19 November 2018

LightingEurope Feedback to the 1st Oeko Clarification Questionnaire on the LightingEurope Exemption Request for the use of Cadmium in Quantum Dot LEDs for Lighting Applications

Responses to clarification questions:

1.

a. Why is the CRI threshold proposed as 80 instead of higher?

The general lighting market is mainly split between CRI 80 and 90, with ~70% CRI 80 and 10-15% CRI 90 LEDs [Yole report: Phosphors and Quantum Dots, 2017]. Although the advantages provided by the inclusion of QDs is greater for CRI 90, the technology can also be applied to raise the efficiency of CRI 80 by a significant amount. Efficacy gains for CRI 80 of >10% and CRI 90 >20% are achievable if the limitation on Cd ppm is raised to 1000, making the cumulative positive effect of Quantum Dot converters in CRI 80 LEDs even higher than that of CRI 90 LEDs.

b. Why does the exemption wording refer to CRI only instead of CRI, R9, etc? (ie why not limit it further)

The use of Cd-based Quantum Dot converters does not create any benefit below a certain CRI and at cool white color points. Also, negative R9 values do not make sense for these high-color-quality LEDs. Therefore, a limit to CRI>80 with R9>0 and CCT <6500K can be considered.

c. What is the scientifically accepted standard for specifying the quality of light, in particular when a warm light is targeted?

Metrics employed today in the lighting industry are Color Rendering Index (CRI) and R9 for warm light in particular (see above). In the scientific world, there are many proposals for improved metrics. Modern metrics always define several quality parameters for different (competing) targets like accuracy of rendering versus color preference or color gamut. Currently the most popular of these is the TM-30 metric. However, as yet there is no commonly accepted scientific standard beyond CRI and R9.

2. Clarify the term “luminous efficacy”:

Luminous efficacy is a measure of how efficiently a light source produces visible light. It is the ratio of luminous flux to input electrical power, measured in lumens per watt of energy used.

3. **The application specifies that "The broad spectrum of conventional red phosphors causes a large drop in luminous efficacy as the emission further reaches deep red and infrared wavelengths" (LE 2017). This phenomena is understood to result in a "waste" of energy.**
    a. **Please confirm understanding and provide data/figures to clarify the relationship between broad spectrum and energy loss.**

The luminous efficacy of a light source consists of 2 different parts:

1. The amount of electrical energy converted to light energy ("Wall-Plug Efficiency", WPE). This can be expressed by a simple percentage (e.g. 55% of electrical energy is converted to light energy)
2. The overlap of the generated light spectrum with the human eye response curve (green curve in Figure 4 of the LightingEurope exemption application, see below). This so-called "Luminous Efficiency of Radiation" (LER) is measured in Lumens per (optical) Watts. It defines how large the brightness impression on the human eye is per amount of light energy, so to say "how visible the light is".

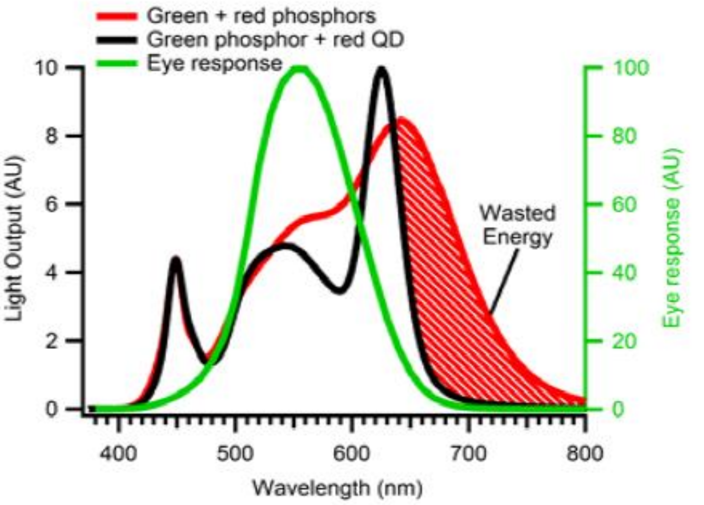

Figure 4. LED light output from downconverting phosphor systems. The red curve is a two phosphor system, the black curve consists of the same LED chip, the same green phosphor, but replaces the red phosphor with a red QD. The green line indicates the human photopic (eye sensitivity) response (right axis).

The total luminous efficacy is the simple multiplication WPE x LER, measured in Lumens per (electrical) Watts.

Since the conversion of blue to green and red photons is already very efficient, innovation in converter materials mainly acts on the second part: when generating a spectrum with better overlap with human eye sensitivity, the generated photons will be more "visible", generating a higher LER without changing the Wall Plug Efficiency. Figure 4 shows that for the same LED (same WPE) and same color point and color quality, a much higher overlap with the eye response curve can be generated with Quantum Dot converters (black curve) than with conventional phosphors (red curve). The difference between the black curve and the red curve at low eye sensitivity (red hatched region) can be considered “wasted” in this context.

The quantitative reduction of “wasted” energy can be seen in table 5 of the SEA (copied below), where the energy usage during use (line 3) is directly related to improved LER.

