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Dynamic Life Cycle Assessment of competing Quantum Dots-enabled Consumer Electronics

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Quantum Dots (QDs)

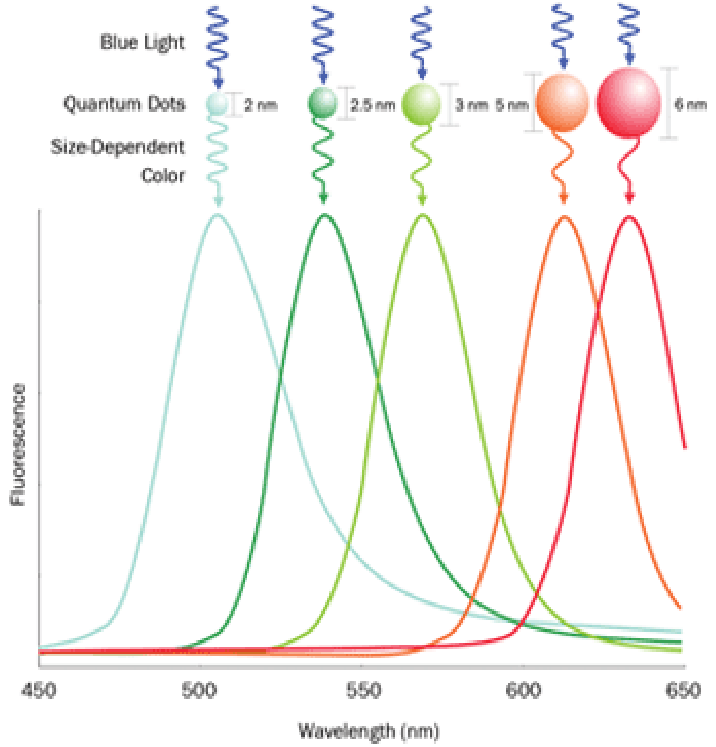
Semiconductor nanocrystals (2-10 nm)

- Exhibit photo- and electroluminescence properties

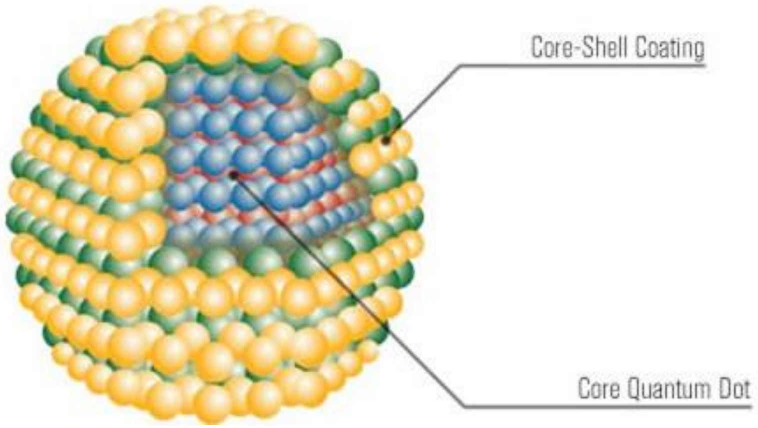
Quantum Confinement effect allows precise tunability

- Group (II-VI) or (III-V) compound semiconductors:

  For example, **CdSe, InP**



Quantum Dot Structure:



Quantum Dot Applications and Market

QD-enabled displays to be worth ~$10bn by 2026

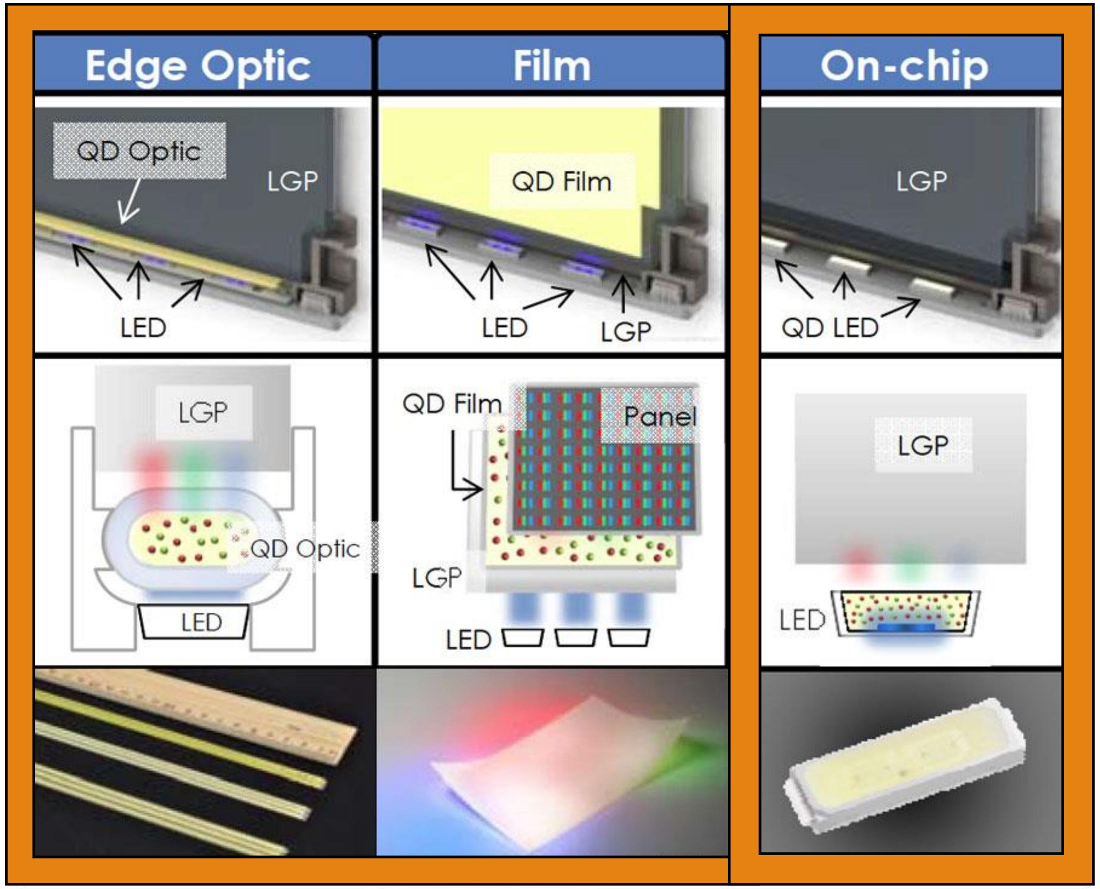
Demand for QDs expected to grow from less than 100 kg/yr at present to several tons/yr

