Environmental assessment of OLED lighting foils

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Abstract:

The development of OLED lighting foils is currently at a stage that choices can still be made between different materials and process options. Holst Centre acknowledges the need to include the environmental impact of these choices as a factor in the consideration during development. To assess the environmental impacts of these choices, the environmental impacts of five different OLED designs were assessed and compared in detail. The goals of this study were:

- to give insight in the environmental impacts of the entire life cycle of the five different OLED lighting foils,
- to identify the main sources of environmental impact,
- to give a comparison between the five different OLED designs and
- to identify gaps in scientific knowledge on OLED environmental impacts.

The main differences between the five designs were the materials used for anode manufacturing and the substrate material used: the 'Printed Ag' and 'Printed Cu' OLEDs have a printed silver or copper anode, the 'Fast2light' and 'Embedded' OLEDs have an electroplated copper/gold anode, while the 'Top emission' OLED is based on a different principle where the light escapes from the opposite site in relation to the other flowcharts. All but the Top Emission OLED are produced on a transparent, plastic substrate. The Top Emission OLED is produced on an aluminium or copper foil substrate. Two different end of life scenarios were considered: precious metal recycling and municipal solid waste incineration. One of the identified gaps in scientific knowledge was the potential environmental risk of nano silver use in OLED manufacturing. A literature study was performed on this subject to assess this potential environmental risk.

Conclusions:

Main conclusions from the environmental assessment of five different OLED designs (see section 4.4.5):

- Electricity use in the use phase has by far the largest contribution on all impacts, making luminous efficacy the most important factor in determining the environmental impact of the devices.
- The printed copper OLED has the best environmental performance of all studied OLED designs.
- The use of consumables has the highest contributions in the manufacturing and end of life phase, except for the end of life phase of silver use.
- The high ecotoxicity associated with silver emissions makes silver anode OLEDs particularly unsuitable for municipal waste incineration and landfilling.
- Substrates, temporary substrates and liner foils cause high environmental impacts for all OLED designs due to their high material contributions. Recycling of the waste from liner foils and temporary substrates reduces the impacts significantly, but the contributions remain relatively large.
- Due to lower amounts of material used, the use of a 35 µm aluminium or copper substrate has slightly lower impacts on non-renewable energy use (NREU) and Climate change than a 125 µm thick Poly(ethylene terephthalate) (PET) substrate; this reduction is entirely offseted by the use of the temporary substrate in the Top Emission production process. On the other impacts, the use of aluminium or copper has higher impacts due to high impacts associated with the mining and extraction of these metals.

- Other causes of large impacts are the use of gold (Fast2light) due to high impacts associated with the mining and extraction of gold and the barriers, due to high contribution of silane for the SiN layer and the use of acrylate in the OCP layers.

Main conclusions from the literature study on nano silver risks (see section 5.5):

- There are reasons to expect increased eco toxicity of silver nanoparticles as compared to bulk and ionic silver.
- It is likely that the emission of silver particles occurs in the life cycle of OLED devices at the production phase of the nano pastes and in the production processes using the pastes for OLED manufacturing. Further research on this topic is necessary to find out exactly where and how much of the nano silver particles are emitted into the environment.
- Users of the materials should keep a close eye on the development of scientific knowledge on the subject, but also on legislation regulating the use of these materials.

Main conclusion from the comparison with other lighting technologies (see appendix F):

- Comparison with other lighting technologies (LED and fluorescent lighting) showed that at the moment, OLED lighting has higher environmental impacts than the other technologies. This is explained by the dominance of the use phase in the life cycle impacts of all lighting technologies. In order to compete with current LED and fluorescent lighting, the luminous efficacy of the OLEDs should be comparable to those of the other lighting technologies.

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Contents

List of abbreviations

CED	Cumulative energy demand
CFL	Compact Fluorescent Lighting
CoO	Cost of Ownership
CR	Collection Rate
DALY	Disability Adjusted Life Years
ESP	Electrostatic precipitator
HDPE	High density polyethylene
ISO	Insulating layer (used to protect the device from electrical short-circuiting)
ITO	Indium Tin Oxide
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDPE	Low density polyethylene
LEP	Light emitting polymer
LFL	Linear Fluorescent Lighting
MLm-h	Mega-lumen-hour
MSDS	Materials safety data sheet
MSWI	Municipal solid waste incineration
MY	Metallic yield of the smelting process
NREU	Non Renewable Energy Use
OCP	Organic compound for planarization
OLED	Organic light emitting diode
PC	Poly carbonate
PEDOT	Poly(3,4-ethylenedioxythiophene)
PEEK	Polyether ether ketone
PEN	Poly(ethylene naphthalate)
PET	Poly(ethylene terephthalate)
PGMEA	propyleneglycolmethyletheracetate
PI	Polyimide
PMMA	Poly(methyl methacrylate)
Ppm	Parts per million (mass fraction)
PPY	Pre-processing yield
R2R	Roll to Roll
REACH Directive	Registration, Evaluation, Authorisation and Restriction of Chemicals Directive
RoHS Directive	Restriction of Hazardous Substances Directive
RR_{NY}	Recycle Rate of non-yield
RR_{oled}	Recycle Rate of recyclable metals in OLEDs
RR_{waste}	Recycle Rate of wasted metals
SiN	Silicon nitride (Si_3N_4)
sl	Standard litre (one litre of gas at standard temperature and pressure)
TY	Total process yield
WEEE	Waste electrical and electronic equipment

1 Introduction

Worldwide, lighting uses 19% of the total global electricity production. [1] Historically, most electric lighting technologies have relied on heating filaments in incandescent light bulbs to produce light. The cost, lifetime and environmental impacts associated with the high energy use of incandescent lighting are considered an important drawback of these technologies. At times in which both consumers and governments become ever more concerned with environmental preservation, the above makes lighting technology an important target for energy efficiency improvement. Many governments have implemented regulation requiring the phase-out of inefficient lighting technologies, e.g. the European Union by the directive on ecodesign requirements for energy-related products of 2009, leading to a ban on the selling of incandescent bulbs in 2012. [2] These developments have stimulated the demand for alternative, less energy consuming technologies such as fluorescent, metal-halide and sodium-vapour lamps. Recently, semiconductor light sources in the form Light Emitting Diode (LED) and more recently Organic Light Emitting Diodes (OLED) lighting were added to this list. Compared to the conventional lighting technologies, OLEDs offer some unique design possibilities. Contrary to being a point source of light, such as LED and incandescent light bulbs, OLEDs form an area of uniform light. They can be made flexible and transparent, enabling a whole range of new types of applications. At the moment, the OLED lighting market is still in a very early stage of development. Several companies, e.g. Osram, Philips and Lumiotec, have introduced OLED lighting panels on glass substrates to the market, but none of them is currently mass producing them, and efficiency and prices are still not competitive with conventional lighting devices. However, it is expected that in a few years, efficient panels will enter the market at competitive prices. [3]

1.1 Organic and Printed Electronics

Organic and printed electronics form a promising new field of electronics technology. An organic semiconductor is an organic material with semiconductor properties. These organic semiconductors can be made soluble, offering advantages compared to their silicon counterparts in the way they can be utilized in cost-effective solution production processes. For example, organic semiconductors can be used in printing processes to make electronic devices on thin, flexible substrates. The development of (nano) metal inks and pastes also makes it possible to print conducting structures on these flexible substrates. Therefore, organic and printed electronics technology has the potential to offer great opportunities; next to being light weight, flexible and (potentially) cost effective to produce, printed electronics are also assumed to be an environmentally friendly alternative to conventional electronics. [3] [4]

