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TCO Certified (displays)

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Abstract

The manufacturing, use, and subsequent waste of electronic devices are having a large impact on the environment. One way to combat this problem is by informing customers of more sustainable options using certifications. However, in a field such as electronics, where new technologies are developed and sent to the market at rapid speeds, setting the criteria for these technologies is not an easy task. In this report, we focus on electronic displays, specifically the newer technologies microLED, QNED, and WOLED. We investigate the performance and sustainability aspects of these displays, using the criteria on displays set by TCO Certified, and compare them to the currently used OLED and LCD. Our findings show that information on sustainability and environmental factors of new display technologies is scarce. The newer technologies show performance improvements compared to OLED and LCD, and improvements in energy efficiency and expected lifetime. In most cases, information on hazardous materials, conflict minerals, or recyclability could not be found, and in the cases where it was available, it showed no significant improvement compared to old technologies.

1. Introduction and Problem formulation

As display technologies develop, they have become ubiquitous in our society. They are found in all parts of our lives, as smartphones, TVs, control panels, billboards, and much more. The market for displays is constantly growing, and the demand for new and better display technologies increases with it. The two most commonly used display technologies today are LCD and OLED[1]. However, recently there has been a boom of different displays trying to one-up these technologies. The rapid development of new, improved, devices does however come at a cost. Humans are estimated to produce 50 million tonnes of electronic waste every year, waste which to the most part does not get recycled properly [2, 3]. This, combined with reports of poor working conditions for those producing the electronics, gives a clear incentive to determine how sustainable the new technologies developed are and should be. It also shows how important it is that somebody takes responsibility to evaluate new technologies coming to market to make sure that they meet up to certain standards. This helps consumers to make better environmental choices. Aiming to promote sustainable IT products, companies such as TCO Certified who is the client of this report provide their certification for sustainable IT products. A certification is a formal confirmation that the product and its production fulfill defined environmental and social standards. These standards are referred to as criteria and can in the case of sustainability be criteria about, for example, workers' rights or water pollution. Such certifications have the potential of creating an incitement for the manufacturers to fulfill the sustainability standards.

In this paper some of the upcoming screen technologies will be investigated, focusing on MicroLED, QNED, and WOLED. We want to see how they compare in performance, including factors such as image quality, and the different technologies' sustainability factors, including life expectancy, production process, materials used, recyclability, and energy efficiency. We will attempt to compare these factors for the newer technologies with the older ones, in order to suggest criteria for sustainability certifications.

2. Purpose and Goals

2.1 Purpose

The purpose of this report is to in an easily comprehended way give TCO Certified an overview of emerging screen technologies and their possible sustainability issues. By doing this, we hope to provide them with information and ideas for when they do a more comprehensive and detailed study in their process of determining criteria for a sustainability certification of the new displays.

2.2 Project Goals

The main goal of this report is to investigate how new display technologies differ, performance and sustainability-wise, from each other and older technologies. This report aims to answer the questions:

- How do µLED, WOLED and QNED compare to each other and LCD respectively OLED performance-wise?
- How do µLED, WOLED and QNED compare to each other and LCD respectively OLED from a sustainability point of view?

3. Project Design

This study was based on a literature study using scientific, popular scientific sources and contact with industry representatives. The choice of using popular scientific sources was made due to a lack of scientific sources covering some aspects of the study. Those types of publications tend to come as the technologies develop and gain popularity. The scientific sources used were publications such as reports, articles, and patents. The informal channels used were technology reviewers and blogs. One issue with using informal channels can sometimes be a lack of reliability and peer-reviewing. However, as the client of this study encouraged the use of it and as this was weighted to other options the decision made was to use them.
Some of the search terms used when searching for information include: LCD, OLED, MicroLED, QNED, WOLED, White OLED, Diodes, Lifetime, Lifespan, Brightness, Price, Production, Manufacturing, Materials, Sustainability, Energy efficiency, Energy consumption, Performance, Hazardous, Color rendering, Contrast, Quantum Dots, Harmful Chemicals, Recycling, Displays, Toxicity.
The databases used were those provided by the KTH Library. For this report, mainly IEEE Xplore, ScienceDirect, Nature.com and KTH Primo were used to search for scientific articles and papers.

The first step in this study was to decide what aspects to look into when evaluating the different technologies. For this, the TCO Certified criteria were used as a guideline to get a better idea of important and relevant criteria that could be used (see Appendix 5.2). The TCO Certified criteria are presented in the order of a life-cycle of a product, from manufacturing to end-of-life treatment. In this report, this order will be kept, in order to provide a logical order of presentation of findings. Based on those criteria and based on what information was found during the study the following aspects were formed:

Material and Manufacturing:

- Use of hazardous and toxic materials
- Manufacturing: Complexity of manufacturing, cost of production and pricing.

Use and Reuse

- Product performance: Image quality, energy efficiency, energy consumption, expected lifetime

Recyclability

- End of life treatment: Material recycling, environmental, social and economical impacts

Hazardous and toxic materials refers to materials that can be toxic or hazardous to either living beings or the environment. This could include substances which negatively affect aquatic life, carcinogenic substances or materials which contribute to ocean acidification. Hazardous and toxic materials are of importance in all stages of the products' life, but in this report it will for simplicity of reading only be addressed in the Material and Manufacturing stage.

Complexity of manufacturing was assessed by looking at the difficulty of the manufacturing process for each technology, and by examining any issues or challenges that arise during manufacturing.