Quantum Dot-Enabled Displays

Different QD display technologies are being developed:

Blue LED provides the source of light

- QDs downconvert to red and green spectrums



Concerns Over Quantum Dot Toxicity

Cadmium Selenide (CdSe) core based QDs preferred for displays

- High color gamut, color accuracy and quantum yield, but toxic

Firms disagree on need for cadmium quantum dot technology

14 October 2015 / Europe, Electrical & electronics

Consultation opens on cadmium quantum dot RoHS exemptions

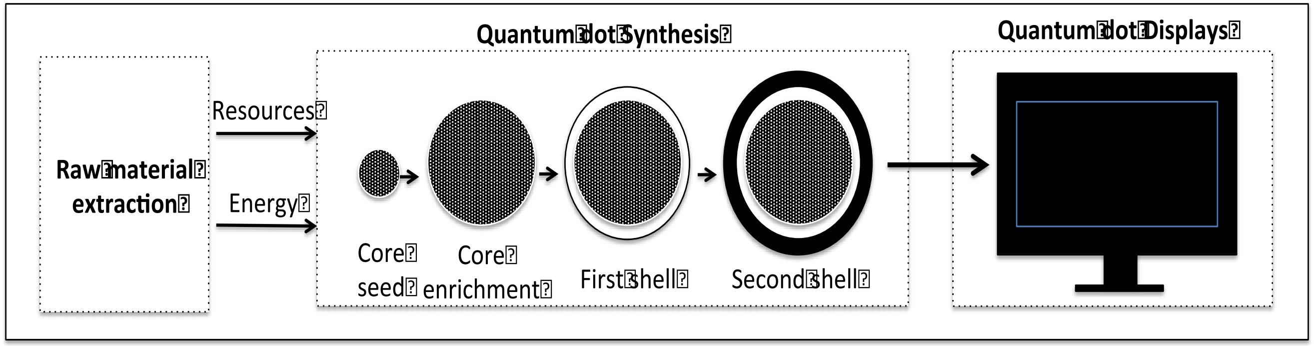
5 November 2015 / Europe, Electrical & electronics

Cadmium ban in TVs: Balancing innovation and regulation

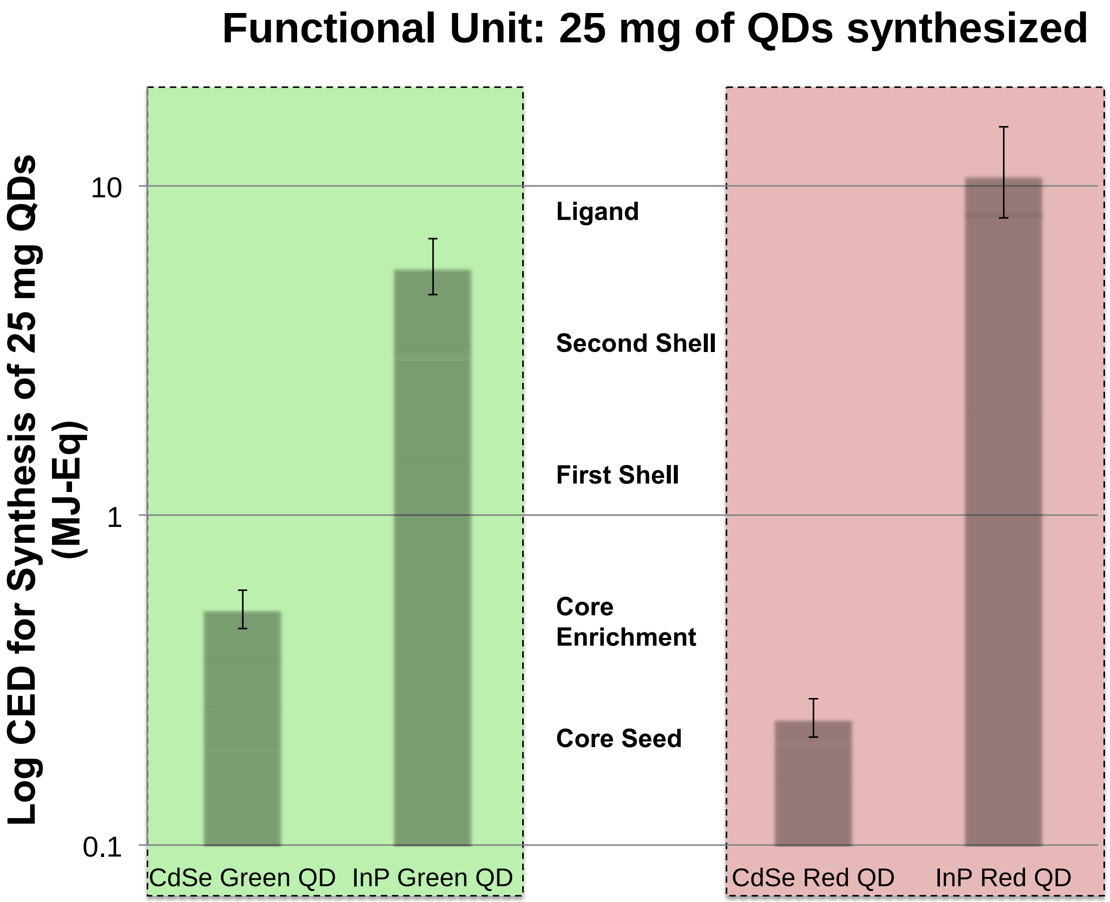
EU restricts the use of certain heavy metals including cadmium in electronics