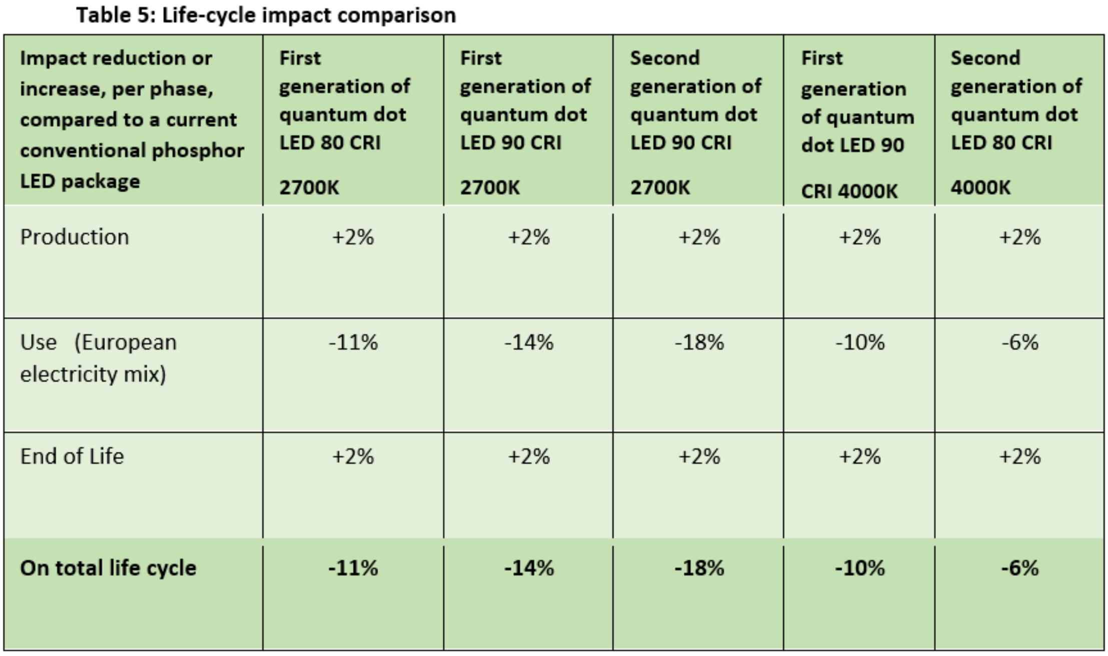

Table 5: Life-cycle impact comparison

Impact reduction or increase, per phase, compared to a current conventional phosphor LED package	**First generation of quantum dot LED 80 CRI 2700K**	**First generation of quantum dot LED 90 CRI 2700K**	**Second generation of quantum dot LED 90 CRI 2700K**	**First generation of quantum dot LED 90 CRI 4000K**	**Second generation of quantum dot LED 80 CRI 4000K**
Production	+2%	+2%	+2%	+2%	+2%
Use (European electricity mix)	-11%	-14%	-18%	-10%	-6%
End of Life	+2%	+2%	+2%	+2%	+2%
On total life cycle	**-11%**	**-14%**	**-18%**	**-10%**	**-6%**

b. Explain how luminous efficacy relates to CCT and CRI, with specific light source examples

There are two concurring effects that determine the dependence of efficacy versus CCT:

1. Lower CCTs (warmer colors) require a higher degree of conversion and conversion-related losses (especially Stokes-Shift = energy difference between absorbed blue photon and emitted converted photon), reducing the efficacy when moving towards warm white
2. The maximum achievable LER depends both on the CCT and the CRI requested (see graph below). A detailed analysis of achievable LERs can be found at [Julia M. Phillips et al: “Research challenges to ultra-efficient inorganic solid-state lighting”, Laser & Photon. Rev., 1–27 (2007)].

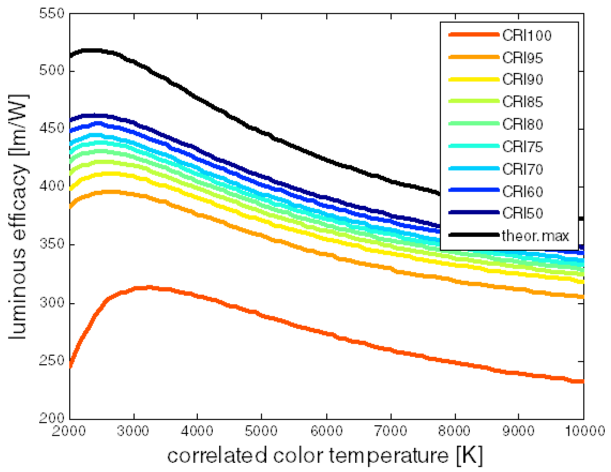

Figure: Maximum achievable LER for different CCTs and CRI (OSRAM in-house calculations)

Combination of both effects gives approximately the following relation (normalized to 4000K CRI 80):

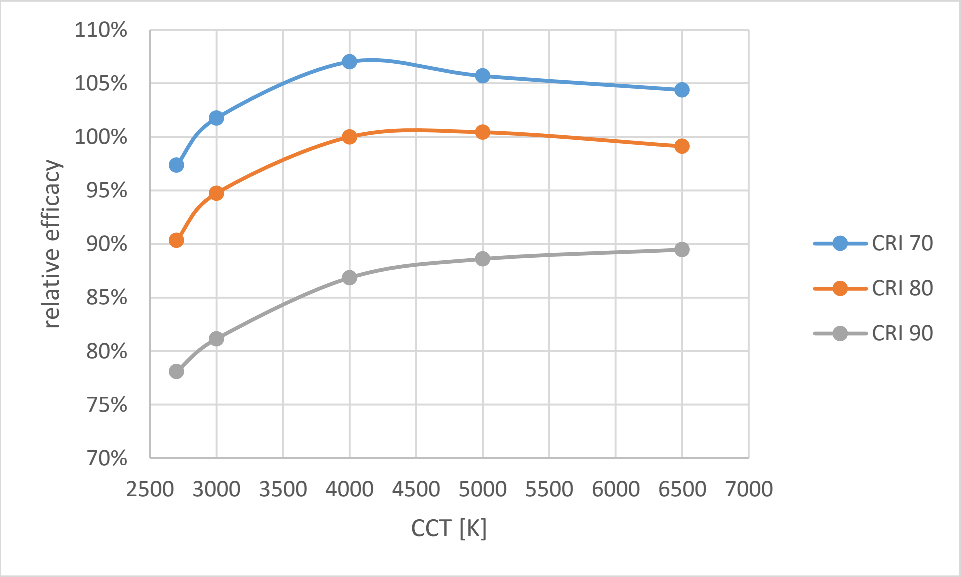

Figure: typical relative efficacies between different CRIs and CCTs (OSRAM in-house data based on typical phosphor systems)

4. Comparisons of CdQD light sources to other typical LED light sources

a. Compare CdQD LEDs with conventional technologies on the system level, ie comparison of CdQD LED based luminaire with discharge lamp-based luminaires

i. If relevant discuss the phase out of conventional technologies

ii. Compare the following: luminous efficacy, energy consumption, total content of RoHS restricted substances

The relevant comparison for general lighting is the comparison of a CdQD LED versus a best in class Cd-free LED (traditional phosphor-converted LED) as presented in Table 5 of the SEA (see above). CdQD LED can be used in any light source e.g. in an LED retrofit lamp or in an LED luminaire or in non-lighting applications, therefore a system-level comparison will always be reduced to a comparison on LED level.

LED technology	Luminous efficacy	Energy consumption	Total content of RoHS substances
Cd-free LED	100 %	100%	< 0.01% in homogenous materials
CdQD	+10-20 %	-10-20%	< 0.01% in homogenous materials + < 5 µg Cd per LED

Remarks: (for more information, please turn to page 11 for details on the Cadmium emissions)

Amount of Cadmium:

The total absolute amount of Cadmium used for CdQD LED in the production process can be calculated (within a certain variance) from the used raw materials. The concentration in the raw material is requested to be allowed to be up to 0.1%. The total amount for a typical mid-power LED is estimated to be 1.61 microgram (depending on size and light quality).