In order to evaluate the technologies' energy consumption the external quantum efficiency (EQE) was investigated for the diodes used in each technology. Since the EQE differs between different colors and diode sizes this study chose to present the results as an interval from the lowest found to the highest for each LED type. In reality, there are many more factors that affect the energy consumption of a screen, such as driving circuitry and light modulating filters [1]. In cases where existing efficiency data was available those were presented as a fraction between displayed light to the viewer and the energy input.

Image quality was assessed by studying the technologies contrast performance, color rendering and brightness.

Material recycling refers to the recyclability of a product. If a product is manufactured with a plan for recyclability in mind, materials can be reclaimed and recycled. However, if products are not manufactured for being recycled, they can contain harmful or non-recyclable materials or components which are hard to disassemble, making recycling more difficult.

4. Results

In this section, a short presentation and description of the different display technologies are given first. After this follows a section on sustainability certifications and criteria. Lastly, we compile the performance and the sustainability differences.

4.1 About the Technologies

4.1.1 LCD (Liquid Crystal Display)

An LCD is a flat panel that uses liquid crystals, polarizers, and a backlight unit to create images by modulating light. This means that the LCD is a transmissive technology that does not emit its own light [1]. Today, LCD is the most dominant display technology, together with OLED, partly due to being relatively cheap [1].It is used in everything from televisions and computer monitors to smartphones.

4.1.2 OLED (Organic Light Emitting Diode)

OLED is a self-emitting technology that first came to market in 2004 in the form of TVs, excelling over LCD with its superior image quality and reduced power consumption. However, there were some issues with OLED in its infancy. The lifespan was very short and they were very expensive to produce. It would take roughly 10 more years before OLED would become a competing technology [4]. OLED is a self-emissive technology where each pixel is controlled individually. The LEDs are made of organic material whereof its name [5].

4.1.3 microLED

MicroLED is a technology that consists of arrays of microscopic LEDs, with a diameter or cross-sectional area of 0,1 mm or less [6]. Just like an OLED, these pixels are self-emitting and individually controllable, however, the main difference is that microLED uses inorganic material as opposed to OLEDs organic material [7, 6]. The technology is still under development by companies such as Samsung, LG, eLux Displays, and LuxVue. Because of its simple structure, microLED displays could be even thinner than both LCD and OLED (see Figure 4.1).

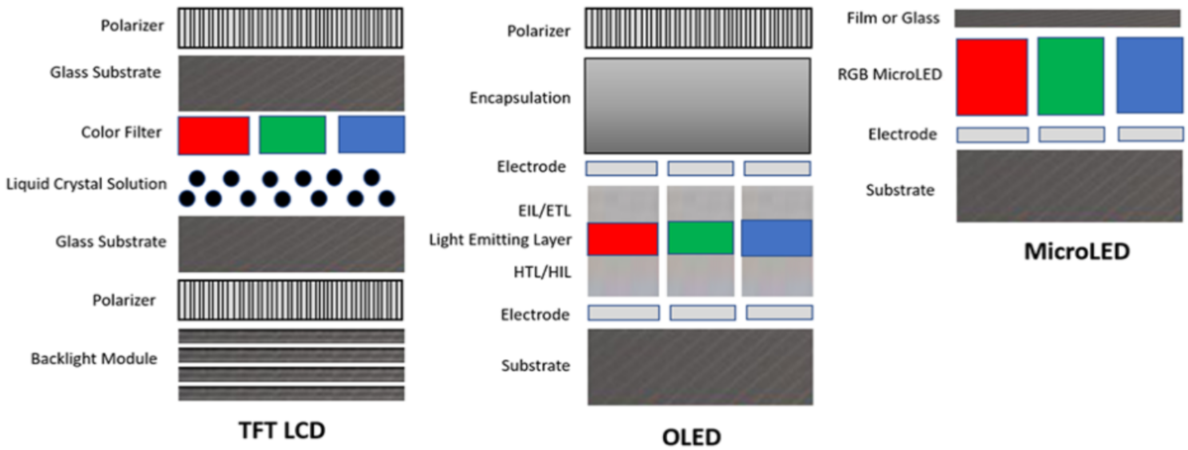

Figure 4.1: Illustrative LCD, OLED and microLED structure comparison [8]

4.1.4 QNED

QNED is a marketing label used by LG and Samsung to refer to two different display technologies.

LG's type refers to Quantum-Dot NanoCell LED, and is a new type of LCD TV. Quantum-Dot converters are used between the LCD panel and the BLU to refine regular color ahead of the screen. Quantum-Dots are artificial nanoscale crystals that are capable of transporting electrons. These semiconducting nanoparticles can emit light of diverse colors when they are struck with UV light. The quantum-Dot layer assists in attaining pure white light from the backlight which helps in realizing wider color gamuts [9].

Samsung's type refers to the Quantum Nanorod Emitting Diode which is still in the early research and development stage. It is self-emissive, uses gallium nitride-based blue light-emitting nanorod LEDs as a provider for the primary light source. Nanorods are cylindrically shaped and very small, and they are used to hold extremely small LEDs. Their shapes help in increasing the amount of light the LEDs emit. Quantum-Dot converters, as before, are used to absorb the blue light and convert it to red or green [10, 11]. Since Samsung's QNED technology is still in reseach and development, this report will be focusing on LG's QNED solely.

4.1.5 WOLED (White OLED)

WOLED is a technique where each pixel is formed by a white, red, green, and blue (WRGB) subpixel. This is similar to the techniques used in OLED, however, in OLEDs there is no white subpixel, as seen in Figure 4.2. The RGB sub-pixels are constructed using color filters on top of white OLEDs. The white subpixel is not configured with a color filter, meaning it will show pure white. This gives WOLED the benefit of improved color rendering and wider viewing angle [12, 13].