- Development of high quality, **Indium Phosphide (InP)** core QDs for displays required

Previous Cradle to Gate LCA Results

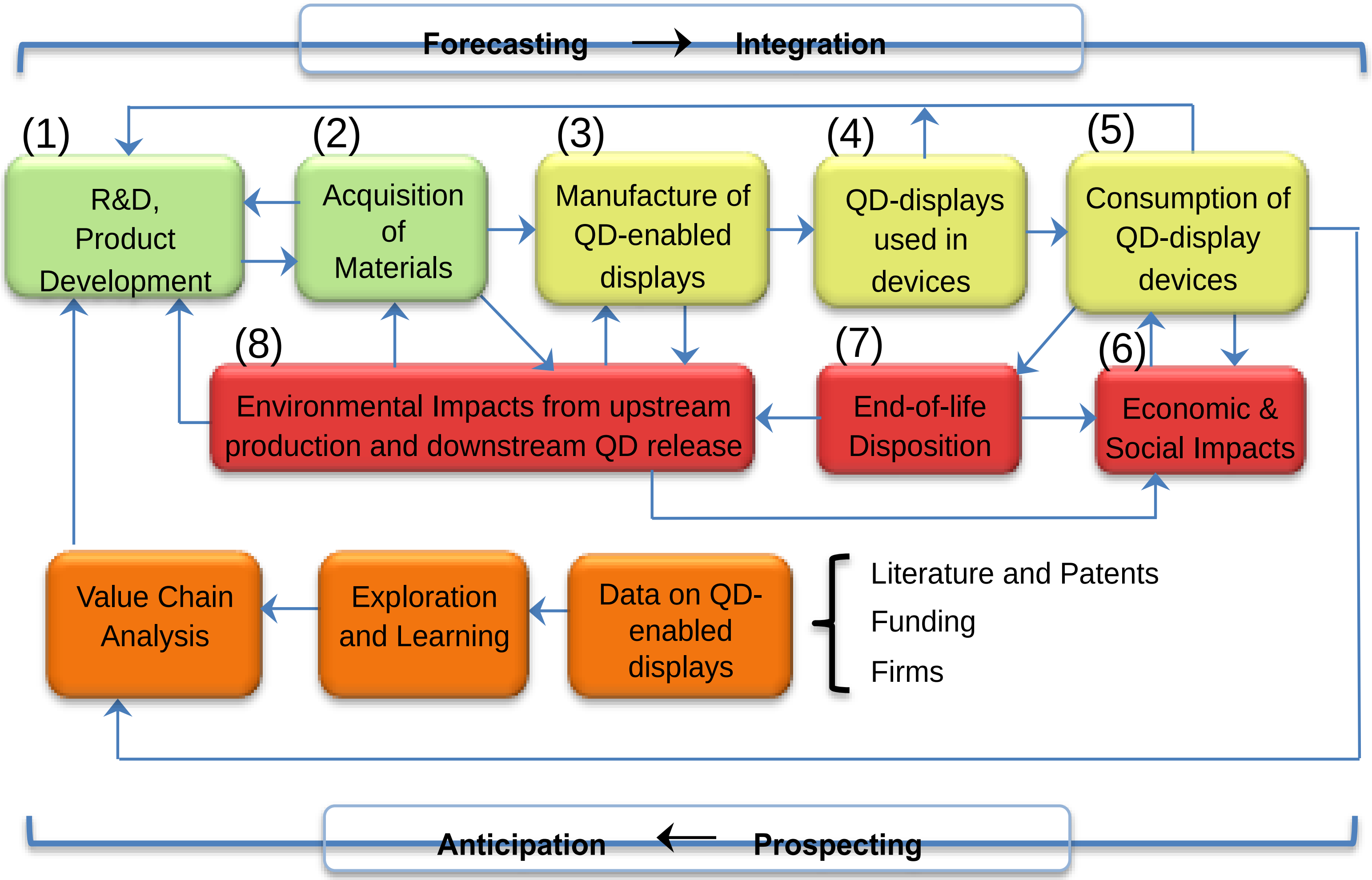


- Comparison of CdSe and InP QD synthesis
- Data for QD synthesis obtained from patents filed by Nanosys (InP) and QD Vision (CdSe)
- Many assumptions made to develop a first estimate of potential environmental impacts
  - *E.g.* 40 times more InP QD is needed for a comparable picture quality in LCD display