The content (percentage) in the "homogenous material", which is the relevant factor for the threshold limit, is much more difficult to be estimated. This is due to the small size of the component and the overall small total amount. It is depending on the production process on the one side (= processing of raw materials during production) and on the dismantling process on the other side ("*separated into different materials by mechanical actions such as unscrewing, cutting, crushing, grinding and abrasive processes"* according RoHS Directive).

Possible contamination within RoHS conformity:

The RoHS limit for Cadmium is 0.01% in homogenous materials. So it can be that a 100 gram plastic part of a luminaire contains 0.005 % Cadmium compounds (e.g. in pigment), which is 5 mg and still the part conforms with RoHS, while an LED containing 0,01 mg Cd but exceeding 0.01% in the homogenous luminescent material does not conform.

A 1 kg luminaire could theoretically contain up to 100 mg Cadmium if equally distributed among all homogenous materials of the product and is still conforms with RoHS.

Resource Efficiency:

The improved efficacy of Quantum-Dot containing LEDs can be used for different targets:

- Using the CdQD LED with increased luminous efficacy of 10-20%. Then, energy is saved and correspondingly fewer LED are needed.
- Fewer LEDs require lower power consumption and produce less heat. Then, less materials are needed for cooling measures as well as for ballasts.
- Reduced operating temperature due to less heat production leads to higher lifetime of the component and thus the whole luminaire.

5. **In can be understood that the CdQD on-chip configuration is viable for all Exemption 39 areas (lighting + display). It can also be understood that on-chip configuration has significant advantages over other configurations**

Surface/edge applications are only available for the display market; there is no significant market penetration for use of QD materials in lighting other than directly on-chip.

   a. **Please specify the parameters and provide comparative data for on-chip vs surface/edge applications. Possible parameters to compare: Total Cd usage, economic viability (system cost),**

As explained above, this comparison is not relevant as surface/edge applications are not relevant for lighting applications.

   b. **Please explain whether surface and on-edge should be excluded or not.**

Yes, it should be excluded. Both because it is not economically viable to use surface/edge configurations in lighting and in the spirit of narrowly targeting specific applications where the greatest benefit is achieved for the least amount of Cd.

6. **Please specify what LED applications applying CdQD configuration are already market-ripe**

A member company of LightingEurope will release products containing Cd-based QD materials in the next few months and have confirmed that these could be easily modified to realise much higher efficiency gains (up to 3 times higher) if this exemption were approved.

7. **It can be understood that different compounds can be used in the production of CdQD (CdSe, CdS, alloys). Does the compound used affect the contents of the Cd in the LED on-chip configuration or the performance of the light source in terms of spectral output, energy consumption, etc?**

The compounds used in the production of the Cd-based quantum dot materials do affect the conversion efficiency (quantum yield) and reliability of the QD materials, and therefore affects the optical output and reliability of the LED which incorporates the QD materials. The Cd-based QDs which perform on-chip use reagents based on Cd, Se, S, and Zn precursors, and the outcome is a specific combination of CdSe, CdS, and alloys of Cd/Zn/S/Se. However, it is not possible to atomically map the structures and understand the exact metal and chalcogenide distribution, therefore the exemption should list only Cd metal, which can be measured. The use of these compounds in this arrangement does affect the amount of Cd in the LED, since more QDs (and hence more Cd) are needed to achieve the same color point and luminous efficacy if the performance is worse, and fewer QDs (less Cd) are needed if the performance is better.

8. **Thermal quenching is understood to be of relevance in the on-chip application, for example shortening the LED lifetime if waste heat is not dissipated. Does this sensitivity also apply to LEDs using QDs, or do LEDs using Cd-based QDs have an advantage in this respect?**

LEDs using QDs are also sensitive to thermal stresses, and the lifetime can be shortened if excessive heat is present at the LED level. Cd-based QDs do not confer an advantage to the LED in this respect, reliability of the Cd-based QDs under heat stress is very similar to red phosphors. However, LEDs incorporating QDs have a higher efficacy which would allow for driving the parts at lower current while maintaining lumen output, and therefore would extend the lifetime of the LEDs.

9. **In the application, the answer for question 4a1 (page 8) is not clear, what is meant by 1 in this context? 4A1 is "To which EEE is the exemption request/information relevant?" and the number 1 is listed.**

This was a typo and has no meaning.

10. **In the application document the answer for 8(a)2 (page 18) is not clear.**

8 (a) 2 is asking for the REACH relevant information. The answer is "NA Material will be below 1 metric ton". This statement is understood to mean that REACH registration is not required for this material because less than 1 metric ton per year will be imported into the E.U. Any article (LED package) contains far below 1000 ppm of a Cd-containing SVHC. One LED package contains typically less than 5µg of Cd. A 60W replacement lamp contains typically 7-8 LEDs, resulting in <40 µg Cd per lamp.

11. **As part of the evaluation, socio-economic impacts should also be compiled. LE has submitted a socio-economic analysis but it is not released for publication. Assuming this document is to remain confidential, please provide information on:**

    a. **Possible impacts to employment in a scenario where the exemption is not granted, and specify manufacturers impacted**

We do not see a short- or mid-term direct impact here. The technology is an innovation which can provide significantly higher efficiency for LED. In case the technology increases the change from conventional technology to solid state lighting positive indirect effects are possible.

b. Please specify impacts in terms of additional costs for various sectors if the exemption is not granted

Below you may find an overview of various segments that may be impacted from a socio-economic perspective:

Environmental and health impacts

This section aims to quantify in monetary terms the costs that are related to the use of cadmium in semi-conductors for lighting applications. To assess society's benefits in the exemption scenario, we analyse the emission of carbon dioxide (one driver for climate change) that can be attributed to the energy consumption that is related to lighting and quantify its economic burden. Further, we evaluate cadmium emissions. In order to provide a full picture, we do not only consider cadmium that is contained in semiconductor material but also cadmium emissions that occur during the energy production. In addition to environmental impacts, we analyse health impacts, and this section also contains a discussion of the conducted life-cycle analysis.