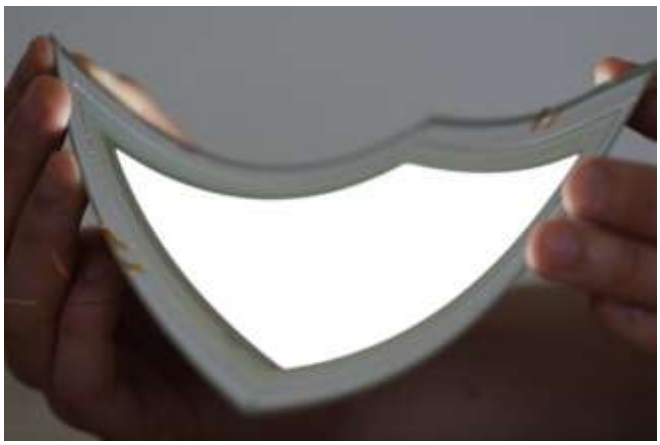

Figure 1. OLEDs can be made flexible.
Source: Holstcentre.nl

1.2 Environmental issues of Organic and Printed electronics

There are several reasons why printed electronics are considered to be more environmentally friendly than conventional electronics. The first being that, in general, printed electronics require less parts, making material use for the manufacturing lower. Moreover, the production processes used for manufacturing printed electronics produce less waste and require less energy compared to conventional technologies. [3] Secondly, most printed electronics do not contain any toxic heavy metals such as mercury. Since the field of organic and printed electronics is fairly new, research on the environmental impacts resulting from these technologies is also in its infancy, and claims regarding its sustainability are based on limited research. With little experience on large scale production, environmental assessment of these new technologies may be challenging, and most research is based on prototype devices. This is illustrated by the evaluation of a prototype wristband which can be used to control a mobile device, such as an MP3 player. The researchers compared a wristband produced using inkjet printing with one produced using conventional processes. They showed that more information on the use of new materials and more process optimization were needed before it could be claimed that the printing of electronics is indeed more environmentally friendly than the conventional process. [5] Another example of research on the environmental merits of organic and printed electronics is a life cycle assessment study by GAIKER, which compared a prototype OLED with LED and fluorescent lighting technologies. Their conclusion is that, in order to compete with other lighting technologies (on both environmental impact and on energy efficiency) the luminous efficacies need to be comparable to those of the other technologies. The GAIKER report also points to lack of data on new materials and processes. [6] Another study focussed on End of Life (EoL) challenges of Printed Electronics, pointing out the leaching of silver in landfill and potentially toxic emissions formed during incineration of waste. [7]

A study that did assume industrial scale production methods compared the environmental impacts of polymer photovoltaic panels on glass and PET substrates with multicrystalline silicon photovoltaic panels. They showed that, per watt-peak, the polymer photovoltaic had 20-60% lower impacts than the multicrystalline panels when a glass substrate was used, and it scored 80-95% better in case PET substrates were used. The difference between the glass and PET substrate was explained by the assumption that the PET modules did not require framing and no balance of system (BOS) was included, but also by the roll to roll (R2R) process used for the PET modules, which consumes less energy than the batch process used for the glass-based modules. [8]

Example of new materials used for many printed electronic devices are nano silver and copper pastes. Even though much research has been conducted on the potential toxicity of these materials, but due to their versatile nature, currently no quantitative assessment of the environmental toxicity effects can be made.

The fact that organic and printed electronics are fairly new makes the assessment challenging because of limited available quantitative information. On the other hand, this gives the opportunity to consider sustainability from an early stage of development, and may avoid the ‘lock in’ of environmentally harmful materials or processes.

1.3 Research goals

One of the targets of the Holst Centre is the development of OLED lighting foils. The goal is to develop OLEDs that are compatible with R2R processing. At the moment, Holst Centre is at a stage in the development that choices can still be made between different material and process options. Next to material properties and economic arguments, Holst Centre acknowledges the need to include the environmental impact of these choices as a factor in the consideration. Currently, knowledge on the environmental impacts of organic and printed electronics technology is too limited to make these comparisons. Therefore, the main goal of this study is to investigate the environmental impacts of OLED lighting foils. With the results, the main drivers of environmental impacts are identified and the developers of the technology will be able to include the environmental perspective into their decision making process, improve the environmental performance of the OLEDs and ease their industrial adoption. To achieve this, the research is divided into three parts.

1.3.1 Assessing and comparing different OLED designs

One important question is whether printing of electrode metals is a more environmentally friendly alternative to conventional methods. The conventional method is, similar to a method used in conventional circuit board

manufacturing, a subtractive process involving plating the entire surface of the device with copper first, and then removing unwanted materials, around 90% for OLEDs. (See Figure 2 on page 3). This method involves wasting a lot of metal, and the use of corrosive chemicals. The alternative process is additive and is the printing tracks of copper or silver only on the locations where they are needed, avoiding the waste of metal (see also Figure 2 below). The research question answered in this part of the research is: 'What are the environmental impacts of OLED designs using printed anodes compared to OLED designs using electroplated anodes and how can the differences be explained?'

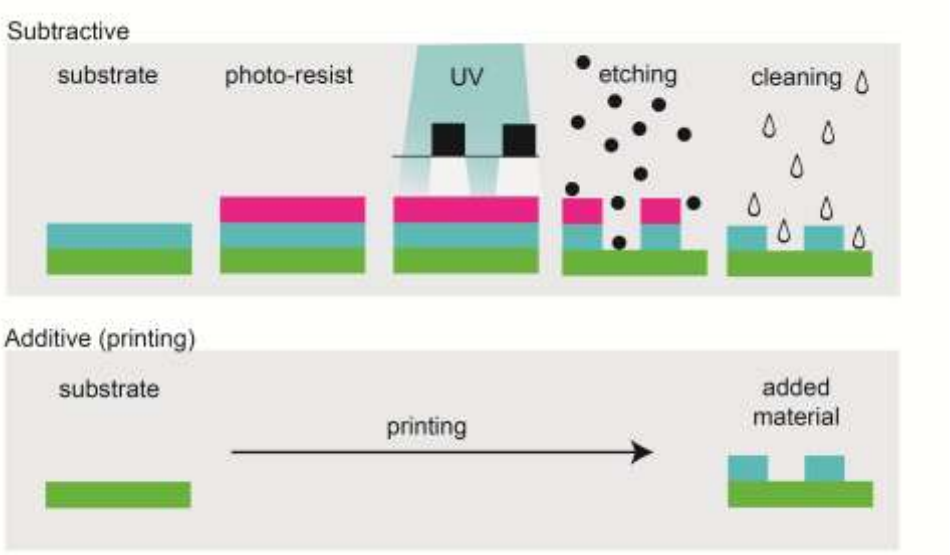

Figure 2. Electroplating and printing anodes

1.3.2 Comparing different substrates

The second part of this research focusses on the different options for substrate materials. OLEDs can be produced on different substrate materials, including PET or PEN, but aluminium or copper foil form also an option. The most important difference between plastics and metals is that the latter is non-transparent, rendering them only suitable for top-emissive OLEDs. The research question answered in this part of the research is: 'Which of the available substrate material options has the lowest environmental impact?'

1.3.3 Sustainability issues of nano silver and copper

A possible drawback of the printing of metals is the use of nano metal pastes. The morphology of nano-scale particles in these pastes might comprise additional threat to health and the environment as the distribution in the environment and metabolism in organisms might be different from other shapes of metals (dissolved salt and bulk). Silver nano particles and ions are becoming common in textile, cleaning applications, cosmetics and in electronics, even though knowledge on their potential eco toxicity is still limited. [9] The use of these pastes is fairly new, their eco toxicological properties are yet not fully understood, and their environmental impact is not yet available in Life Cycle Assessment (LCA) databases. It is therefore not possible to include all environmental impacts resulting from intentional or unintentional release of these substances into the environment. The use of these materials may pose a risk since they may turn out to be environmentally harmful or may be banned by regulatory agencies. Therefore the nano silver and copper pastes will be studied separately, using a slightly different approach in chapter 4.4.4.2. The research question addressed in this part of the research is: 'What are the possible environmental risks of the use of nano metal pastes for OLED manufacturing?'

1.4 Reading guide

After this introduction, this report continues with a description of the research methods used for the assessments (chapter 2). Then, a short introduction into organic electronics, OLED devices and R2R

production methods is given (chapter 3). The report continues with the environmental assessment of five different OLED designs and the environmental assessment of different substrate materials (chapter 4). In the chapter on environmental issues of printed silver and copper, the LCA and environmental risk assessment methods are used to give an overview of current literature on the toxicological aspects of nano silver in electronics production (chapter 5).