S. S. Chopra and T. Theis, *Environmental Science: Nano*, 2017.

Reduce Uncertainty of Life Cycle Implications

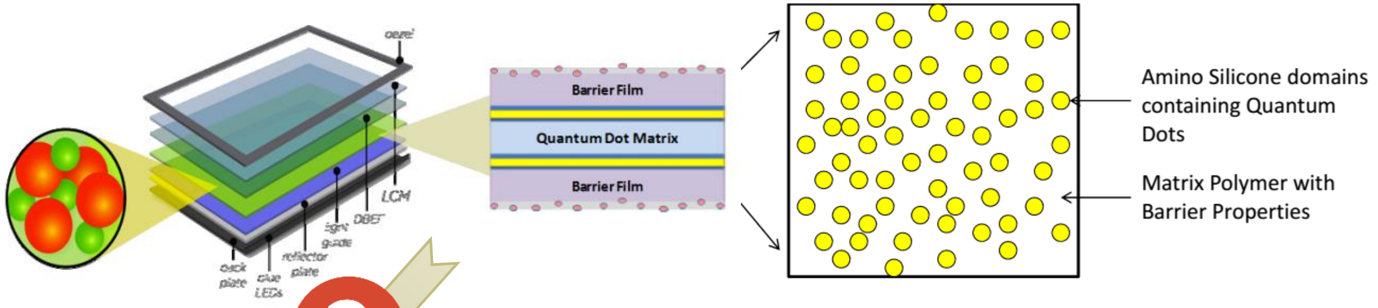


- For QD displays, the product manufacture and EoL stages suffer from high uncertainty
- Dynamic LCA framework (*dLCA*) for prospective evaluation of sustainability of NEPs through iterative collaborative research

Research Objectives

- Reduce uncertainty associated with life cycle impacts of emerging technologies: *QD-enabled displays*
- Experimentally quantify the amount of QD incorporated in commercially available devices during the manufacturing stage
- Also, estimate the quantities of QD material released during their end-of-life (EoL)
- The following consumer electronics are considered
  1. **Amazon Kindle Fire HDX 7-** Incorporates *CdSe-based* QDs using On-surface technology
  2. **Samsung 60" 4K SUHD TV UN60KS8000-** Incorporates *InP-based* QDs using On-surface technology

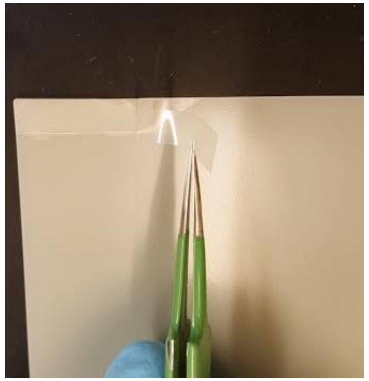
Quantification Procedures for QD Materials



1

UV transillumunator for quick screening of QD film

2



QD enhancement film

Ashing at 800 °C for 6 hr

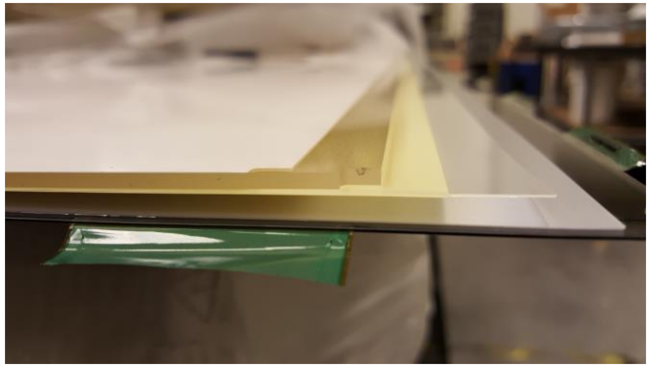
Reaction in concentrated HNO_3 for 3 hr (heated to 100 °C)

ICP-MS for quantification of 64-elements

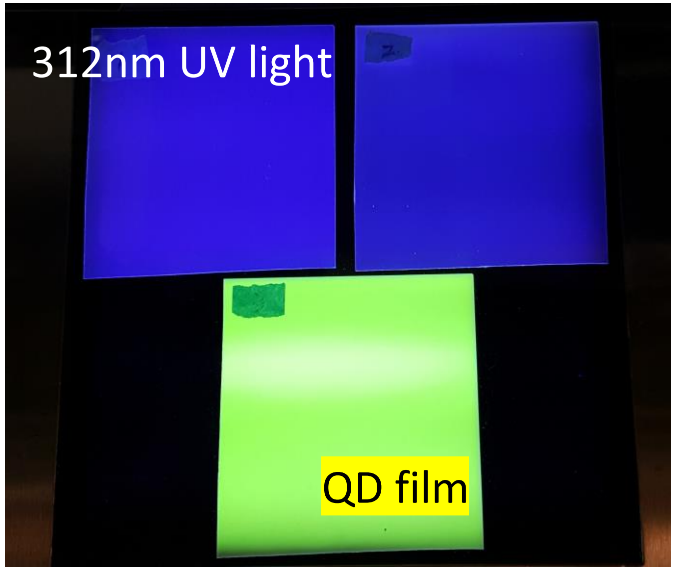
Prescreen QD Enhancement Films in Electronics

Amazon Kindle Fire HDX 7

Samsung 60" 4K SUHD TV



Both LCD displays use **on-surface QD display technology**, where sheets of QD films cover the entire display area.