Greenhous gas emissions (environmental)

LED technology that uses cadmium as semiconductor material can help to fight climate change because it reduces the energy use that is related to lighting. Therefore, harmful greenhouse gas emissions can be reduced. In order to monetize this environmental impact, the price of one tonne of carbon dioxide (CO_2) has to be determined. This price should represent the estimated damages associated with a marginal release of CO_2 in to the atmosphere during one year. According to the Intergovernmental Panel on Climate Change (IPCC), the carbon price is defined as: "*The price for avoided or released carbon dioxide (CO_2) or CO_2-equivalent emissions. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic cost of mitigation, carbon prices are used as proxy to represent the level of effort in mitigation policies*."[1]

Several studies have estimated the price of carbon and the results vary significantly. The values vary between few to over 1000 US Dollars per tonne. We decided to present three values used by authorities and well cited university studies and use the mean to calculate the price of carbon:

1. European Emission Allowance Auction price 6.90 EUR per tonne of CO_2 (8th September 2017).[2]
2. A recent U.S. government study estimates the costs of carbon to be $ 36 per tonne of CO_2 (2015).[3]

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[1] IPCC, 2014: Annex II: Glossary. In: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp. 117-130. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_Glossary.pdf

[2] European Energy Exchange (EEX), EU Emission Allowances: Primary Market Auction, available at: https://www.eex.com/de/marktdaten/umweltprodukte/auktionsmarkt/european-emission-allowances-auction--eua----global-environmental-exchange/47312#!/2017/09/11

[3] Interagency working Group on Social Cost of Greenhouse Gases, United States Government, Technical Support Document: Technical Update for the Social Cost of Carbon for Regulatory Impact Analysis, Available at https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

3. The Stern review suggest that the social cost of carbon is in order of $ 87 per tonne of CO_2 (2006).[4]

The following table summarizes the social cost of carbon per tonne of CO_2 and converts all values to EUR 2017.[5]

Table 1: Carbon price

Price of carbon per tonne of CO_2			
Study 1			**2017**
			6.90 €
Study 2	**2015**	**2017**	**2017**
	36.00 $	37.18 $	30.95 €
Study 3	**2006**	**2017**	**2017**
	87.00 $	105.64 $	87.93 €
Average[6]			**41.93 €**

To assess how many tonnes of carbon can be avoided, in case of a granted exemption, we need to understand how much LEDs containing cadmium will be sold in the coming five years. As cadmium-containing quantum dot (QD) LEDs are a new technology, it is difficult to estimate sales in the coming five years with certainty. It is expected that in the first years, cadmium containing QD LEDs will be demanded by users that require a high quality of light. We will explain those uses in more detail in section 3 below. A broader market penetration will be achieved as of the third year when prices of QD LED are expected to come down further.

The following table outlines the expected market penetration.

Table 2: Expected market penetration

Year	2018	2019	2020	2021	2022
Total Light Output EU (in TLm[7])	10.77	10.77	10.77	10.77	10.77
Expected market penetration	**1%**	**1%**	**2%**	**2%**	**5%**
Light output Cd QD LED (in TLm)	0.1077	0.1077	0.2154	0.2154	0.5385

In case the exemption is being granted and under the above described assumptions regarding the market penetration in the EU, reductions in electricity consumption would occur and with that a reduction in CO_2 emissions. In case LED technologies using

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[4] Stern, N. (2006): Stern Review on the Economics of Climate Change, *HM Treasury*, London.

[5] Using an inflation calculator (available at: http://www.usinflationcalculator.com/) and the conversion rate of 1 USD=0.8324 EUR, according to http://www.xe.com/de/currencyconverter/convert/?Amount=1&From=USD&To=EUR (applicable on September 11th 2017).

[6] (6.90 + 30.95 + 87.93)/3 = 41.93

[7] TLm = tera Lumen

cadmium based semi-conductors were not to be excluded from the RoHS Directive, we assume that the market share would be taken by conventional LEDs, and cadmium-based technologies in the lighting market would disappear. This would mean that the EU would lose the additional CO_2 reduction inherent in the use of cadmium based lighting and the EU would not benefit immediately from the increased efficiency. This would also mean that CO_2 emissions would be higher for the case that a Cd exemption is not granted.

The following table summarizes the power savings that can be achieved in the coming five years, in case cadmium based QD LEDs partially substitute conventional LEDs.

Table 3: Cumulative power savings[8]

Year **(expected market share)**	**Total power consumption per year in GWh[9] QD LED**	**Total power consumption per year in GWh Conventional**	**Total power savings per year in GWh[10]**	**Cumulative power savings in GWH until 2022 in GWh[11]**
2018 (1%)	805.65	946.99	141.34	706.70
2019 (1%)	805.65	946.99	141.34	565.36
2020 (2%)	1611.29	1893.98	282.69	848.07
2021 (2%)	1611.29	1893.98	282.69	565.38
2022 (5%)	4028.24	4734.94	706.70	706.70
Sum				**3392.21**

To calculate the overall cost of carbon that are related to an exemption of LED technology from the RoHS Directive, we compare the additional CO_2 emissions that occur under the exemption scenario with the emissions that occur under the non-exemption scenario. In 2018, an exemption of Cd QD LEDs would lead to a replacement of 1% of conventional LED with cadmium-based LEDs. This would translate into a decrease of 141.3 GWh. The electricity savings are expected to be up to 706.7 GWh in 2022. **An exemption for the coming 5 years would in total translate to power savings of about 3,339.2 GWh.**

If we take the German energy mix of 2016 as a reference value, 1 avoided kWh results in a reduction of 0.527 kg of CO_2 emission[12]. Thus, in order to calculate the social costs of carbon, we take the above stated electricity reduction of 3,392,200,000 kWh and translate it into reduced CO_2 emissions for the coming 5 years:

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[8] The power consumption and power savings data are derived from the calculations provided in the Exemption Request form, see section "*Performance improvements based on a reference LED package*" and "*Total energy savings and total cadmium use by means of transition scenarios*".

[9] GWh = Giga Watt hour

[10] Total power savings = Total power consumption per year in GWh Conventional - Total power consumption per year in GWh QD LED

[11] Total power savings * number of years until 2022

[12] Umweltbundesamt (2017): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 – 2006, available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2017-05-22_climate-change_15-2017_strommix.pdf .

$$3{,}392{,}200{,}000\ \mathrm{kWh} * 0.527\ \frac{kg\ of\ CO_2\ emissions}{\mathrm{kWh}}$$

$$= 1{,}787{,}694{,}670\ kg\ of\ CO_2\ emissions$$

$$= 1{,}787{,}695\ \text{tonnes}\ of\ CO_2\ emissions$$

Multiplying this value, with the average price for carbon of 41.93 EUR (derived in Table 1 above), we expect that the **European society will save 75 million EUR[13] due to reduced CO_2 emissions**.