2 Research methods

For the environmental assessments, LCA methodology is used. For the research on the potential environmental issues resulting from nano silver use, the LCA methodology is combined with environmental risk assessment methods. This chapter will first explain the LCA methodology, and then the environmental risk assessment methodology.

2.1 Life Cycle Assessment

Environmental impacts associated with a product can originate from the mining and production of its raw materials, during production and use, and in the final disposal stage. Impacts occur in the form of raw material use or by emissions to water, air and soil. When comparing alternatives, it is important to take into account all different stages of a products life cycle. Only then a fair comparison can be made, and unintentionally unfavourable trade-offs can be avoided. LCA is a widely accepted method for performing environmental assessments. The method has been standardized by the International Organization for Standardization in the ISO-14044 standard. The standard requires the following steps: goal and scope definition, inventory analysis, impact assessment and interpretation of results. [10] The steps are similar to the more familiar introduction/methodology, data collection, data processing/results and discussion/conclusion paradigm used in other (natural) science disciplines. The steps will be described shortly in this section.

2.1.1 Goal and scope definition

The goal and scope phase is important since it determines which data are included in the analysis. Therefore, ISO standards divide the goal and scope definition into the following parts: Purpose of the analysis, functional unit definition, definition of the system and selection of the impacts to be evaluated. Different purposes may be i) to provide decision support for R&D agendas, ii) indications about needs and possibilities for process improvements, iii) information for marketing purposes. [11] In ISO standards, the functional unit is the measure of performance of the functional output of the product system and it provides a reference to which the inputs and outputs can be related. By the definition of the system, the unit processes which should be included in the LCA are determined. [10]

2.1.2 Inventory analysis

In the inventory analysis, a quantification of all environmentally relevant material and energy in and out flows of the defined system is constructed along with transport requirements.

2.1.3 Life cycle impact assessment

In the impact assessment, inputs and outputs with comparable effects are aggregated into impact categories or indicators by use of so-called characterization factors. For these calculations, several methods exist, giving results in several levels of aggregation. Results can be given in the so-called midpoint indicators, relative to a common cause of environmental harm (e.g. the effect of all greenhouse gasses can be expressed as kg CO_2 – equivalent emissions, or kg 1,4'DB – equivalents for human toxicity) or resource use (e.g. kg Fe – equivalents for metal depletion). Results can also be further aggregated into endpoint indicators, e.g. Human Health or Resource use.

2.1.4 Interpretation of results

The interpretation phase is the final phase of an LCA. In this phase, conclusions are drawn from the results of the inventory assessment and the impact assessment. Recommendations can be formulated, e.g. on which technology is the most promising from an environmental perspective, or which processes in the lifecycle dominate the environmental impacts.

2.2 Environmental risk assessment

For the ecotoxicology related impacts of nano silver use, LCA methodology alone does not suffice. As the production and use of these materials is relatively new and a large variety of different nano materials exists, little data exists on their potential ecotoxicology to quantify their impacts when released into the environment. As suggested by Shatkin (2008) and Wardark et al. (2008), LCA methodology can be combined with environmental risk assessment methodology to assess the possible adverse effects of nano materials production, use and disposal. Combining the two methods makes it possible to give an indication of whether environmental problems are to be expected, and from which point in the OLED life cycle they arise. The main drivers that may require more detailed analysis can be identified, without quantifying the impacts. [12] [13]

This section first explains the Risk Assessment paradigm that is widely used in risk assessment of chemicals, and then explains how it has been applied in this study to assess the risks of using nano silver for electronics production.

2.2.1 The Risk Assessment paradigm

The ecological risk of a chemical is a function of effect and exposure; without either one of them, there is no ecological risk. Textbooks on environmental science and toxicology (e.g. [14] or [15]) identify the following steps in the risk assessment of chemicals:

Effect assessment

In this step of the assessment, the question of whether a substance has the potential for causing adverse effects on humans, animals or ecosystems is answered. This can be done by direct observation in nature, from epidemiological data or by laboratory experimentation. If data on dose-response relations are available, this step is further divided into *hazard identification* and a *hazard characterisation.* In the hazard characterisation step, a quantitative relation between dose and adverse effect is developed.

Exposure assessment

A hazard can only be a risk if some sort of exposure occurs. In the case of environmental risk, this means exposure to humans or animals, or emission into sensitive ecosystems. Data on exposure can be taken from concentration measurement in nature or in organisms, or by measuring the amounts of the chemicals released and studying the environmental fate of the chemicals.

Risk characterisation

The results of the effect assessment and exposure assessment are combined to give an answer to the question of whether a considerable risk exists. Preferably, the risk assessment will be quantitative, but in the case of lack of knowledge, it can be qualitative.

2.2.2 Combining Life Cycle Assessment with Risk Assessment

Life cycle methodology can be best incorporated in the exposure assessment phase. Combining the two methods makes it possible to identify potential exposure pathways. This gives an indication of whether environmental problems are to be expected, and where in the OLED life cycle these may arise. The main drivers that may require more detailed analysis can be identified, without quantifying the impacts. [12] [13]

3 Short introduction to OLEDs

Organic and printed electronics is a field of technology that is based on organic conducting and semi-conducting materials as well as printable inorganic materials. Many terms are used for organic and printed electronics; plastic, polymer, flexible, thin film or large area electronics are some of the names often encountered. Some examples of applications are organic photovoltaic cells (OPV), printed radio frequency identification tags (RFID), organic memory, flexible batteries, flexible displays and organic LED (OLED) lighting technologies. [4]

Organic materials used as substrate or as a functional material play an important role in producing these electronic devices. Organic conductor materials such as Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) are highly transparent, making it a suitable replacement for indium tin oxide (ITO) in some applications (e.g. [16] or [17]). Inorganic materials such as silver or copper can be made into inks or pastes to be processed in printing techniques to result in conducting structures.

R2R processing uses rolls of flexible substrate material, on which large numbers of devices are produced at high speeds. An important challenge is to make all production steps compatible with this type of processing, and to combine the speed of R2R processing with the accuracy required to deposit micron-scale features on the devices.

An OLED is, similar to an LED, a semiconductor device that emits light when current is applied. In operation, electrons and holes are injected from the cathode and anode electrodes, respectively. When the electrons and holes meet they recombine into an excited state which upon decay produces photons and light is emitted. An important difference from LEDs is that instead of being a point source of light, in OLEDs a large area is covered with light emitting material, forming a large, uniform area of emitted light. This gives users of the technology more freedom in designing lighting devices rendering the use of lenses and luminaires to disperse the light obsolete

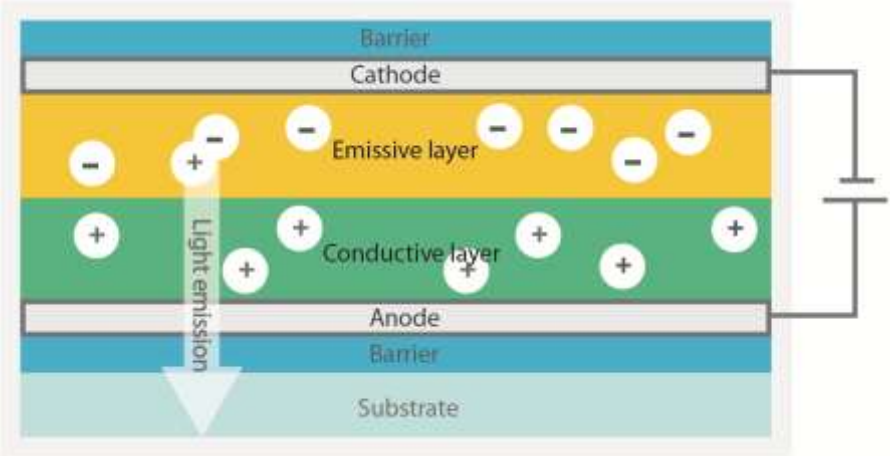

Figure 3. Main features of the studied OLED devices.