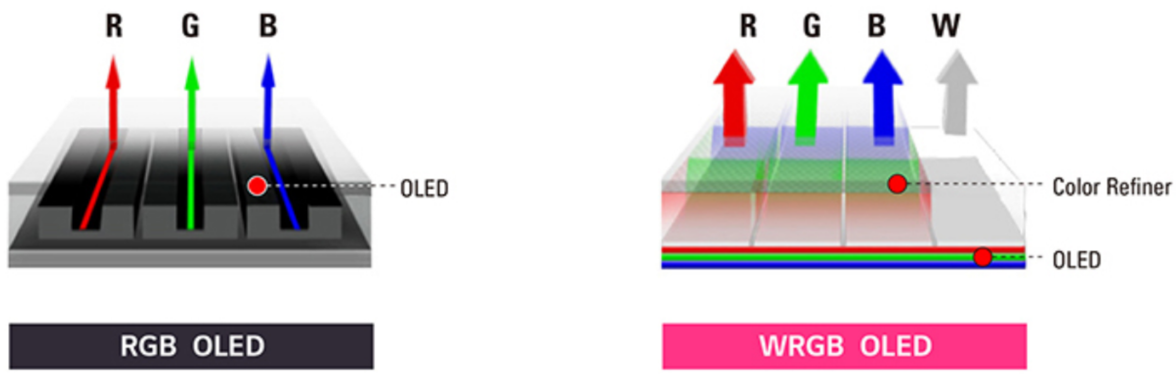

Figure 4.2: Comparison between regular OLED and WOLED structures [14]

4.2 Compilation of Performance and Sustainability Factors

Firstly, the information will be presented in table form in tables 4.1 and 4.2, followed by a more detailed description of each technology's scores. Due to the lack of specific scientific values and concrete numbers for most of our criteria, we have interpreted the sources' information on the technologies in a more general manner and will therefore rate them as poor, decent, excellent.

Table 4.1: Performance of Investigated Technologies (References for values in the table are presented in the text below)

Tech\Criterion	Color Rendering	Contrast	Price	Brightness
LCD	Decent	6,600:1	Low	350 nits
OLED	Excellent	Infinite:1	High	500-800 nits
microLED	Excellent	1,000,000:1	High	4000 nits
QNED	Better than LCD, worse than OLED	1,000,000:1	Medium	3000 nits
WOLED	Excellent	Infinite:1	Medium	Not found

Due to lack of precise information about energy efficiency we have chosen to compare the technologies against each other.

Table 4.2: Sustainability Factors of Investigated Technologies (References for values in the table are presented in the text below) **This number is according to scientific studies and not by producing company.*

Tech\Criterion	EQE	Energy Efficiency	Harmful Chemicals	Expected Lifetime	Recyclable
LCD	50-60%	Inefficient	Yes	60,000 hours	Yes
OLED	10-30%	Greater than LCD	Yes	14,000*-100,000 hours	Yes
microLED	20-40%	Greater than OLED	Yes	100,000 hours	No process yet developed
QNED	5-50%	Greater than OLED	Yes	Not found	Not found
WOLED	Not found	Lesser than OLED	Yes	16,000* hours	Not found

4.2.1 LCD (Liquid Crystal Display)

Material sourcing and Manufacturing

One has found that LCDs, among others, contain hazardous materials such as mercury and arsenic. If not properly managed, both mercury and arsenic can cause harm to humans and the environment [15]. Mercury exposure can damage the nervous systems, skin, eyes to mention a few. It is considered one of the top ten major chemical health problems by the World Health Organisation [16]. Polyethylene terephthalate (PET), produced from ethylene glycol (EG) and terephthalic acid (TPA), has been found in film reflectors. Those are toxic substances with the potential of polluting soil and water. Moreover have many other, many times more environmentally hazardous chemicals been found [15]. During the manufacturing process, hazardous gases NF3, SF6, SiH4 have been found to be used [15]. NF3, is a toxic and strong greenhouse gas [17], SF6 a potent greenhouse gas [18], and SiH4 a toxic gas [19]. Mercury has also been found in LCD screens using cold cathode fluorescent lamp (CCFL) backlighting.

Use and Reuse

LCDs have a reported EQE of about 50-60% [apendix 5.2]. However, because light is polarized and filtered in many stages, much of the light produced by the BLU is not displayed to the user which gives LCD TVs a brightness of up to 350 nits [20]. The exact fraction between displayed and produced light differs between different sources. Some sources report a fraction between 2-30% [appendix 5.2][15, 6]. The LCD display is from this point of view power inefficient. There are some clear benefits of LCDs however. They are considered to be long-lasting, up to 60,000 hours [21]. They also do not suffer from burn-in and are currently the cheapest technology sold. The contrast of LCDs vary greatly from product to product. Numbers ranging from 150:1 to 6,600:1 have been reported [22, 23].

Recovery and Recyclability

There are methods developed for LCD screen end of life treatment. If handled the right way, it is possible to in a safe way take care of LCD waste and recycle metals such as tin, indium and copper to mention a few. However, because it is not always economically profitable to do it, LCD screens, together with other electronic waste, are often exported from industrialized to non-industrialized countries. There, the effects are often negatively impacting the economy, social life and environment [24, 15]. It is important that scarce metals such as indium are recycled from LCD screens. In 2015, 70% of the indium produced worldwide was used for LCD screens solely. The short term demands of the metal is possible to meet, however if the recycling process is not scaled up enough the long term demand will be a challenge to manage [25, 26].