When we take the European Emissions Allowances Auction price of 6.90 EUR per tonne of CO_2 emission, the most conservative study, as our reverence value, the expected savings for the coming years are expected to be more than 12 million EUR.[14]

Cadmium emissions

The exemption request is for LED lighting applications that use cadmium as semiconductor material. Cadmium is a by-product of the extraction and smelting of zinc, lead and copper.[15] Thus cadmium is produced independently of its use in the lighting industry. Furthermore, the amount of cadmium needed for one LED is expected to be 1.61 microgram (1.61 10^{-06} gram). Even if the entirety of lighting in Europe would be provided by Cd QD LEDs, less than 163 kg of cadmium per year would be necessary to cover the demand.

During normal operating conditions, cadmium LEDs generate electricity without cadmium emissions (see life-cycle analysis for a more detailed information). In non-routine circumstances (e.g. catastrophic events like fires or earthquakes), potential cadmium emissions remain well below human health screening levels. As cadmium is a hazardous substance, environmental releases of cadmium should be minimized. However, as depicted below, the majority of the yearly cadmium emissions in Europe relate to cadmium impurities in fertilizers and the emissions to air from fossil fuel power generation. Only 0.03% of the recorded emissions are related to industries, which are deliberately using cadmium and its compounds (e.g. battery manufacturers, steel processors and the electronics industry, including the use in LEDs).

Figure 1: Yearly emissions and deposition onto soil of cadmium and compounds[16]

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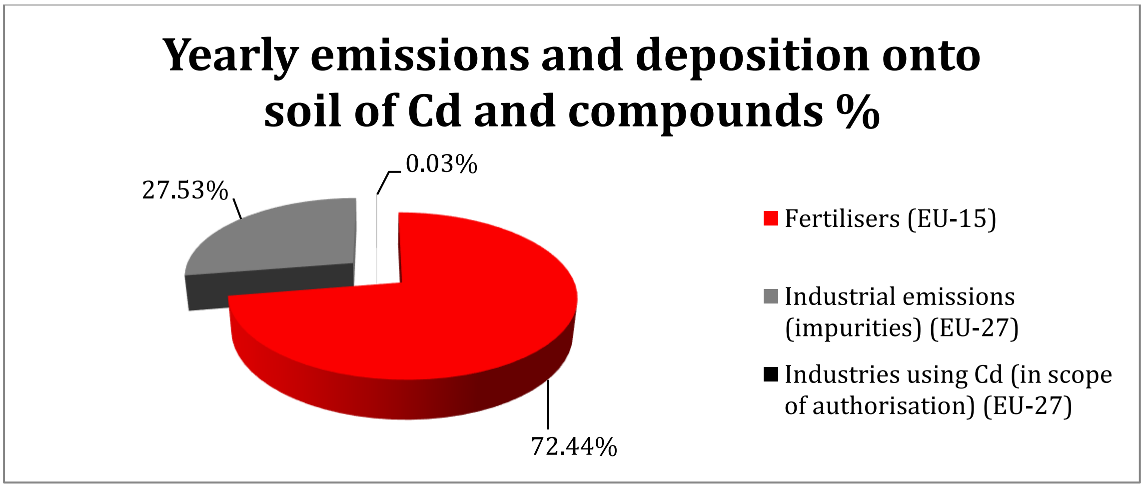
[13] 41.93 EUR/tonnes $CO_{2\text{-eq}}$* 1,787,695 tonnes CO_2 = 74,954,086 EUR.

[14] 6.90 EUR/tonnes $CO_{2\text{-eq}}$* 1,787,694.7 tonnes CO_2 = 12,335,093 EUR.

[15] See for example: http://www.cadmium.org/introduction .

[16] Source: Cd REACH Consortium (2014): Prioitisation Scoring for Cadmium Metal, CAS Nr. 7440-43-9.



The safe use of cadmium in LEDs thus not only provides a reuse for primary cadmium, but also effectively reduces the emissions of cadmium to the air as less electricity is consumed than with conventional LEDs. In view of all of the above, a future low demand for cadmium, for its use as semiconductor material in LEDs, has been identified as potentially beneficial to the environment.[17]

Table 4: Total amount of cadmium emissions avoided in EU

Year	**Total amount of Cd in LED required in kg**	**Total amount of Cd emission avoided per kWh in µg**	**Total amount of Cd emissions avoided per year in kg**	**Total amount of Cd emissions avoided until 2021 in kg[18]**
2018 (1%)	1.63	3.8	0.54	2.70
2019 (1%)	1.63	3.8	0.54	2.16
2020 (2%)	3.26	3.8	1.08	3.24
2021 (2%)	3.26	3.8	1.08	2.16
2022 (5%)	16.3	3.8	2.69	2.69
Sum		**19**	**5.93**	**12.95**

Taking into account the life cycle emissions related to the use of cadmium in semiconductors of LEDs, the overall cadmium required per LED is very low. Interestingly, the electricity production and distribution were found to be responsible for a large part of the life-cycle emissions of cadmium. The table above demonstrates that an increase in efficiency in lighting due to cadmium-containing QD LEDs will result in a net decrease of cadmium emissions to the environment because most cadmium emissions were indirectly caused by the fossil fuel electricity used in the electricity production processes. No cadmium emissions were found to occur in the use phase of LEDs. Even in the case of

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[17] Cha, K. et al. (2013): Substance flow analysis of cadmium in Korea, *Res Cons and Rec*, Vol. 71; Matsuno, Y. et al. (2012): Dynamic modeling of cadmium substance flow with zinc and steel demand in Japan, *Res, Cons and Rec*.

[18] Total amount of Cd emissions avoided until 2022 in kg = Total amount of Cd emissions avoided per year in kg * number of years until 2022.

accidental fires, since so little cadmium is present in LEDs, no danger to human health is expected.

Health impacts

Consumers

Any potential health impact on European customers of LED technologies that use cadmium as semiconductor material are unlikely to occur as cadmium is safely encapsulated within a solid matrix only destructible at very high temperatures (more than 1000 °C).

Without exposure to the quantum dot there is no health risk. Quantum dot LEDs are not likely to be handled, mechanically treated, or otherwise modified by a consumer in such a way that cadmium could be released. The cadmium element is bound by covalent bonds within the semiconductor material, the semiconductor quantum dots themselves are in turn bound inside a chemically stable silicone matrix cured on top of the LED chip, thus forming an LED package, which is in turn integrated into the final product, so the risk of consumer exposure to cadmium during the use phase is extremely low. Similarly, exposure of consumers to cadmium released to the environment from these products as a consequence of end-of-life or recycling operations is very unlikely.