Figure 3 shows a schematic cross section of the OLEDs studied in this research. The device has a transparent, plastic substrate, which allows for the produced light to be emitted via the substrate side of the device. Therefore, this type of OLED is called 'bottom emissive'. OLED materials are sensitive to air and water. To protect the OLED from moisture penetrating from the foil substrate, a *barrier* layer is applied between the substrate and the anode. This anode also has to allow the light to pass, and is therefore made out of thin lines of conducting material which can be made by plating and etching a layer of copper (the subtractive process described in the introduction) or by printing (the additive process).

The cathode on the other side of the device is made reflective to maximise the amount of light that is emitted through the anode side. Another barrier layer is applied to seal the device from air and water and finally a Top coat protects the device from possible usage defects as scratches.

A variation to the above described structure is called ‘top emissive’. For top emissive OLEDs, light is emitted through the cathode side of the device, so a reflective substrate (e.g. aluminium foil) can be used. In this case, the metal cathode is thin enough to be transparent and allow the light to escape. The metal foil that the device is built on is a good barrier for oxygen and water, rendering one barrier stack obsolete.

4 Environmental assessment of five different OLEDs

4.1 Introduction

This chapter describes the environmental assessment of five different OLED designs. The most important differences between the five are the materials and processes used for making the anode. Using different anode deposition processes and materials involves more than simply changing the electrode and leaving the rest of the device unaffected. In order to give a complete picture of the environmental impacts, and avoid unexpected side effects, the assessment is based on the complete production processes of five different OLED designs: 'Fast2Light', 'Printed Ag', 'Embedded', 'Printed Cu' and 'Top emission' OLEDs. For detailed production process flows for these five OLED designs, see appendix A. The Printed Ag and Printed Cu use the additive rotary screen printing process for the deposition of the metal tracks; Fast2Light and Embedded use a plating/etching process. Due to the topology of the anodes, some of the designs need an insulating layer (ISO) to protect the device from electrical shorts between the anode and the cathode. The Top Emission OLED is a design compatible with non-transparent substrate materials and is made using an aluminium or copper substrate, which also avoids the use of a bottom barrier.

Table 1. Information on the compared OLEDs

Flowchart	***Information***
Fast2light	Electroplated Cu/Au anode and printed ISO
Printed Ag	Printed Ag lines and printed ISO
Embedded	Barrier embedded electroplated Cu anode, no ISO
Printed Cu	Printed Cu lines and printed ISO
Top emission	Top emissive OLED, printed anode, Aluminium anode

R2R processing is assumed for the studied OLEDs. Using various deposition techniques, several layers are deposited onto the substrate material. The number of production steps varies per OLED design, but many of the processes used for producing the five OLEDs are identical and use the same materials. In total, 29 different materials are used in 38 different processes. Since this research is not only considering the total life cycle impacts of the OLEDs, but also wants to give exact information on how and where these impacts occur, it is important to differentiate between these different process steps, and allocate the environmental impacts to the material and/or process that causes it. Therefore, the assessment will be based on assessments of these individual processes first.

For each process step an inventory assessment for the life cycle stages 'cradle-to-factory-gate' and 'end-of-life' is given (Appendix B). The results are used to calculate the environmental impacts for five different OLEDs by adding the impacts of the different processes according to their process flows (appendix A). This method has the benefit that environmental impacts are calculated for every process individually, so that their contribution to the total impacts can be determined, and they can be aggregated in different ways. This also gives the opportunity to make changes to the process flows without having to repeat all calculations, so that different design options or selected parts of the devices can be quickly compared,

Since this type of research is fairly new to Holst Centre, quite some time has been spent on finding a format for conducting the research and a way of presenting the results. At Holst Centre, there is experience in 'Cost of Ownership' (CoO) calculations. These calculations follow the same bottom up approach as LCA does, systematically analysing every step in the production process and every consumable used. For this study, the inventory of materials and processes used in the 'Cost of Ownership studies for Organic lighting foils' will

serve as a basis for the LCA inventory. [18] To keep the results compatible with the CoO results, the same production parameters and utility use allocations will be used if possible.

Material flows that represent little or no cost or revenue are given little or no attention in CoO, but may be very relevant from the environmental perspective. Therefore, every process step will be considered individually, carefully analysing all associated material and energy flows. The CoO data will serve as a starting point for this analysis.

Since it is expected that the use of the gold, silver and copper will pose an important contribution to the environmental impacts, a detailed assessment of the role of precious metal recycling and end of life treatment has been included in the calculations. A description of the end of life material flows and modelling methods is given in section 4.3.2.

4.2 Goal and Scope definition

4.2.1 Purpose of the analysis

The purpose of the assessment is:

- to give insight in the environmental impacts of the entire life cycle of the five different OLED lighting foils,
- identify the main sources of environmental impact,
- give a comparison between the five different OLED designs described above and
- identify gaps in scientific knowledge on OLED environmental impacts.

With the results, the main drivers of environmental impacts can be identified, the benefits of printing electrodes as compared to plating can be assessed and developers of OLED technology will be able to include the environmental perspective into their decision making process.

4.2.2 Functional unit definition

A unit commonly used for the assessment of lighting devices is the mega-lumen-hour (MLm-h). This unit allows for the comparison of different lighting technologies, which might have different luminous efficacies and/or lifetimes. To give better compatibility of the calculations with the CoO calculations, the inventory assessment will be based on ‘the production of one working OLED device’. The results will be presented in the functional unit ‘one mega-lumen-hour of lighting from an OLED lighting device’.

4.2.3 Definition of the system

For the assessment, only the light emitting foil itself will be studied, so any additional driver electronics, luminaires and assembly processes are not included. This system is chosen as at Holst Centre, only the light emitting foils are developed so any other parts of the devices are outside the scope of their research. In addition, at the moment there are no commercially produced flexible OLED lighting devices available, so no data on luminaires, assembly and driver electronics exists. All the cradle-to-grave life cycle stages will be taken into account.

The production processes studied will be based on the same assumptions as the CoO calculations: a virtual factory capable of producing 10 km^2 (35 million units) of OLED lighting foil per year. OLEDs are produced in a roll-to-roll process, on a web that is 120 cm wide. The OLED itself is 58,5 x 58,5 cm, but has a printing/sealing margin of 5 mm on all sides, making the total printed area 57,5 x 57,5 cm. The active, light emitting, area is 55,5 x 57,5 cm. (See f Figure 4)

Where possible, large scale production of consumables will be assumed. In appendix A, the production process flow charts of the OLEDs are given.

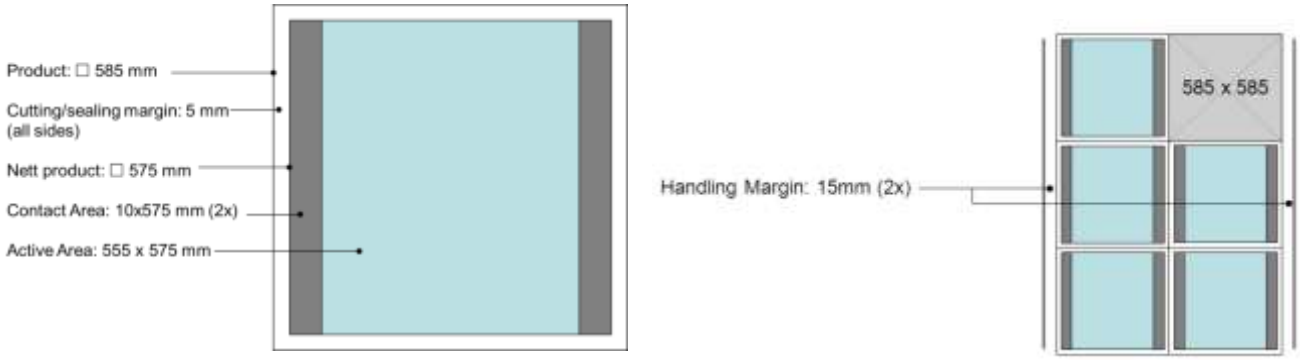

Figure 4. Dimensions of the studied OLEDs and position on the web. [18]

4.2.4 Impacts to be evaluated and used impact assessment methods

For the calculation of environmental impacts, a combination of the cumulative energy demand (CED) and the ReCiPe methods will be used. ReCiPe is a method for environmental impact assessment developed by Pré Consultants, the University of Leiden, Radboud University Nijmegen and the Netherlands National Institute for Public Health and the Environment (RIVM). It calculates results for both midpoint and endpoint impacts. The ReCiPe midpoint indicators are: Climate change, Ozone depletion, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Ionising radiation, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Metal depletion and Fossil depletion. The ReCiPe endpoint indicators are: Human health, Ecosystems and Resources. [19] The CED method gives results for both renewable and non-renewable energy use. The method can be used to calculate energy demand in the categories: Non-renewable, Fossil; Non-renewable, nuclear; Non-renewable, biomass; Renewable, biomass; Renewable, wind, solar, geothermal and Renewable, water.