4.2.2 OLED (Organic Light Emitting Diode)

Material sourcing and Manufacturing

A research study from 2018 looked into what "metal-derived environmental impacts" could be found in LCD and OLED and how they differed. This was done by looking at the potentially hazardous waste, resource depletion, and toxic potential of the screens based on the California state regulations. Results showed that OLED had a much higher hazardous waste potential than LCD. OLED had higher concentrations of Ag, Be, Cd, Co, Cr, Cu, Mo, Ni, Sb, Se, V, Zn, Al, Au, Fe, Mn, Pd, and Sn. Only for As, Ba, Pb, and Ti was it the opposite. Toxic potentials identified were Ag, As, Ba, Cd, Cr, Pb, and Se, all of them higher in the OLED screen except from Ba, Cd, and Pb. In total, the OLED display contained 18 times more metal than the LCD. The OLED display had 1000-2300 higher resource depletion potentials and 2-600 times more toxicity potentials [27].

OLEDs are very technologically challenging to manufacture and require electroluminescent materials [28]. There are some technical problems when creating large displays with high resolution due to manufacturing issues such as precision alignment and contact with the glass substrate [29]. There are many different techniques to produce OLED displays but the most popular one is a vacuum evaporation technique with a mask. It is a simple technique, but wastes material and is difficult to scale up. Some OLEDs can be printed using jet-printing, hopefully, this can be used in the future to efficiently scale up the production of OLEDs [5].

Use and Reuse

OLED is made of organic layers that are thin and flexible which allows them to be thinner than LCDs, foldable, and transparent enabling greater flexibility and freeform factor [1, 30, 31]. Also, OLED does not consume a lot of power, previous studies have reported an EQE of about 10-30%. Since it is a self emitting technology, with no light modulating filter except from a polarizer, most of the produced light is displayed to the user [1]. Some sources report a brightness of around 500-800 nits [32, 33]. It's low power consumption, brightness, and thinness make them very popular for smaller, battery-powered, and wireless devices such as phones today [34] . Due to being able to completely turn off pixels and providing “true black” colors OLED has an infinite contrast ratio [35]. OLEDs are much more expensive than LCDs today, however companies are starting to use these displays more as performance increases and prices decrease [36].

One of OLEDs biggest issues is lifespan and burn-in which may vary between manufacturers [28]. In particular, the blue pixel degrades faster than red and green [37]. Red and green OLEDs have a longer lifetime, 46,000 to 230,000 hours, whereas blue OLEDs may only have a lifetime of up to 14,000 hours. This means that an OLED's lifetime depends on the blue and this has been the biggest problem for OLED displays and their lifetime[38]. However, LG claims that their TVs can reach a lifetime of up to 100,000 hours [39], but we have not been able to find a scientific source of this.

Another issue is that OLED is limited in brightness. Therefore OLED displays are not suitable for use in environments with high ambient light [1, 40, 32]. Also, the higher the luminance, the faster the screen degrades [37].

Recovery and Recyclability
OLED displays do not use any parts that contain hazardous substances such as cadmium and idiom phosphide, which many other displays do, like for example LCDs. Because of the organic materials used in OLEDs, they are biodegradable which is good from an environmental point of view [41]. They also have great resource efficiency and recycling, a big factor to this is that they require much fewer parts than LCDs [42].

Two recycling techniques used are chemical delamination and glycolysis. Delamination has a lower environmental impact than glycolysis. Both of these processes enable metal recovery in a second step which is important due to the precious and rare metals found in OLED displays [43].

4.2.3 microLED

Material sourcing and Manufacturing
Today, just as most inorganic LEDs, µLEDs are most often based on gallium nitride (GaN) [6, 44, 45] [appendix 5.2]. The most dominant manufacturing technique for GaN LEDs is metal organic chemical vapor phase deposition (MOCVD) which is a highly complex chemical process [46, 47][appendix 5.2]. This fabrication method is known to include many environmentally hazardous materials [45]. Not only are the chemicals used to manufacture LEDs hazardous themselves but there are also hazardous byproducts produced [45]. The process is also power consuming as it requires high temperatures as high as 1100°C [47][appendix 5.2]. Some chemicals used in µLEDs are tin and tungsten [appendix 5.2]. Between 2007 and 2017, about 44% of the tin refined was used for electronics soldering. Today, the short term demands of tin can be met, however, not enough is recycled to meet the long term demand. That is due to deficient economic profitability.

In order for the long term demands to be met much more of e-waste tin needs to be recycled [48]. Tungsten has been proven to acidify soil, which affects plant growth, kills certain aquatic life, and affects earthworms' ability to reproduce [49].

There are currently various methods of screen assembly, such as robotic pick and place, inkjet printing and fluidic assembly. The first, used by Sony is done by mounting LEDs on a wafer. The wafers are then individually placed on top of the screen panel by a robotic arm. This method is very time consuming and requires great precision whereof usually high manufacturing costs. Fluidic assembly does not require high precision and is done in a mass transfer maner. LEDs are harvested and mixed with liquid. The liquid is later put on a TFT glass plate after which the LEDs are self aligned into wells. This method is much less time consuming, only takes 15 minutes independent of how many pixels there are to be mounted and is much cheaper compared to pick and place [50].