With the growing use of LEDs and the development of new lighting technologies, many EU citizens are worried that people who have conditions that react to light might be negatively affected by this shift. LED street lighting is claimed to have been associated with reduced sleep and great incidences of obesity. Not all wavelengths of light disrupt bodies at the same level. Short wavelength blue light, which is known to help with alertness in the daytime, seems to be more disruptive at night, and induces the strongest melatonin inhibition. According to SCHEER, “available studies indicate that white-light LEDs can have larger influence on the circadian rhythm compared to traditional light sources, due to their different spectral emission pattern”.[19]. The proliferation of energy-efficient lighting (LEDs) and electronic devices are increasing our exposures to blue light during the night[20]. Therefore, new LED technologies, which allow for a more energy-efficient natural light, should be highly welcomed.

Workers

In production, cadmium can be handled safely so as to pose no risk to workers. Cadmium is already used in various production processes, e.g. for nickel-cadmium batteries, electrical contacts, and filter glass. Adequate measures are in place to safeguard workers in factories. For example, the EU’s Scientific Committee on Occupational Exposure Limits (OEL) for cadmium and its inorganic compounds recommends an OEL of 4 µg/m³ (respirable fraction), based on non-cancer respiratory effects, to protect workers against local respiratory effects of Cd exposure.[21] Furthermore, the industry has extensive experience with handling dangerous substances and has installed the necessary equipment to keep workers’ exposure will below the EU’s recommended OEL limit.

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[19] Preliminary opinion from the Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) on Potential risks to human health of Light Emitting Diodes 10 (LEDs), available at: https://ec.europa.eu/health/sites/health/files/scientific_committees/scheer/docs/scheer_o_011.pdf

[20] Toronto Public Health Briefing Note (2016): Health Effects of LED Street Lighting, available at: https://www1.toronto.ca/wps/portal/contentonly?vgnextoid=4eca7a1ba20c8510VgnVCM10000071d60f89RCRD

[21] Recommendation from the Scientific Committee on Occupational Exposure Limits for cadmium and its inorganic compounds, SCOEL/SUM/136, February 2010. Available at http://ec.europa.eu/social/BlobServlet?docId=6509&langId=en.

Economic impacts

Market overview

Since the invention of the first light emitting diode in 1962[22], researchers have been working on the development of this technology and its lighting efficiency. LED lighting is increasing used in recent years as a result of major policy changes around the world recognizing the importance of reducing carbon emissions, mitigating global warming, and strengthening energy security. The initial penetration was focused on niche markets but with technology improvements the quality of light emitted by LEDs steadily increased, while cost to the end user has steadily declined.

Recent technological achievements suggest that consumers are seeking to enhance their lighting through good quality of light (e.g. high colour rendering, tuneable warm to cool white). The superior quality of cadmium-containing QD LED lighting satisfies this demand without sacrificing efficiency and thus it is likely that its market penetration will increase in the coming years. As the change from conventional phosphor LEDs to Cd QD LEDs is technically relatively straightforward and the new LEDs has been demonstrated to be reliable, prices are expected to decrease in coming years.

The Lighting Industry expects that Cd QD LEDs will first enter markets where accurate colour rendering is of high importance, i.e. when the surroundings should look natural and realistic. The general lighting market can be divided in multiple ways. In their 2012 report McKinsey divides the general lighting market into seven categories: residential, office, shop, hospitality, industrial, outdoor and architectural lighting. High quality of light is not limited to a specific application. Examples of specific applications are provided below:

- bathrooms (to be able to accurately apply makeup, to accurately see the colour of your skin, teeth etc. in the mirror);
- living rooms, dining rooms (to accurately see the colour of food, artwork, people);
- museums (to accurately see the colour of paintings);
- retail/shops (to accurately and appealingly reproduce the colour of objects for sale);
- hospitality/hotels (to appealingly represent the colours of artwork, furniture, and people);
- stadium lighting (to accurately represent the colours of the athletes both to the audience and the TV cameras);
- surgical lighting (to ensure the colours of tissue are accurately represented indicating to the surgeon the oxygenation level of tissue. In this instance high efficiency lighting has added importance beyond simply energy savings; it means the surgeon does not sweat under the heat of the lamps generating the intense light required for surgery).

In cases where it is only relevant to see an object, but not see colour accurately, light can be of a lower colour quality (e.g. in parking lots) and these markets are currently not the main target groups.

Energy efficiency

The efficiency gains from the use of quantum dots are biggest for warm-white, high colour rendering index (CRI) products with a high quality of light, i.e. they are similar to the light from incandescent or halogen lamps commonly used in residential applications. Quality of light is often seen as one of the blocking points for the adoption of new lighting technologies. Slow uptake of compact fluorescent lamps is attributed in part to their poor quality of light when the technology was first introduced to consumers. Poor quality of light

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[22] T. Okon and J. Biard (2015): The first practical LED, available at: http://edisontechcenter.org/lighting/LED/TheFirstPracticalLED.pdf

also risks the slow adoption of efficient LED lighting technologies. Enabling LED products with superior light quality through the use of quantum dots will further accelerate the uptake of highly efficient solid-state lighting technology. The general lighting industry trend is to work on more efficient down converter materials. Introduction of the cadmium QD LEDs is expected to accelerate this trend.

Quantum dots can be made with alternative non-cadmium materials, but the quantum efficiency and reliability have not been resolved in other material systems such as silicon, indium phosphide, lead perovskite, copper indium sulphide, and manganese-doped zinc selenide QDs. In other words, the same energy savings cannot currently be achieved with similar technologies while maintaining product reliability and lifetime. There are also other challenges with alternative non-cadmium materials such as limitations in achieving narrow emission peak width, full tunability of the emission, or insufficient excitation at 450 nm. Finally, new materials such as lead perovskite QDs may have similar toxicity concerns as cadmium-based QDs.