4.3 Inventory analysis

4.3.1 The OLED life cycle

Figure 5 summarizes the process chain of the OLED life cycle which can be divided into three phases: the cradle to factory gate, the use and the end of life.

4.3.1.1 Cradle to factory gate phase

In the cradle to factory gate phase, the pre-manufacturing of the used consumables and the production processes within the OLED factory are considered. From the production phase, several flows are of importance for the environmental impact assessment: the use of consumables and utilities, and the non-yield, waste and emissions produced.

Non-yield inevitably occurs in any production process. A fraction of the produced devices will contain defects and will be discarded directly after production. In the current design of the R2R factory, defect OLEDs will finish the entire production process, and are discarded as non-yield at the end of the line. At the moment, it is difficult to make accurate estimates of the yield of individual process steps but from experience with other products an overall yield of at least 70% will be demanded before industrial production can be considered. For this study, an overall process yield of 70% will be assumed and the sensitivity of the end results to this assumption will be assessed.

Another source of waste are the materials and fractions of materials that do not end up on the OLEDs but are lost in the production process, e.g. photoresist that is used for the plating process, incomplete evaporation or material spills and protective liners in-between machines. Some of this waste contains valuable materials which may be recyclable. The assumptions made for the CoO calculations will be used to

estimate the amount of materials spilled. Emissions occur when solvents or thinners are evaporated, or gaseous consumables are spilled. Evaporated solvents are assumed to be recycled or emitted to air.

Figure 5. Simplified process chain for the production, use and end of life phases of OLED light emitting foils.

4.3.1.2 Use phase

Apart from electricity use, the OLED devices are assumed to be environmentally benign in the use phase. Based on expert judgment from Holst Centre scientists, a luminous efficacy of 50 lm/watt, a luminous power of 3000 lm/m^2 and a lifetime of 20 000 hours will be assumed here. Therefore, during its lifetime the OLED will consume a total of 382.95 kWh (106.38 MJ) of electricity and produce 19.15 MLm-h of light output.

4.3.1.3 End of life phase

In order to assess the life cycle environmental impacts of any device, some scenario must be assumed regarding its end of life fate. Since no large scale production of OLED lighting exists, no experimental data is available on the end of life fate of the devices. For the assessment of OLED lighting, it is difficult to develop concrete scenarios. The general end of life options for electronics are: reuse of the product or its parts as such, recycling of materials, utilization of the energy content (by incineration) and landfill. From an environmental perspective, reuse is generally the best option. Since printed electronics are planned to be used in low cost high volume products, it is often more economical to purchase new products than it is to

repair or upgrade older models. Reuse can therefore be considered very unlikely for the OLED lighting foil and printed electronics in general. [7]

The eventual end of life treatment will depend i.a. on the application the OLED fulfils in the use phase, the willingness of users to dispose the device in a proper manner, the economics of collection and recycling processes, the development of waste management technology and the development of regulation. Since OLED lighting (and printed electronics in general) is still in the R&D phase, no experiences exist in any one of the above described. Therefore, in the next section two end of life scenarios will be developed, a combination of which will serve as end of life scenario for this study.

4.3.2 End of Life scenarios and waste management

Scenarios that will be taken into account are recycling with precious metal recovery and waste incineration in a municipal solid waste incinerator (MSWI). To determine the probability of a particular scenario a short feasibility assessment is conducted. The environmental impacts calculated with these scenarios can be used to identify the most favourable end of life scenario for OLEDs, and to complete the OLED life cycle assessment model developed in this project. Figure 6 on page 15 gives the process chain and system boundaries for the two scenarios.

4.3.2.1 Precious metal recovery

Using various physical and chemical separation techniques, the gold, silver and copper fractions can be recovered from electronic waste. [20] [21] [22] Recovery of the precious metals may result in a significant reduction in resource and energy use because of the avoidance of production of primary metals. [22] [23] In addition, contamination of the environment is prevented, e.g. through leaching of silver from landfills. [7]

In general, two approaches for assessing the benefits of recycling can be used: the *recycled content* and the *end-of-life* approaches. In both, part of the input of primary materials is replaced by recycled (secondary) materials.

The *recycled content* approach is commonly used in environmental labelling and focusses on material feedstock sourcing. For this approach, the actual amount of recycled material that is used for the manufacturing of a product is determined, and this amount is included in the inventory. It was introduced to provide an incentive towards using recycled materials rather than virgin materials, and is considered the appropriate way to assess the recycling of materials that lose quality during the recycling process (down cycling). [24]

The *end-of-life* approach is considered more in line with the ISO 14040 and 14044 standards, and more appropriate for modelling metals recycling. The quality of recycled metals from electronic waste is such that it offsets the production of virgin materials. The effects of recycling metals can be modelled by replacing part of the primary metal input with secondary metal from the appropriate source (closed metal loop). The fraction of primary metals replaced by secondary metals should reflect the actual amount of metals that will be recycled, rather than the fraction of recycled materials that was used for the production of the devices. [10] [24] [25] There are several parameters that determine the amount of metals that will be recycled: the collection rate, the yield of pre-processing the waste stream and the metallic yield of the recycling process.

Collection rate

The collection rate is the fraction of metal in the OLED that is collected for recycling after the OLED's use phase. Since the OLED does not lose any materials during normal use, this can be assumed to be equal to the fraction of devices that is collected. For reasons described above, no numbers on these rates specific for OLEDs or printed electronics exist. However, from a recent study on Dutch electronic waste recycling rates it is known that in 2010 about 50% of lighting devices (luminaires and lamps) was recycled. [26] Targets posed in the European Waste of Electrical and Electronic Equipment (WEEE) directive are also 50% for 'other equipment'. [27] Therefore, here, a collection rate of 50% will be assumed.

Pre-processing yield

In current WEEE recycling technology, electronic devices are pre-processed in regional recycling facilities. Pre-processing starts with the manual removal of hazardous components (e.g. batteries). Thereafter, the waste is shredded and the plastic and metal fractions are separated using magnets and eddy current separation. [21] [22] [23] A potential problem with the recycling of OLEDs is that the metals cannot be

separated from the substrate mechanically, and shredding will yield only smaller pieces of OLED foil. Because of the low metal content, these will be recognized as plastic instead of metal. Therefore the OLEDs will end up in the plastic fraction and the metal content will be lost in the process. Once larger amounts of printed electronics enter the WEEE waste stream, these processes can be adapted to facilitate the separation of OLEDs and other printed electronics into the metal containing fraction. [21] With the above in mind it is here assumed that the OLEDs will end up in the metal containing fractions of WEEE waste. It is important to keep in mind that these are bulk processes. Due to technical and economic constraints, yield will never be 100%. Pre-processing yields of 70% have been reported as optimistic assumptions. [28] For this assessment, a 70% pre-processing yield will be assumed. The other 30% is separated out of the recycling process and eventually will end up in a municipal solid waste incinerator or comparable waste treatment facility.

Metallic yield

After mechanical separation, the metal containing fractions are transported to the so-called complex smelters, where the copper, silver and gold content can be recovered using several (electro) chemical processes. The organic constituents of the OLEDs will be incinerated in these processes, thereby substituting part of the cokes as a reducing agent and providing part of the energy required. [23] This process is similar to normal municipal solid waste incineration, therefore, for the non-recoverable parts of the OLEDs, municipal solid waste incineration is assumed.