One issue with µLED is that the fabrication plants need to be much more cleaner compared to those used for regular LEDs and mini-LEDs. Since µLEDs are much smaller the defect tolerance is also much less [51]. Clean rooms are usually very power consuming and can be 30-50 times more energy consuming compared to regular buildings. Air conditioning, required for keeping low particle concentrations, is usually the biggest energy consumer and can consume 30-65% of the total energy [52].

Use and Reuse

Just like OLED, microLED has ultra-low black levels but even higher brightness levels, up to 3,000 nits according to Samsung [53] with a contrast ratio of 1,000,000:1 [7]. MicroLEDs can produce 5 times more light than OLED and are more energy efficient [54, 55]. microLED also provides excellent color and near-perfect off-angle viewing. MicroLED is also nearly immune to burn-ins and is supposed to be less expensive to make in the long run over OLEDs [28].

Because µLED is a self emitting technology, without any need for light modulation, all of the light produced in the LEDs is available for the viewer [1, 6, 53][appendix 5.2]. Blue gallium nitride (GaN) and AlGaInP µLEDs have an EQE of up to 60% [1]. This number is however decreased the smaller the µLEDs are made due to unavoidable damage to the edge of the diodes [1][appendix 5.2]. µLEDs may only have an EQE of 20-40% [1, 6]. Because µLED is based on non-organic materials, it has a much longer lifespan compared to OLED [8]. Blue GaN LEDs have an expected lifetime of at least 50000 hours [6]. According to Samsung, their MicroLEDs will be able to operate for around 100,000 hours, which is over 11 years of constant use [53].

One drawback of the microLED when compared to OLED is the pixel size. Even though microLED pixels are very small they can not get quite as small as OLEDs, meaning that you will always be able to fit more OLEDs than MicroLEDs in a display of the same size. This means that OLEDs can have higher resolution than microLED [11, 56].

Recovery and Recyclability
According to Scheule, no end of life treatment is currently developed or planned for eLux displays [appendix 5.2]. Recyclable methods tend to come after a technology has come to market [15].

4.2.4 QNED

LG Nordics and US were contacted for information about their QNED TVs, but they did not respond with any useful information since their QNED TVs have not been released yet.

Material sourcing and Manufacturing
Two of the most used metals in quantum dot (QD) cores are Cadmium and Selenium, these are known to cause acute and chronic toxicities to humans and animals. Several studies have shown that QDs can accumulate in organs and tissues. Under oxidative and photolytic conditions, QD core-shell coatings can degrade and potentially expose these toxic materials [57]. QDs could also end up in the aquatic ecosystem where they can cause harm. According to some studies QDs can accumulate in microorganisms and get carried up the food chain[58]. In order to try and prevent toxic materials from getting out from QD cores, they are coated in a protective polymer[59].

The MiniLEDs used as the backlight source in QNED's are manufactured with inorganic Gallium Nitride (GaN) that does not degrade over time, unlike OLED. GaN is a very efficient semiconductor that is a great replacement for silicon conductors. Thanks to the high efficiency, it reduces energy costs and makes the finished product more sustainable [60]. It also allows LEDs to be lighter and more compact while delivering the same or even improved illumination [61].

Use and Reuse
The backlight is of mini-LED backlight technology, which contains 30,000 tiny LEDs that form light. These LEDs can be separately turned off when illustrating dark areas in an image. Using a large number of LEDs allows for more "dimming zones". This offers an enhanced brightness and contrast ratio of 1,000,000:1 which is far superior to regular LCDs, but not as accurate as OLED displays[62]. It is also more power-efficient than OLED, which makes it less sensitive to burn-ins. The inorganic material and the power efficiency give mini-LEDs a better life span than OLED. LG claims that their new QNED models can achieve a brightness of 3000 nits [33].

LG's QNED uses quantum dots to convert colors between the backlight and the LCD panel. Quantum dots have special physical properties given by their ability to be photoluminescent and electroluminescent. These properties allow QNED TVs to achieve purer colors than regular LCD, and to have lower power consumption [9]. NanoCell technology is used to help enhance the performance of the LCD screen. This technology uses nanoparticles to absorb unwanted light wavelengths to achieve purer reds and greens. It also improves viewing angles and color gamuts [63].

LG has not made a statement about the expected lifetime of their new QNED miniLED TVs yet. However, since the technology uses a miniLED backlight and an LCD screen panel, we can assume that its expected lifetime will be longer than OLEDs.

Recovery and Recyclability
The display technology has not been released to markets yet, so there is little information about its recyclability or recovery programs available.

4.2.5 WOLED (White OLED)

When LG Electronics Nordic was contacted about the production of their WOLED displays, the response was that they currently have no WOLED displays in production and thus were unable to answer any questions on the topic.

Material sourcing and Manufacturing
WOLED uses phosphorescence-based materials instead of fluorescent materials which are more expensive, leading to it being roughly 8 times more expensive than an LCD panel of the same size [64]. However WOLED has a high defect tolerance, and because of this is easier to manufacture than OLED, which would mean that WOLEDs would become cheaper than OLEDs if mass-produced. Its high defect tolerance also means it's perfect for large-area displays. However, WOLED has a higher power consumption than OLED [65].

Results of examining materials used for WOLED fabrication [appendix 5.2]:

1. perylene, used in blue fluorescent dye is considered to be a hazardous pollutant.

2. 1,1,4,4-Tetraphenyl-1,3-butadiene (TPD): GHS07, Acute toxicity (oral, dermal, inhalation), category 4. Specific Target Organ Toxicity – Single exposure, category 3.

