 mm²	1658,88 mm²	265,4208 mm²
Total amount of Cd	2,0736mg	8,2944mg	2,0736mg	18,6624mg	8,2944mg	1,327104mg

The configurations in table 2 are in technological development which is challenging. Prototypes of TV screens with much larger chips have been demonstrated by other companies at the Display Week 2022. For high resolutions as 8K pixel and chip sizes need to shrink. One might think about using much larger chips (miniLEDs) and convert them, especially if development is slow and µLEDs might be not bright enough at current *state of development. In our opinion, the use of miniLEDs is not favoured because of high costs on one hand and conversion by Cd-containing quantum dots on chips > 100µm could be replaced by the use of direct emitters on the other hand. To avoid high amounts of Cd on large chips we fully agree with the approach to limit the total amount of Cd per device to the necessary amount.*

Comments on other configurations mentioned by Nanosys:

QD conversion for OLED displays:

The configuration is not considered as an on-chip technique as there is an OLED backplane and a separate frontplane with the red and green conversion areas. It is not a homogenous sheet as other "on-surface" technologies, but it is certainly a conversion unit in screen size.

We think that the total amount of Cd is overestimated in Nanosys' calculation as well, as there are distances between red and green sub-pixels, and blue is not converted. Still, around 30-50% of the total screen area is converted on surface (~200-300mg); much more than for the direct use in "on-chip" configuration.

Electroluminescent QD displays:

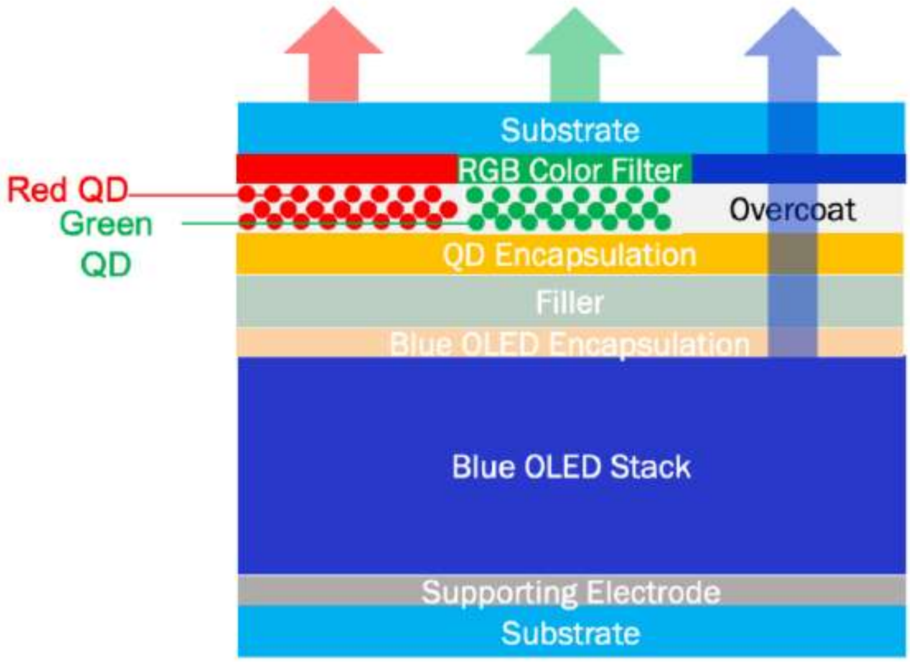
This is an interesting research approach where CdSe as well as InP quantum dots seem possible. We consider both material groups to be still in development for this implementation. CdSe is more mature but far from commercialization. Efficiency and reliability are challenging.

The layers needed are certainly thin but with all colours full screen area is needed. We assume that ~0,05µg Cd/mm² screen area, resulting in < 60mg Cd for a 65"TV. This is 10 times more than Nanosys estimated. Within the next five years there should be a more clear picture on this".

A.2.0 Appendix 2: Direct view technologies

Direct view technologies can be differentiated from transmissive technologies. The latter includes a single homogenous QD matrix for all pixels, whereas the former requires the QD matrix to be homogeneous on pixel or sub-pixel level as the pixels or sub-pixels emit light individually. For example, for QD-OLED the backlight of each pixel is blue with red and green QD matrices for two of the subpixels. The schematic drawing in Figure 1 shows the arrangement of quantum dots on top of the blue light emitting background for OLED technologies. It is understood that Nanosys also calls this configuration "on-chip", whereas Osram does not. Indeed, the QD are not inside the LED package, but inside a layer close to the package with the same size and pattern as the packages.

Figure 1: **Schematic drawing of QD colour conversion on OLED**



Source: Nanosys Inc. (2022)

For microLED each subpixel consists of a light source and one QD matrix, either red, green or blue. In the interview with Nanosys, direct view technologies were described as on-surface but similar to on-chip, as these films do not form a homogeneous matrix across all pixels but have the size of the LED package. "*QD-OLED displays use a blue OLED emitter to generate light combined with a layer of inkjet-printed red and green QDCC [*Quantum Dot Colour Conversion*] materials. Each pixel contains three subpixels, one that is clear to pass through blue light, one with green QDCC to down convert blue into green, and one with red QDCC to down convert blue into red. QD-OLED is quite similar to on-chip LED applications in that the QD's must be patterned [across the whole display], are placed very close to the emitter, and must down-convert essentially 100% of the blue light to achieve good colour and efficiency performance. One example is the QD-OLED display sold by Samsung Display Corporation which uses HMF [heavy metal free]-QD for "on-chip" colour conversion*." (Nanosys Inc. 2022).