The minimum metal content for economic feasibility of this process is about 2.5% for copper, about 100 ppm for silver and about 10 ppm for gold (at current metal prices). [21] The metallic yield is the efficiency of the metallurgical process converting scrap into metal. [24] Because of the high value of the metals, total metallic yields of these processes are usually very high, approaching 100%. [21] For gold, metallic yields of 95% have been reported. [22] [28] For gold, silver and copper 95% metallic yields will also be here assumed.

4.3.2.2 Non-yield and production waste

Non-yield from the production process poses a well-defined, homogeneous stream of waste; the above described problems with recycling logistics do not apply. These OLEDs can be moved directly to smelter companies for recovery of their precious metals, the only losses that occur are those during the smelting processes. [21]

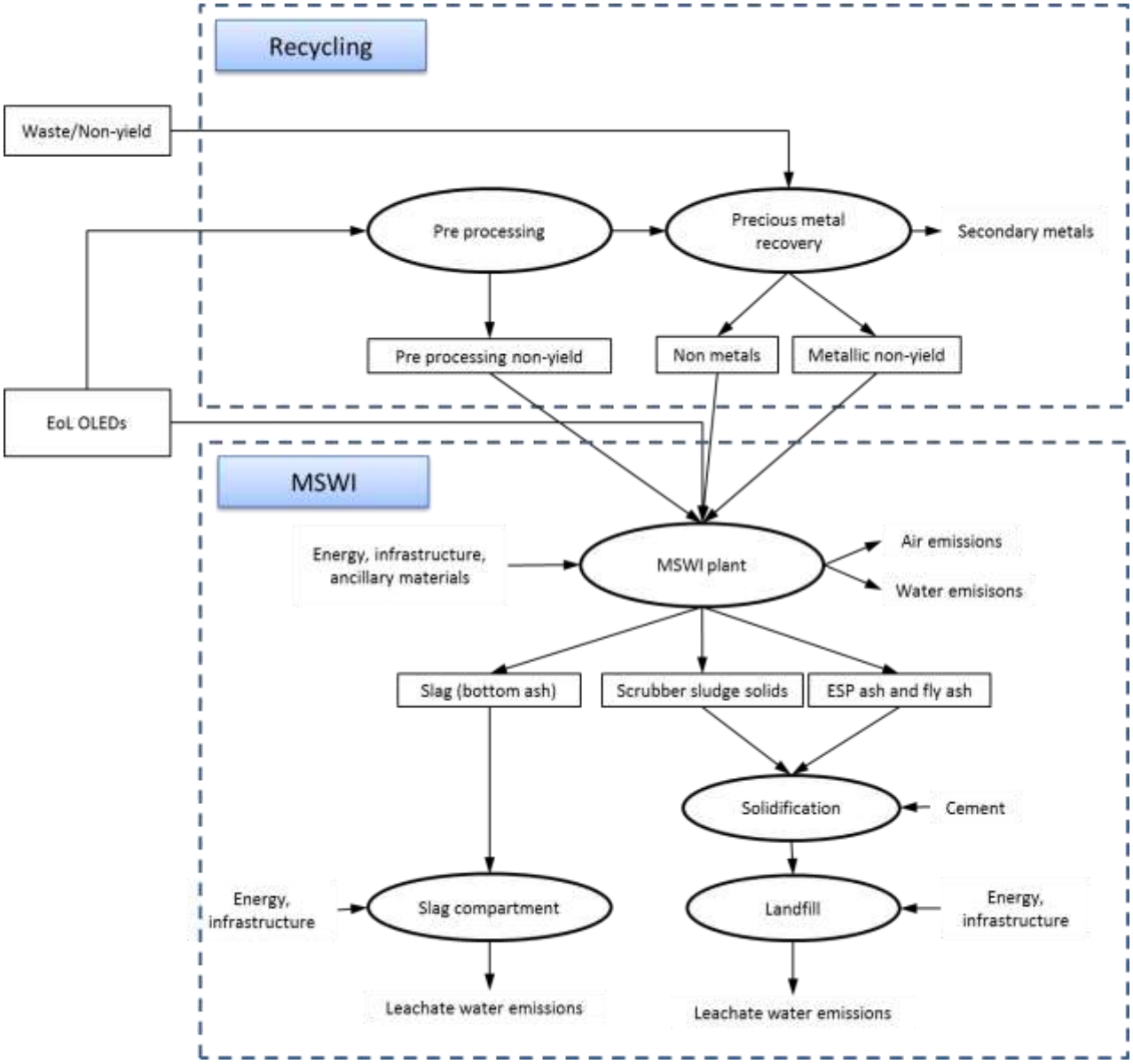

Figure 6. Process chain for two end of life scenarios. The MSWI scenario adapted from [29]

4.3.2.3 Modelling precious metal recycling

The ratio primary/secondary metal inventoried is a function of the total process yield (*TY*), the collection rate (*CR*), the pre-processing yield (*PPY*) and the metallic yield of the smelting process (*MY*), which determine the total recycle rate. The recycling rate of material spills and metal in the non-yield fraction are not subject to the collection rate and pre-processing yield, and therefore different from the recycling rate of materials that end up in the OLED. Therefore the production phase and end-of-life stage are treated separately.

For recyclable metals used in the functioning OLEDs, the total recycle rate (RR_{OLED}) is given by:

$$RR_{OLED} = CR \times PPY \times MY = 0.5 \times 0.7 \times 0.95 = 33\%,$$

where *CR* is the collection rate, *PPY* is the pre-processing rate and *MY* is the metallic yield of the recycling process.

For recyclable metals used for the production of non-yield the recycle rate (RR_{NY}) is:

$$RR_{NY} = MY = 95\%.$$

For wasted recyclable metals the total recycle rate (RR_{waste}) is given by:

$$RR_{waste} = MY = 95\%$$

Therefore, given the amount of metal in the OLED (Q) and the amount of metal wasted in the production process (Q_{waste}) the amount of primary metal in the inventory ($Q_{primary}$) is given by:

$$Q_{primary} = Q \times (1 - RR_{OLED}) + \left(\frac{Q}{TY} - Q\right) \times (1 - MY) + \frac{Q_{waste}}{TY} \times (1 - MY)$$

And the amount of secondary metal ($Q_{primary}$) by:

$$Q_{secondary} = Q \times RR_{OLED} + \left(\frac{Q}{TY} - Q\right) \times MY + \frac{Q_{waste}}{TY} \times MY$$

The amount of metal that ends up in the municipal solid waste incineration scenario is equal to the amount of primary metal inventoried.

4.3.2.4 Incineration and landfill

When an OLED is not recycled for its precious metal content, it is assumed to end up in a waste incineration process. Recovery of precious metals from waste incineration ashes is possible, but due to the complexity of the processes involved, most European MSWI ashes are not recycled. If recycling is implemented, less than a third of the non-ferrous metals are recovered. [30] Therefore, the potentially recyclable contents of the OLED are assumed to be lost in the process. In modern waste incinerators, a part of the energy that is released by this process is used for heat or electricity production. This will result in a positive LCA score in the form of avoided heat and electricity production. On the other hand, incineration of waste requires energy and infrastructure and results in emissions of potentially harmful substances. For the incineration of many materials data on these energy and infrastructure use emissions are available, but for others these need to be calculated using a waste incineration model.

The waste incineration model

Environmental fate of waste during disposal can be calculated from the composition of the waste on the atomic level using the so-called transfer coefficients. These coefficients are derived from measurements and represent the fraction of each element ending up in the solid compartments ‘slag’, ‘boiler ash’, ‘electrostatic precipitator (ESP) ash’ and ‘scrubber sludge’, and water and air emissions. The slag goes to a slag compartment (landfill). Boiler ash, ESP ash and scrubber sludge are first solidified and subsequently also go to landfill. From landfills, emissions occur along with water outflow (leachate) and by the formation of landfill gasses (see also Figure 6 on page 15). The amount and rate in which these gasses and leachates are produced depend i.a. on the quality of the landfill sealing, chemical parameters such as pH and redox potential and the chemical composition of the waste. For the short term, these emissions can be measured at existing landfills. For the long term, it is expected from calculations that emissions of metals and chemically inert or persistent compounds continues for very long times after closing the landfill (several hundred thousand to several million years). It can be argued that, if long enough timespans are considered, all potential pollutants will be released from the landfill, and that from LCA perspective, landfills postpone environmental burden from today’s waste, to future emissions. [29] [31] From measurements and

calculations, transfer coefficients similar to those used for incineration can be used to calculate the emissions from landfills.