3. 9,10-Bis(2'-naphthyl)anthracene (BNA): H413: May cause long lasting harmful effects to aquatic life.Hazardous to the aquatic environment, long-term hazard

4. Bis(2-methyl-8-quinolato) (triphenylsiloxy): H361: Suspected of damaging fertility or the unborn child. Reproductive toxicity

5. Bis (2-(2-hydroxyphenyl)benzothiazolate)zinc (Zn(BTZ)2): H360: May damage fertility or the unborn child. Reproductive toxicity.

Hazard codes and description[66]:

Use and Reuse
A benefit of WOLED is when creating white light. OLED creates the color white by having its three RGB pixels shining at the same, usually very high brightness. This leads to OLED consuming a lot of energy when producing white color, and affecting the OLEDs lifetime. By having the extra white pixel in WOLED, it is much easier to produce the white color and reduce the load, which increases WOLEDs lifetime[67]. However, the overall power efficiency of WOLED displays are still lower than OLEDs because of the color filter used which will always have some absorption of light [29]. The average lifetime on of an white OLED is 15,912 hours [68]. Just like OLED, WOLED has a infinite contrast ratio [14].

Recovery and Recyclability
It was difficult to find any specific information about this part for WOLED. One of the reasons is probably that it is not a very popular display technology today. But as we have seen it is very similar to OLED, and we can assume that the recycling and recovery techniques and processes would be very similar.

5. Discussion and Conclusion

5.1 Discussion

It is clear that many hazardous and toxic materials are used in the manufacturing of displays, both for new and for older screen technologies. It was found that µLED are most often based on GaN, just as most inorganic LEDs. Therefore, µLED are most likely to share many of the sustainability issues that other GaN-based LEDs. This as the fabrication process is the same, namely MOCVD and the materials used as well. However, as µLED are less defect tolerant, this affects the fabrication process to be more energy demanding.

Focusing on EQE, LCD screens seem to have the highest reported values. However, as most of the light is absorbed in the LCD panel the EQE can not solely be used to measure energy efficiency. Previously reported energy efficiency was in the interval of 2-30%. OLED was found to have an EQE of 10-30%, as only one polarizer is used, not as much light is absorbed as in LCD screens but not everything is displayed to the user. µLED was reported to have an EQE of 20-40% and since all of the light is displayed to the user this number can be an indicator of the energy efficiency. For QNED using miniLED backlighting, the EQE was in the interval of 5-50%. Since miniLED backlit QNED screens use an LCD panel most of the light is absorbed before reaching the viewer. For WOLED no data could be found. Out of the presented data, It seems like µLED screens have a better energy efficiency potential than LCD and OLED screens. However, there are many factors affecting the EQE as well as the energy efficiency itself.

There seem to be recycling methods established for LCD and OLED screens but not for the newer screens. eLUX displays said that they did not have any method for their screens. It is possible that recycling methods come after the technologies have come to market. As mini LED-backlit QNED screens use an LCD panel to modulate the backlight it is possible that established methods for LCD recycling can be used for those as well. One problem with LCD end-of-life treatment was that these sometimes get exported from industrialized to non-industrialized countries. There is a risk that the new screen technologies are to follow the same patterns if no action is taken to overcome the problem.

Performance-wise, all of the screens had their pros and cons. µLED, just as OLED is able to produce true black colors. Since WOLED uses the same technology as OLED, except for having white OLEDs with color filters it should be able to produce true black as well as the OLED diodes are individually controllable. This is however not anything that is validated by the results and should therefore not be surely claimed. µLED was found to be the brightest technology followed by QNED, both of them better than OLED and LCD. No established source for brightness data could be found for WOLED. Results showed that µLED displays had the longest expected lifetime potential with 100,000 hours. OLED was in the interval of 14,000-100,000 hours. LCD had a lifetime of 60,000 hours and WOLED 16,000 hours. For QNED no data was found. Regarding color rendering, no straight answer can be given to how they compare. µLED seems to have better color rendering compared to LCD. WOLED is better than OLED at displaying wider colors due to its extra white subpixel. Moreover is QNED better than LCD at displaying purer colors. Burn-in which is a problem for OLED screens isn't something this report has found to be a problem for other screens. However, as WOLED does use organic LEDs as OLED this is likely to be an issue for that as well.

It has been shown many times that electronic waste is a huge environmental problem, and since displays are used in many electronic devices it is important that they can be produced ethically, long lasting and that there is a plan for end-of-life management. To see an electronic components effect on the environment, one can perform a life cycle assessment (LCA) of a product [69]. However, this is likely impossible for the consumer to perform. Using certifications to show the sustainability of a product gives an easy way for a consumer to opt for a more sustainable option, and gives companies which value sustainability something concrete to show. In many other areas these certifications are used more liberally, such as organic and FairTrade food and textiles, and LEED certified buildings. The sustainability of computer and television displays is rarely focused on, either in marketing or as it seems in development and research. This differs, in our opinion, from how it is handled in many other areas. Sustainability has come into fashion in other consumer product areas, such as clothing and appliances, but has not yet reached the market for electronics to the same degree. When sustainability in electronics is addressed, it is mostly about the energy consumption or expected life-time, meaning aspects which will directly affect the consumer financially.

It is difficult to prioritize or decide between sustainability criteria. A criteria such as expected life time might seem most important, as owning the same device for longer is a sure way of decreasing the environmental impact, but is it always the life time which determines for how long something is used? Even a fully functional display will in many cases be replaced, simply because its performance is not as good as the current technology. Taking this into account, would it be better to develop a display which is modular, or easy to recycle without high environmental impact, but which lasts a shorter time? This is an important question to ask, since in the case of OLED, the screen will degrade faster, but if the end-of-life process is less harmful it could provide a net profit in sustainability.