QD enhancement film is identified based on Fluorescence Properties under UV light .

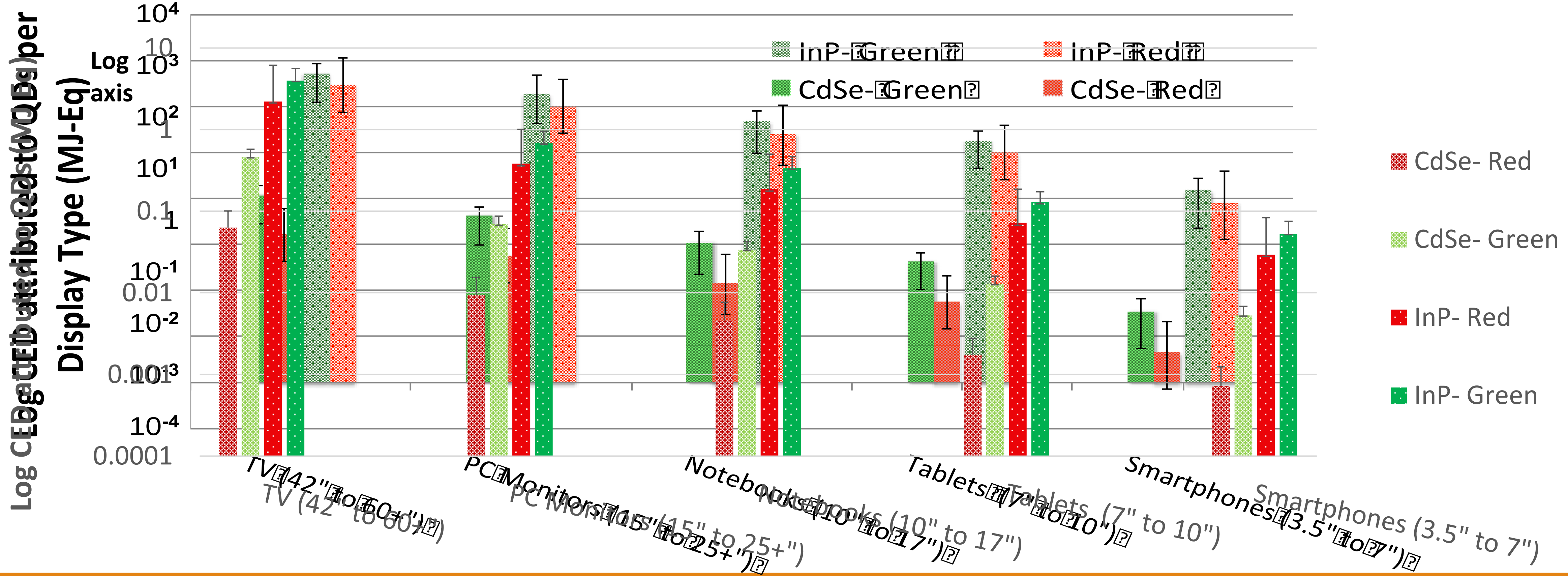
Quantification Results and Comparison

	Kindle Fire Tablet (7'')	Samsung SUHD TV (60'')
CdSe (μg/cm²)	**3.92 ± 0.32**	n/a
InP (μg/cm²)	n/a	**3.56 ± 0.24**
Theoretical conc. (μg/cm²)	~ 3 - 5	> 120
Total CdSe amount (μg)	**877.3**	n/a
Total InP amount (μg)	n/a	**35836.5**
Product year	2011	2016
MSRP ($)	$ 150	$ 2299

- The concentration of CdSe in the film is comparable with InP.
- The results contradict with our initial hypothesis that *InP concentration should be 40 times more than CdSe in displays for a comparable performance.*

Life Cycle Impacts per Display Type

Ratio of Green to Red QD embedded per display type depends on the color gamut required- anywhere between 12:1 to 1:1