Electricity cost

Lighting appliances play an important role in European households' electricity consumption and therefore technological progress plays an important role for potential energy savings in the coming years. Furthermore, promoting technologies that increase efficiency can increase industries competitiveness. Lighting is therefore part of the European legislation on energy savings (Directive 2009/125/EC [23] on eco-design requirements for energy-related products, Directive 2010/30 EU [24] on indication by labelling and standard product information of the consumption of energy and other resources by energy-related products). The European Commission is also emphasising the importance of developing energy efficient technologies in the Energy Roadmap 2050, stating that *"products and appliances will have to fulfil highest energy efficiency standards."*[25]

Thus, switching to more efficient lighting sources is an important aspect of saving energy. The use of cadmium in LEDs for lighting can reduce the energy consumption by more than 15%, when compared to conventional LEDs. The following analysis is therefore aimed at demonstrating that if an exemption 39 is granted, European households will gain important benefits in terms of reduced energy bills due to expected electricity savings.

The following analysis is based on the following assumptions:

- The analysis concerns the EU market
- The time horizon is 5 years, i.e. the requested exemption period
- The analysed product category is lighting
- The prices of electricity for EU consumers and industry are considered

The average price of electricity in the EU-28 in 2016 for households was 0.21 EUR per kWh.[26] However, the variation of electricity prices varies within the EU, as the following Figure demonstrates.

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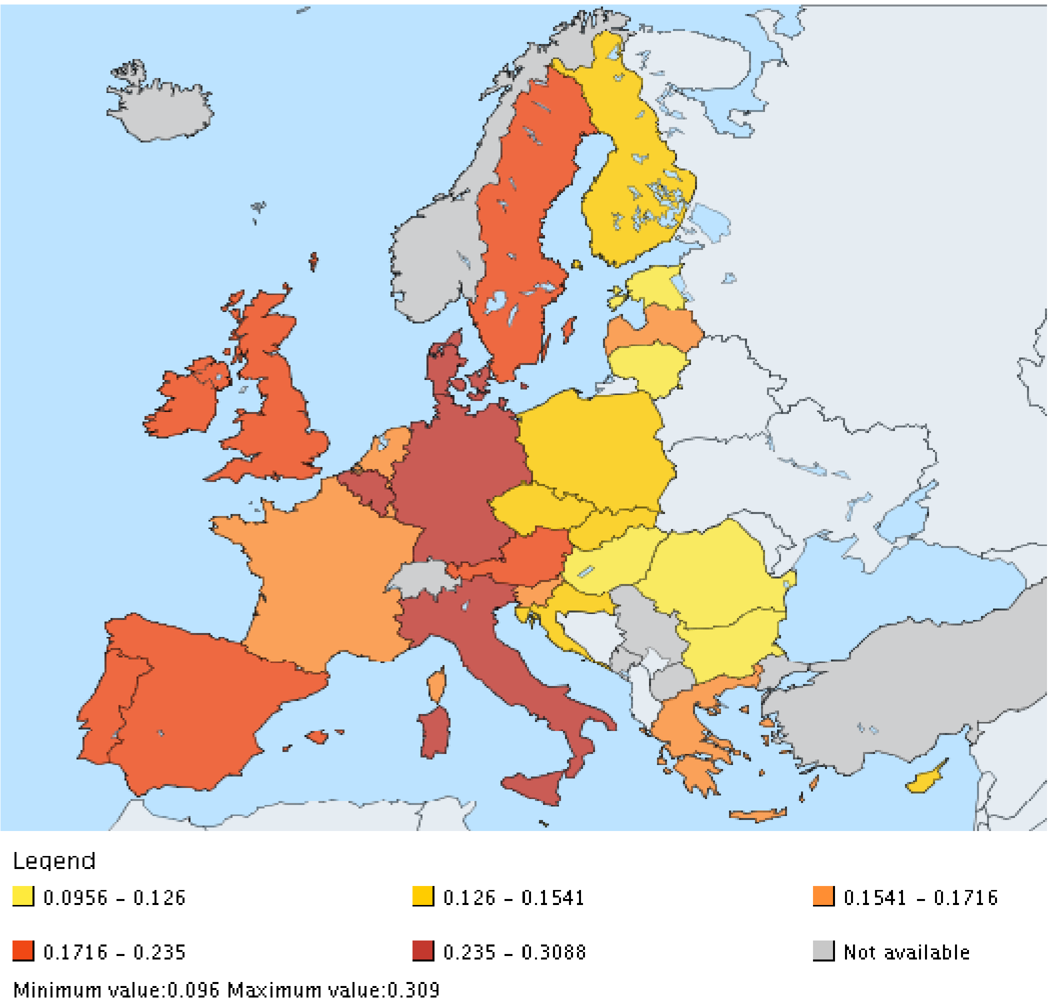
[23] Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0125

[24] Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0030

[25] European Commission (2012): Energy Roadmap 2050, available at: https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf

[26] Eurostat (7th September 2017), available at: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=ten00117

Figure 2: Consumer electricity prices, EUR per kWh, 2016[27]



As calculated in Table 3 above, the cumulative power savings for the EU in the coming 5 years is 3,392,200,000 kWh. Under the assumptions above, this would lead to **energy savings of 696,081,492 EUR for European households for the coming five years**.

The average price of electricity in the EU-28 in 2016 for medium-sized industrial consumers was 0.08 EUR per kWh.[28] The following Figure shows the differences in the EU.

Figure 3: Medium-size industrial consumers, electricity prices, EUR per kWh, 2016[29]