One limitation of our methodology was the sources we in the beginning tried to gather information from. The websites by producing and marketing companies contained little to none relevant information, and only for the older technologies OLED and LCD could we find much relevant information from test-sites and tech-magazines. This is in hindsight not strange, as neither microLED, WOLED or QNED are sold or marketed to consumers at this point, and those with an interest in new technologies on the subject are possibly more interested in progress made in performance than in sustainability.

Our research was made difficult by the lack of relevant information available from the producers and sellers of the technologies. This can be seen in the case of microLED, where we could get a lot of relevant information from a contact at eLux, compared to WOLED or QNED where there was no relevant information given on request to the developing companies.

The lack of information made it very difficult to find anything concrete for the recycling and recovery processes. We found this to be very unfortunate as we felt that recycling plays a huge role in all of modern technology. One idea we had was to try and look into specific parts of the display structures, for QNED we tried to look into quantum dots and see how recyclable they are, however this proved difficult as quantum dots have broad use and the scientific articles mentioning their recycling possibilities were very hard to make any sense of.

There is some information about WOLED used for lighting fixtures, and whether this is the same as the technology used for WOLED displays is difficult to find out. It is important to keep in mind that the same technology which is less sustainable when used in one field can be more sustainable when used in another, depending on the requirements of the environment the device is put in. In the case of WOLED, using the technology in light fixtures can improve sustainability by reducing energy spent[70].

5.2 Conclusion

After researching these new technologies and learning about what lies in focus, it seems that the main focus for companies in the display industry is to strive for performance and image quality. We found that these factors were much easier to find information about than the sustainability factors, likely as it is more marketable towards consumers. Regarding the new technologies, we see that they have clear advantages in performance towards the older technologies, and sometimes in sustainability aspects too. Sustainability and the environment do not seem to lie in focus, gladly we have organizations such as TCO Certified which incentivise companies to hold up to certain standards. Without these organizations, it would be harder for consumers to purchase more sustainable options, and companies would likely ignore environmental and sustainability to an even greater extent than today.

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Appendix A

Questions answered by Paul Schuele, CTO and founder eLux, Inc.

Do you have any concrete data about the energy efficiency of your product?
The efficiency question for displays is quite complex. There are currently three competing display technologies with different strengths and weaknesses. The incumbent technology is Liquid Crystal Display (LCD) technology which has the lowest efficiency. Only 2-3% of the light generated in the backlight is available for viewing and the rest is absorbed in polarizers, metal lines and color filters. Looking at the backlight the blue LEDs are about 50-60% efficient (EQE) but about 2/3 of the generated light is absorbed by a color conversion phosphor (50 to 80% efficiency) to generate white light. So of the energy input to the panel, less than 1% results in an image to the viewer. The other display two technologies are Organic LED (OLED) and microLED (uLED). Both of these technologies are direct emitting so essentially all of the generated light is available to the viewer. uLED has a small advantage because inorganic (GaN and AlGaInP) LEDS have EQE up to about 60% for blue LEDS compared with about 6% EQE for blue OLEDs. However efficiency of inorganic LEDs decreases with size because of the parasitic losses caused by damage at the edge of the device so small microLEDs may only be 20-30% efficient. The big difference between LCD and emissive technology is that the emissive displays do not waste energy by generating photons in sub-pixels that are off. This gives much better contrast compared with the LCD display as well as better efficiency. Newer LCD displays improve this problem by decreasing the backlight intensity for low light scenes. There are also LCD displays with backlights that control brightness of individual zones to improve contrast. As you know there are a lot of components in a display and the power supplies and control circuits are different for each technology. So the best way to answer the efficiency question would be to compare displays of the same size for each technology by measuring the input power while playing the same content at the same level of brightness and color balance. Unfortunately I do not have a display to run this type of test because we are currently only making development prototypes. Based on all of the above issues I expect uLED displays to be slightly (10%) more efficient than OLED. So the OLED display will use about 60% as much power as an LCD display and a uLED display will use about 54% as much power as an LCD display. For an all black image the LED displays should be about 25% that of the LCD display.
Have you found some advantages/ disadvantages for fluidic assembly compared to other methods, seen from an sustainability perspective?
Our assembly technology is very simple. To harvest the uLEDs we use a beaker and to assemble we use a simple flowing liquid cell. The amount of materials is low as is the

complexity and the amount of energy for assembly. All of the fluids are recyclable as are the uLEDs that do not assemble. The competing technology is pick-place which is much more complex and costly and assembly proceeds in a serial fashion. Because we use a cheap tool and our assembly is massively parallel there is a significant cost advantage which is also more sustainable. Having said that the LED fabrication process takes place in a high temperature MOCVD reactor (up to 1100C) using complex chemistry. We use the same process as is used to make large LEDs for general lighting.

How recyclable is your screen? How does eLux work with conflict materials?

I do not know about recycling. Our screen will probably be more difficult to recycle than OLED screens because GaN is a very high temperature material. It will be easier than LCD because we do not have the separate backlight/polarizer stack and we do not have the color filter. For conflict materials I am not sure how that is defined for you. In the US that means tin, tungsten, tantalum and gold. The fabs that make our LEDs use tin and tungsten. eLux does not have a policy and our process requires tin with no possible substitution. My personal opinion is that the definition of "conflict minerals" is a political rather than a moral stance. If one looks closely at any extractive material a strong case can be made that it is a conflict material. This is a sensitive subject for me because of the long history of copper related conflict in the western United States. Because copper is endlessly recycled it is probable that some portion of my devices contains copper extracted by miners involved in those conflicts. Because copper is essential to everything it is convenient to forget those conflicts.