Spread sheet calculation tools have been developed by the Swiss Centre for Life Cycle Inventories which are commonly used to apply the above described methodology to user-definable waste compositions, and to user-definable MSWI facilities. The spread sheets calculate the process specific burdens which are not attributable to a specific waste component, e.g. from the waste treatment logistics and energy and water consumption. With these tools, inventories of emissions and processes can be generated. [29] This model does not consider interaction between different waste fractions; therefore the sum of the inventories calculated for different fractions is equal to the inventory calculated for the sum of the fractions. This makes it possible to calculate and attribute environmental impacts to specific materials and processes used in the production of OLEDs. The inventories calculated with the Swiss Centre for Life Cycle spread sheets are included in appendix D.

4.3.3 Life Cycle Inventory Assessment per process step

An inventory assessment has been performed for every process step individually. A description of these assessments is included in appendix B.

4.4 Results of the environmental assessment

The inventories described in paragraph **Error! Reference source not found.** are used to calculate the total nvironmental impacts of the five OLEDs. To improve readability, only a selection of the most important results is included in this section. Five environmental impact categories are selected, which are representative for most of the results. The selected indicators give information on energy use, climate change, human toxicity, ecotoxicity and resource depletion. For more complete results, see appendix E. The results were calculated per process step, but are presented per machine only.

4.4.1 Results for the complete life cycle

For all OLEDs, the same assumptions have been used regarding the use phase; therefore they have the same impacts. The results for the use phase are presented in Table 2 (expressed per MLm-h).

Figure 7 to Figure 11 show the results for the production phase, use phase and end of life phase. The figures show that for all OLEDs and for all indicators the use phase impacts are several orders of magnitude larger than those of the other life cycle stages.