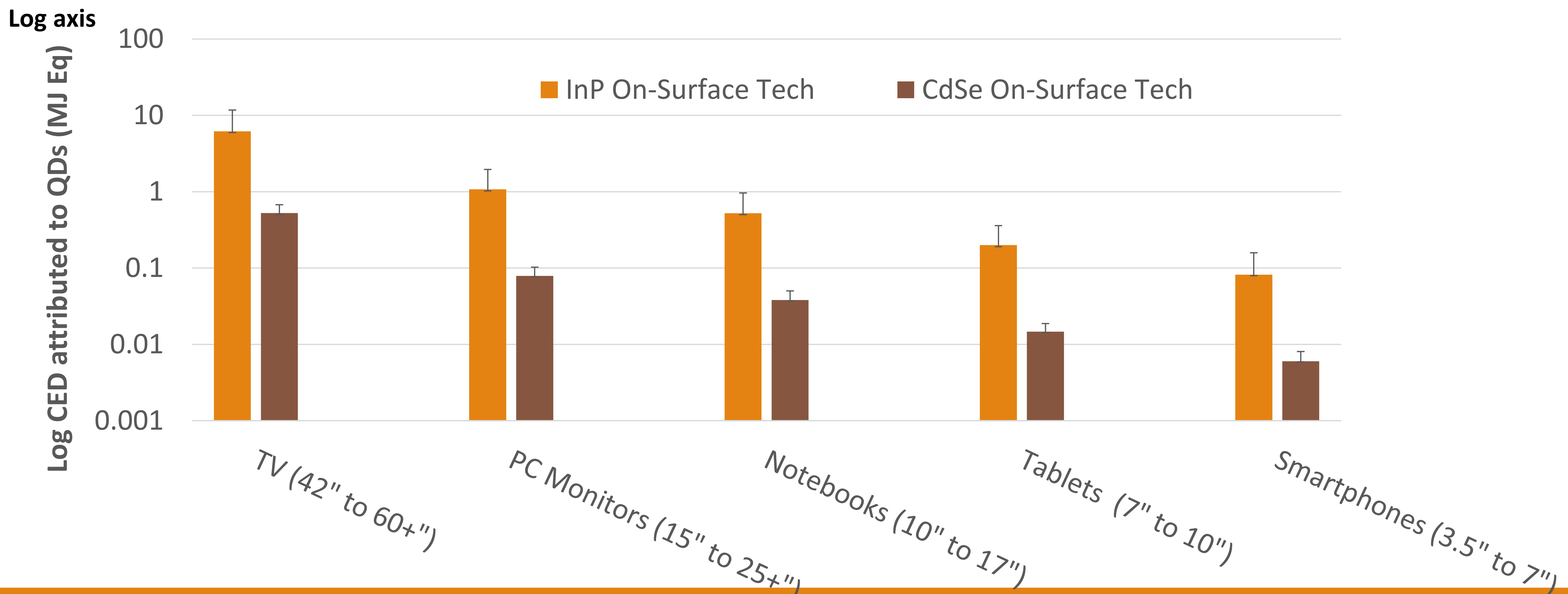


Functional Unit: 1 display for device (μg of QD/cm²)

On-Surface QD technology

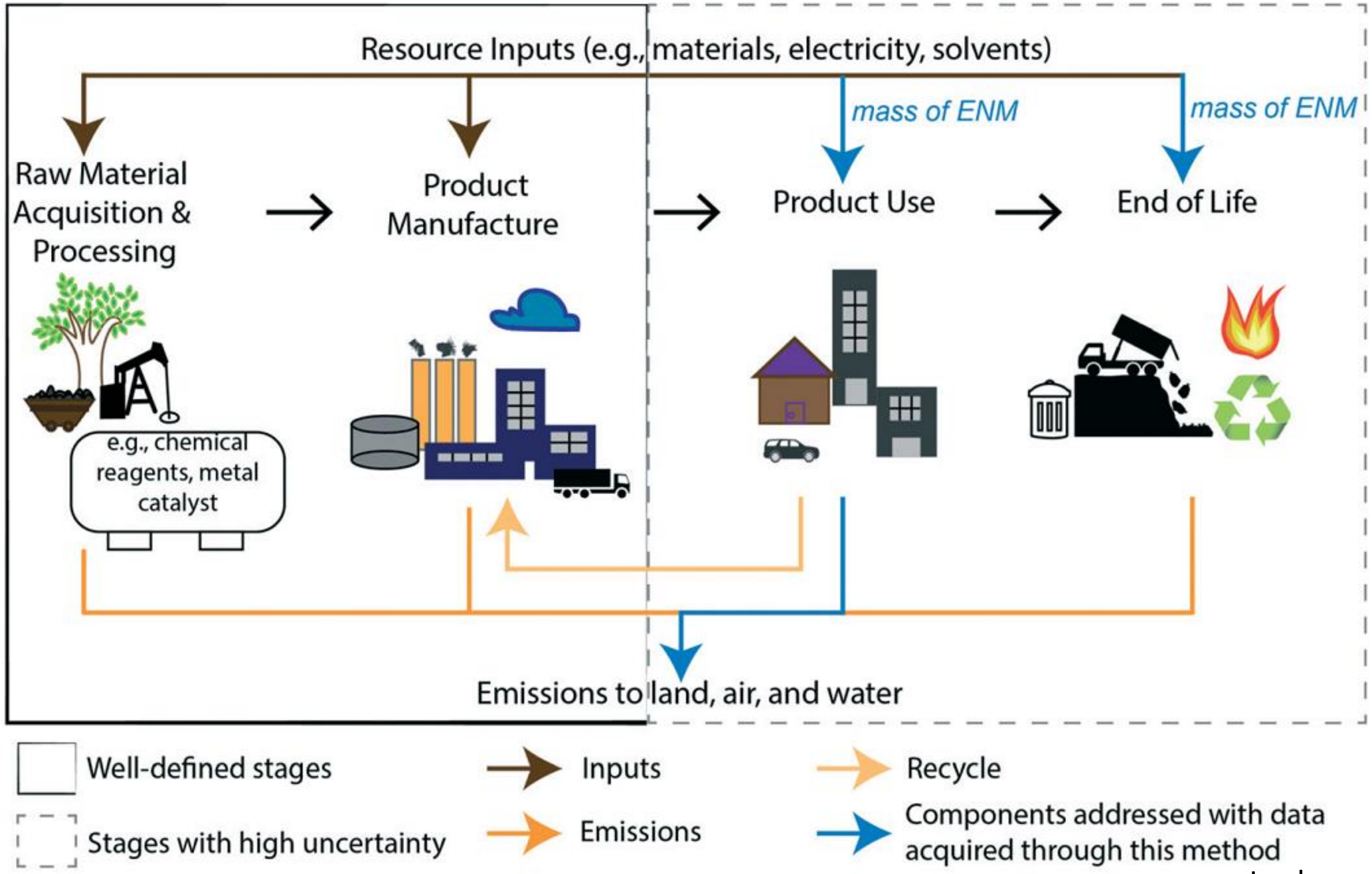
Life Cycle Impacts per Display Type

Performance of InP-based QDs has improved from previous assumptions



Functional Unit: 1 display for device (μg of QD/cm^2)

Reduce Uncertainty in End of Life



Lankone et al., *Environmental Science: Nano*, 2017.