What are the advantages/disadvantages with your microLED screens compared to other manufacturers direct emission displays?

Our advantage over OLED is the reliability of the inorganic uLEDs. Our blue LEDs will not burnin like OLED. Because the technology is based on the LEDs used for general lighting the basic device will have lifetimes over 10k hours at very high power. Also we can achieve much higher brightness than OLED and we are not sensitive to UV so outdoor displays are possible. Compared with other microLED displays (Sony CLEDIS and Samsung "The Wall") our assembly technique is simple fast cheap and scalable. For mass-transfer or pick-place assembly the display needs to be tiled because of the relatively short stroke of the assembly head. Fluidic assembly technology can be simply scaled to very large areas such as Gen 6.5 glass. In addition fluidic assembly is very gentle compared to the pick-place head which mashes the LED into the substrate. So we are able to easily assemble GaAs devices for red LEDs which are quite fragile. The only down side we have is a lot less funding than the competitors (Sony, Samsung, LG, AU Optronics etc.)

Appendix B

List of various host materials and fluorescent and phosphorescent dyes used for fabrication of WOLED, from [71]

Host materials 1. Poly(N-vinylcarbazole) (PVK)
2. 1,1,4,4-Tetraphenyl-1,3-butadiene (TPD)
3. 4,4',N,N'-Dicarbazole-biphenyl (CBP)
4. 9,10-Bis(3'5'-diaryl)phenyl anthracene (JBEM)
5. 9,10-Bis(2'-naphthyl)anthracene (BNA)
6. Bis(2-methyl-8-quinolato) (triphenylsiloxy) aluminum (III) (SAlq)
7. 4-4-(N-(1-Naphthyl)-N-phenylaminophenyl)-1,7-diphenyl- 3,5-dimethyl-1,7-dihydro-dipyrazolo(3,4-b;4'3'-e)pyridine (PAP-NPA)
8. Bis (2-(2-hydroxyphenyl)benzothiazolate)zinc (Zn(BTZ)2)
9. 4,4'Bis(N-(1-naphthyl)-N-phenyl-amino)-biphenyl (-NPD)

Florescent dyes
Red
1. 4-(Dicyanomethylene)-2-methyl-6-(p-dimethyl-aminostyryl)- 4H-pyran (DCM1)
2.4-(Dicyanomethylene)-2-methyl-6-(2-(2,3,6,7-tetrahydro-1H,5H-benzo(I,j)quinolizin-8-yl)vinyl)-4H-pyran (DCM2) (–)
3.4-(Dicyanomethylene)-2,6-di-(4-dimethylaminobenzaldehyde)-pyran (DCDM)
4.4-(Dicyanomethylene)-2-tert-butyl-6(1,1,7,tetramethyljulolidyl- 9-enyl)-4H-pyran (DCJTB)
5. 5,6,11,12-Tetraphenyl-naphthacene (Rubrene) (orange)
6. Zinc tetraphenylporphyrin (ZnTPP)
Green
1. Coumarin6
2. 9-Cyanoanthracene (CNA)
3. Tris(8-quinolato)aluminum (III) (AlQ3)
Blue
1. (perylene)
2. 4,4'-Bis(2,2'-diphenylvinyl)-1,1'-biphenyl(DPVBi)
3. 9,10-Bis(3'5'-diaryl)phenyl anthracene(JBEM)

Phosphorescent dyes
Red
1. Fac-tris(2-phenyl)-bis(2-(2'-benzothienyl)-pyridinato-N,C')(acetylacetonate)Ir(III) (Bt2Ir (acac))
2.Bis(2-(2'-benzothienyl)-pyridinato-N,C3')(acetylacetonate)Ir(III)(Btp2Ir (acac))

3.Bis(2-phenylbenzothiozolato-N,C2')(acetylacetonate)Ir(III)(Bt2Ir (acac))
Green
Fac-tris(2-phenylpyridyl)iridium(III)(Ir(ppy)3)
Blue
1.Bis((4,6-difluorophenyl)-pyridinato-N,C)(picolinato)Ir(III)(FIrpic)
2.Bis2-(3,5-bis(trifluoromethyl)phenyl)-pyridinato-N,C3'iridium(III)picolinate ((CF3ppy)2Ir(pic)) (greenish-blue)

Appendix C

Overview of aspects looked into by TCO Certified when certifying a product, from [https://tcocertified.com/criteria-overview/

Material sourcing and Manufacturing
Socially responsible manufacturing: This includes eg. the sourcing of conflict minerals, reduced exposure to hazardous chemicals, labor laws and anti-corruption, and adherence to the United Nations Convention on the Rights of the Child.
Environmentally responsible manufacturing: Energy consumption and reduced impact from manufacturing
Use and Reuse
User health and safety: Depending on the product category, eg. electrical safety and noise levels
Product performance: Depending on the product category, eg. ergonomics, image quality, and energy efficiency.
Product lifetime extension:
Depending on the product category, eg. durability, availability of replacement parts, and standardized connectors.
Recovery and Recyclability
Reduction of hazardous substances: Reduction of hazardous substances such as heavy metals, safer flame retardants, and plasticizers.
Material recovery: Take-back programs, recyclable packaging.