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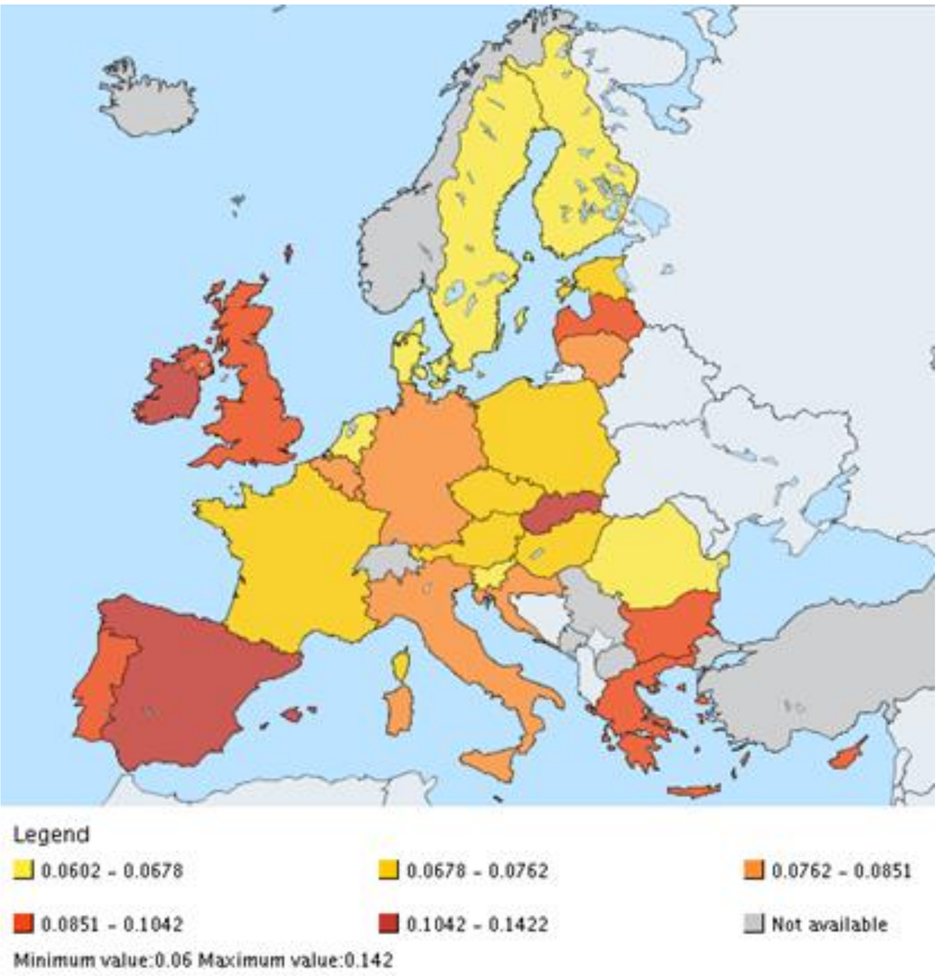
[27] Source of Data: Eurostat, hyperlink to map: http://ec.europa.eu/eurostat/tgm/mapToolClosed.do?tab=map&init=1&plugin=1&language=en&pcode=ten00117&toolbox=legend

[28] Eurostat (20th September 2017), available at: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=ten00117

[29] Source of Data: Eurostat, hyperlink to map: http://ec.europa.eu/eurostat/tgm/mapToolClosed.do?tab=map&init=1&plugin=1&language=en&pcode=ten00117&toolbox=types#



In case the cumulative power savings of 3,392,200,000 kWh would only be for industrial consumers, this would lead to **energy savings of 276,125,894 EUR for the coming five years**.

Note this calculation does not take into account the social cost of carbon, which have been assessed above (Chapter 2.1). In order to integrate the negative impact of CO_2 emissions, the electricity savings (private benefits to European households) can be augmented with a monetary evaluation of carbon and cadmium emissions over the life cycle. Emissions from each of those substances are valued through marginal damage estimates expressed in (EUR/metric tonne). As a consequence, the more a technology pollutes, the higher the total cost of electricity (private electricity cost plus environmental costs). A good proxy for these costs, are the social costs of carbon that have been derived above and the cost of cadmium. Summing up these values demonstrates that European citizens would benefit from an exemption of LEDs.

Research and development

The development of efficient down-converter materials is one of the research and development (R&D) priorities in LED technology. The technical breakthrough of cadmium quantum dot material in on-chip configurations paves the way for developing alternative quantum dot compositions. The exemption for cadmium as written in the original Exemption 39, covering cadmium-based quantum dots for use in lighting, has encouraged the development of QDs compatible with on-chip configuration (used directly in the LED package). After years of R&D, these products have become available on the EU market.

Cadmium quantum dot technology is a stepping-stone in the chase for energy efficiency and superior light quality, until current performance problems with cadmium-free alternatives have been overcome. Cadmium free quantum-dot alternatives fall behind the performance and the stability requirements to reliably increase the efficiency of a white lighting LED up to 20% in combination with a precise control over the light output spectrum.

Research and development is continuing on cadmium-free QD alternatives. The Lighting Industry is committed to phase out cadmium QD materials once reliable cadmium free alternatives become available. The development of efficient, stable, and narrow linewidth down-converter materials is one of the key R&D priorities of the lighting industry.

According to the U.S. Dept. of Energy, "It is already apparent that improvements in LED package efficacy are becoming harder to achieve, and R&D is required to address fundamental technological barriers such as current efficiency droop and the need to develop new high efficiency, narrow line-width down-converter materials."[30]

In order to continue reducing the cost of electricity, and to reach the IPCC deployment targets, different technologies must progress in parallel. This creates sound competition and helps to further reduce costs and increase lighting efficiency. It is therefore of the utmost importance that research and development in this field is supported further. And as the figure above demonstrates, an exemption of Cd QD LED technologies will be needed to increase energy savings, thereby helping to meet decarbonisation objectives.

Comparison and Policy Recommendations

The LED lighting market has been quickly evolving in Europe. This comparably new technology reduces the energy consumption and is therefore helping to reduce negative environmental effects responsible for climate change. Although LEDs exist that do not make use of cadmium as semi-conductor material, the Cd QD technology for which this exemption is requested has significant economic and environmental advantages. Most importantly, this technology has the potential to grow in efficiency and further reduce costs of electricity.

Not granting an exemption for Cd QD LEDs from the scope of the RoHS Directive would prohibit the sale of LEDs containing cadmium compounds above the maximum concentration value tolerated. Paradoxically, including Cd QD LEDs in the RoHS Directive would increase cadmium emissions. Furthermore, a refusal of the exemption would impede the development of a promising technology and slow down efficiency gains.

The results of the cost-benefit analysis conducted in this SEA show that the benefits of using cadmium-based LEDs in the European Union clearly outweigh the costs.

Table 5: Socio-economic impact overview

Impact indicators	Exemption of Cd QD LEDs from RoHS
Environmental impacts	

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[30] US Department of Energy (2015) "Solid-State Lighting R&D Plan", p.3, available at http://www.energy.gov/sites/prod/files/2015/06/f22/ssl_rd-plan_may2015_0.pdf

Carbon footprint	On average EUR 75,000,000 could be saved in the coming five years due to lower carbon emissions
Cadmium emissions	Would decrease substantially
Recycling	LEDs are all regulated under the WEEE Directive
Climate change mitigation potential	Will make it easier to reach European climate goals
Health impacts	
Consumers	Would benefit from reduced carbon and cadmium emission
Workers	Cadmium emissions are below the EU’s Scientific Committee on Occupational Exposure Limits
Economic impacts	
Research and Development	Innovation efforts will likely lead to further energy savings
Private electricity cost	Using cadmium-based LEDs instead of conventional LEDs, the EU society is expecting to save between 276 - 696 million EUR in the coming five years
Total cost of electricity	Total cost of electricity will decrease, due to higher private cost and higher environmental costs.