Toxicity Characteristic Leaching Procedure (TCLP) for QD Leaching

Heavy metals, like cadmium, selenium, and indium, are included as RCRA characteristic hazardous waste determinants because of their toxicity and other adverse environmental and health effects

Simulates EoL via solid waste disposal

- QD film only — **Upper boundary** of QD release
- The rest of LCD display components — **Background** for QD release
- The entire LCD display components — **Lower boundary** for QD release

Marginal Release of In or Cd from QD Films

	Upper boundary	Background	Lower boundary
Leached Cd (µg/L)	1.344	0.079	TBD
Leached Cd (%)	0.021	< 0.01	TBD
Leached In (µg/L)	0.077	negligible	TBD
Leached In (%)	0.003	negligible	TBD

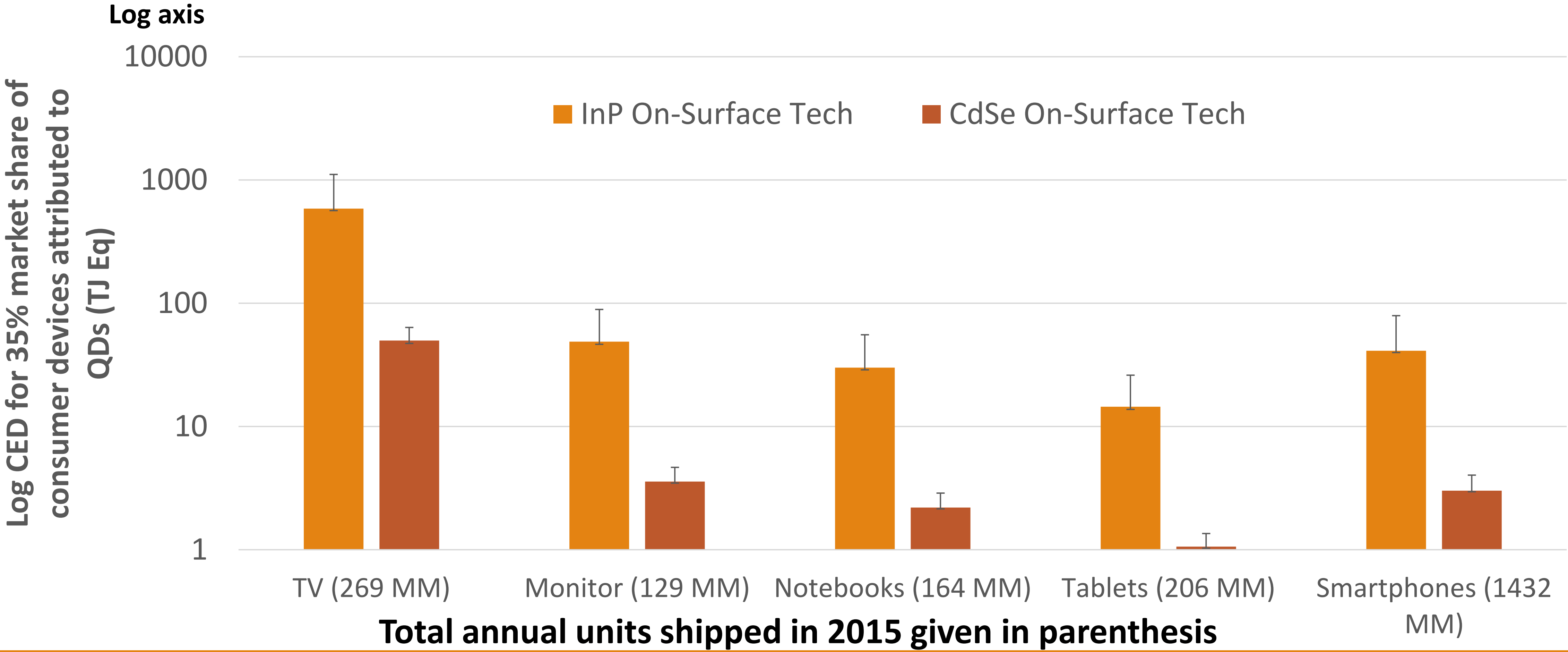
The released metals were in the form of **dissolved ions** → no particles identified by TEM

- The very low release of **Cd or In** is expected:
  - The QD materials are non-volatile and are incorporated into **a polymer matrix** and placed between low-permeability barrier films (to prevent oxidation).
- QD displays do not appear to exhibit properties of RCRA toxicity characteristic hazardous waste
- They are not subject to Land Disposal Restrictions or Hazardous Waste Treatment Standards as per RCRA Subpart D, 40 CFR 268.40.

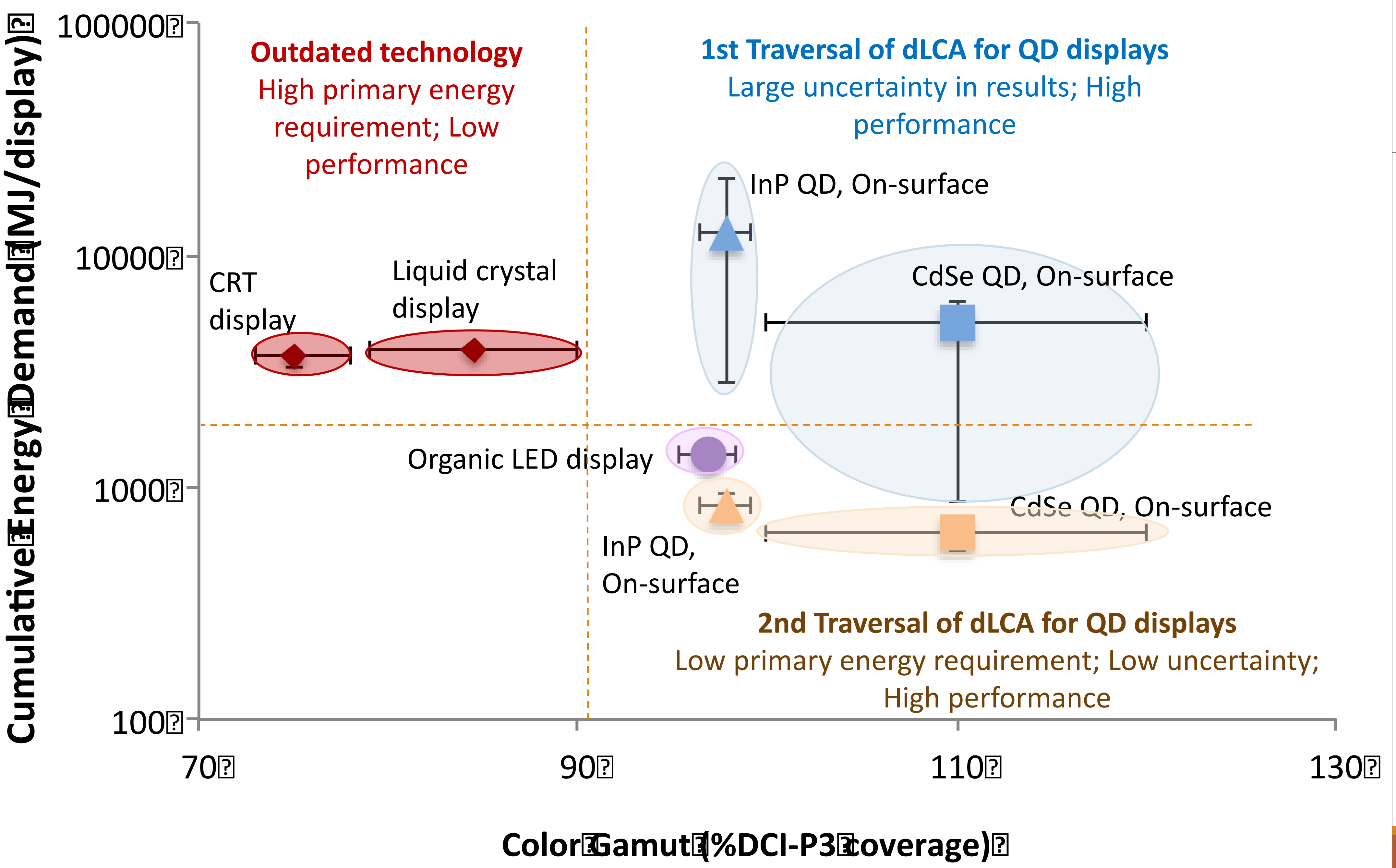
Projection: On-Surface Technology

Implications of large-scale adoption of QD displays

Functional Unit: Market segment



Total annual units shipped in 2015 given in parenthesis



Outdated technology
High primary energy requirement; Low performance
1st Traversal of dLCA for QD displays
Large uncertainty in results; High performance
InP QD, On-surface
CdSe QD, On-surface
CRT display
Liquid crystal display
Organic LED display
CdSe QD, On-surface
InP QD, On-surface
2nd Traversal of dLCA for QD displays
Low primary energy requirement; Low uncertainty; High performance
100000
10000
1000
100
70
90
110
130
Cumulative Energy Demand (MJ/display)
Color Gamut (%DCI-P3 coverage)

Implications for LCA

- Experimental data highlighted that ENM requirements for both InP and CdSe-based QD displays is similar, which allowed refining of the cradle-to-gate LCA model
- Given the low QD release (mainly as ions) at the scale of individual device, EoL impacts associated with QDs will be **insignificant**
  - Implications of large scale adoption of QD technology needs to be assessed, as it may result in unintended environmental impacts
- During EoL stage, potential environmental and human exposure is less likely to occur through **primary handling and recycling**
- The **1st data set** to address the great uncertainty in release quantities, forms and rates from QD-enabled displays.

Future work

- Determine the lower boundary of QD release using TCLP test
- Translate the QD loading and release data into environmental impact characteristics
- Characterization of QD in the polymer films → influence on QD stability and release → comparison with QD model compounds
- Assess QD release and environmental exposure through different EoL scenarios, e.g., incineration

Acknowledgements

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Suggestions/ Questions?