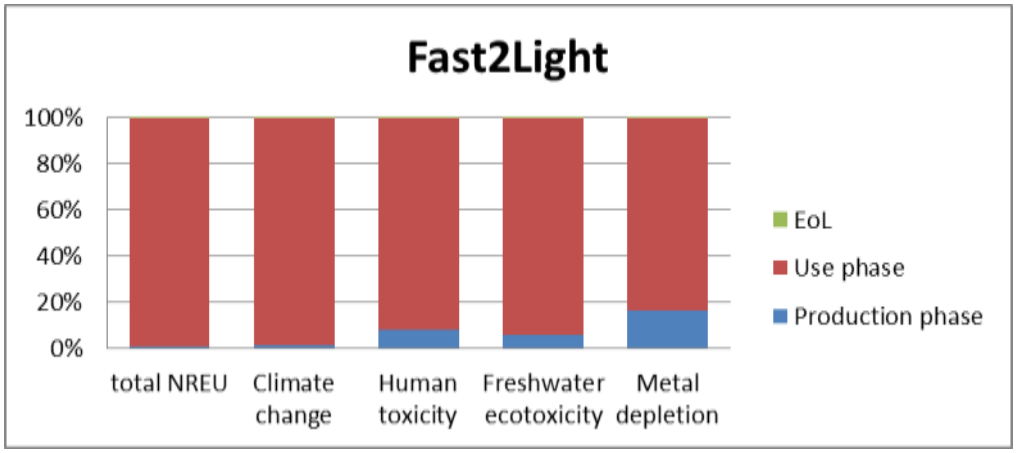

Figure 7. Results for Fast2Light

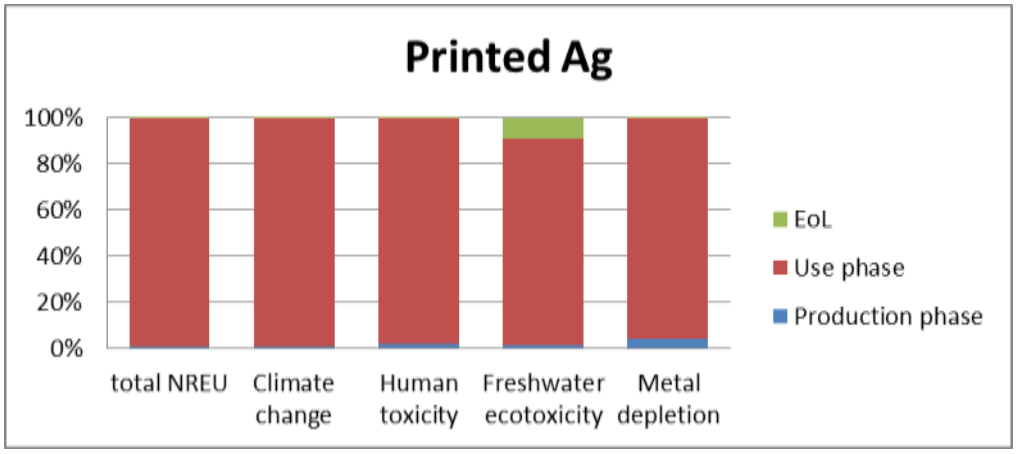

Figure 8. Results for Printed Ag

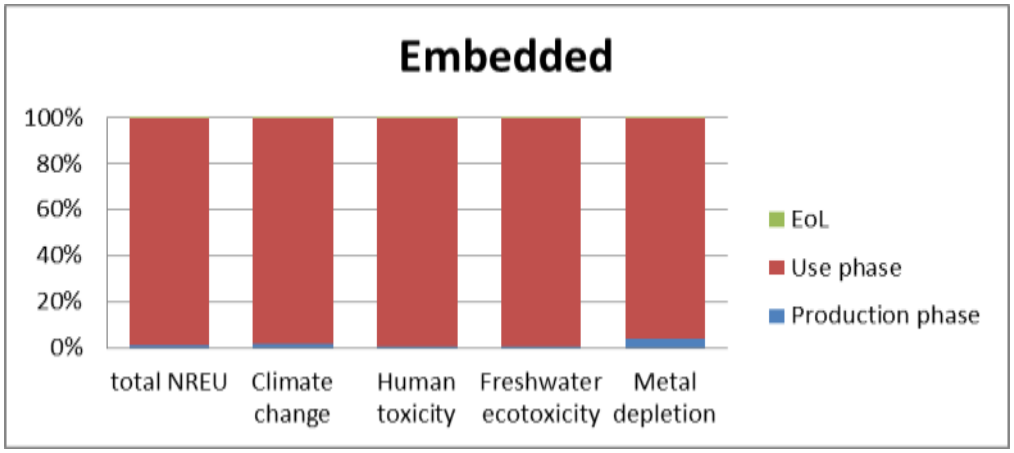

Figure 9.Results for Embedded

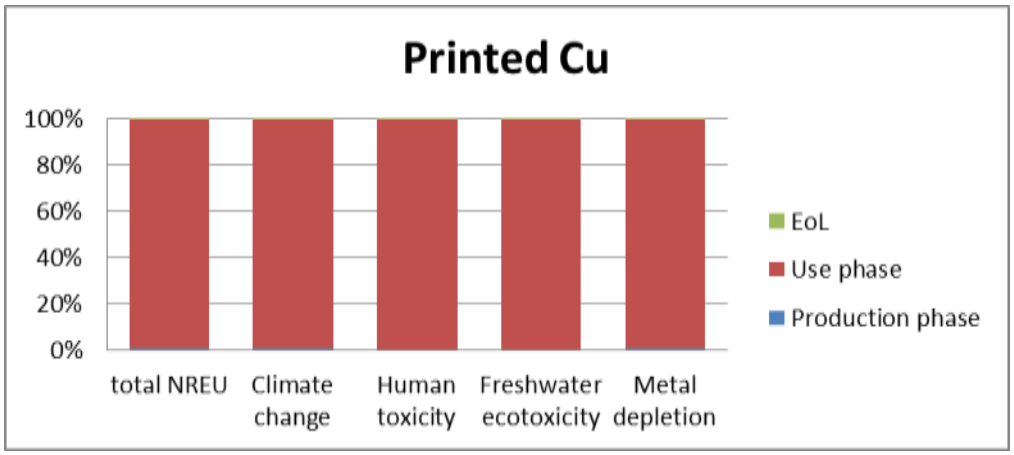

Figure 10. Results for Printed Cu

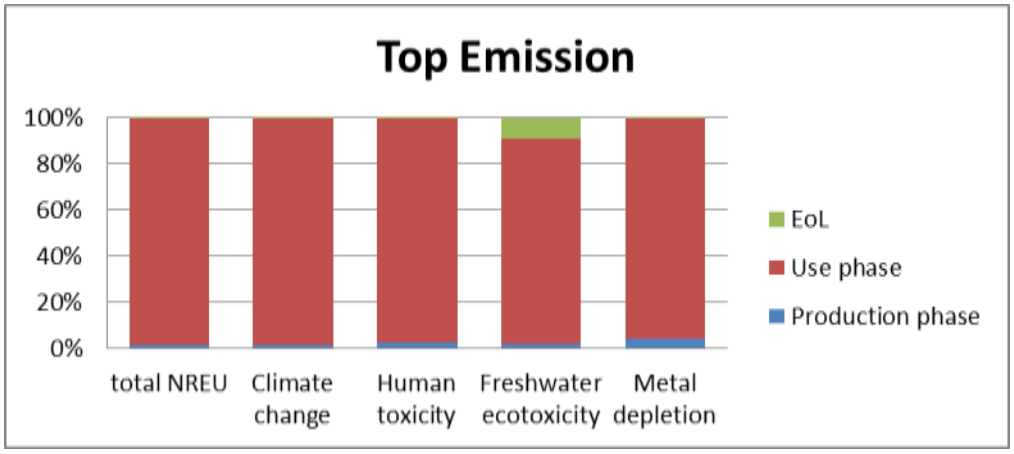

Figure 11.Results for Top Emission

Table 2. Results on selected environmental impact categories for use phase per MLm-h

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**kg CO_2 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg Fe eq**
Use phase	4.31E+03	2.15E+02	1.46E+02	2.82E+00	9.96E+00

4.4.2 Results cradle to factory gate + end of life

A main goal of this research is to compare the environmental impacts of the five different OLED designs. The impacts in the use phase are identical, so it has been decided to keep them out of this comparison. This section first gives the results for the different OLED designs (paragraph 4.4.2.1). In paragraph 4.4.2.2 the environmental impacts of the different scenarios regarding the liner foil waste are compared. In paragraph 4.4.2.3, the results for the five designs are compared.

4.4.2.1 Results per OLED

Fast2Light

The results per life cycle stage (Table E - 5 in the appendix and Figure 12) show large contributions of consumable use on all impacts. On climate change the end of life and waste stages have relatively larger contributions due to the high climate change impacts of plastic (liner foil and substrate) incineration.

The breakdown per machine shows that for NREU and climate change, the PET substrate has the largest contribution, followed by the Cu/Au machine. The barriers (which occur twice in the OLED) also have a large contribution, mainly caused by the use of silane for the SiN layer and acrylate in the OCP layers.

For human toxicity, freshwater ecotoxicity and metal depletion, the gold use in the Cu/Au deposition machine has the largest contribution. The high impacts associated with gold use are explained by the high energy use during mining and extraction of the metal ores, and the use of toxic chemicals such as cyanide during extraction. The contribution of NiCr to metal depletion is mainly due to the chromium used.

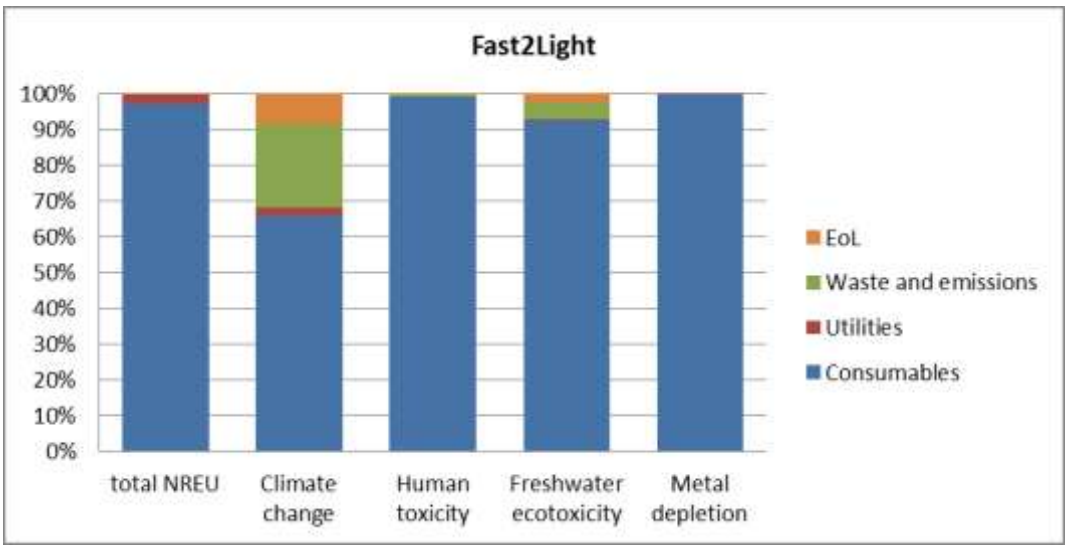

Figure 12. Contributions per life cycle stage for Fast2Light

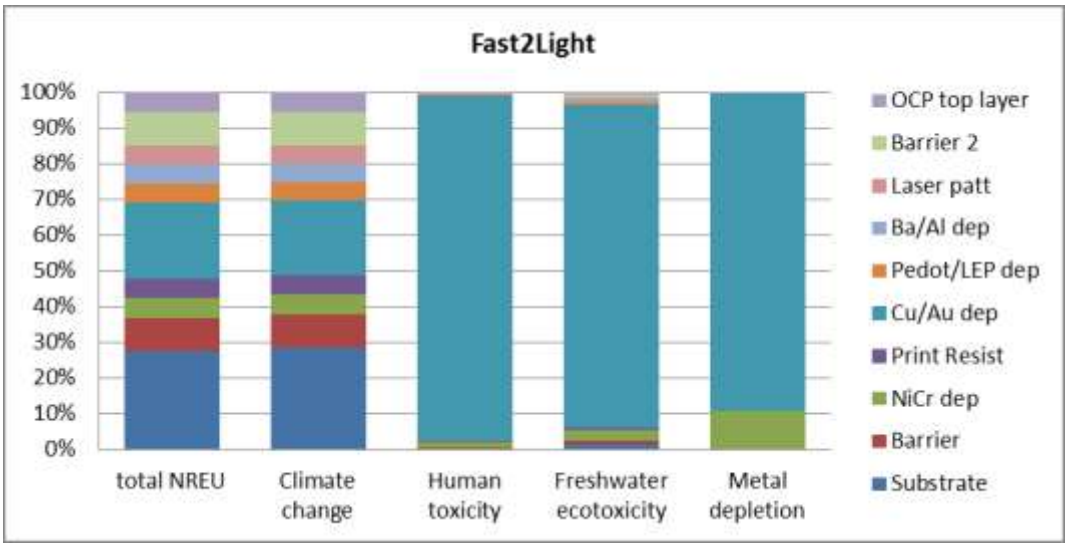

Figure 13. Contributions per machine for Fast2Light

Printed Ag

The contribution of consumables is the largest on all impacts, except on freshwater ecotoxicity. There, the end of life impacts of the used silver has a large contribution. When released into aquatic environments, silver has biocidal properties. After municipal waste incineration, large fractions of the used silver end up in landfills wherefrom they are slowly released into the groundwater (see also chapter 5).

The use of silver also accounts for most of the human toxicity and metal depletion impact, because of high energy use and the use of toxic chemicals during mining and extraction. Because the total impacts on NREU and climate change are relatively smaller, the role of the substrate and barriers is relatively larger than with the Fast2Light design. The laser patterning step causes low environmental impacts, but the laser patterning machine does contribute to NREU and climate change. This is because of the liner foil that is used.

The large contribution of waste and emission is (same as for Fast2Light) mostly caused by the use of liner foils.

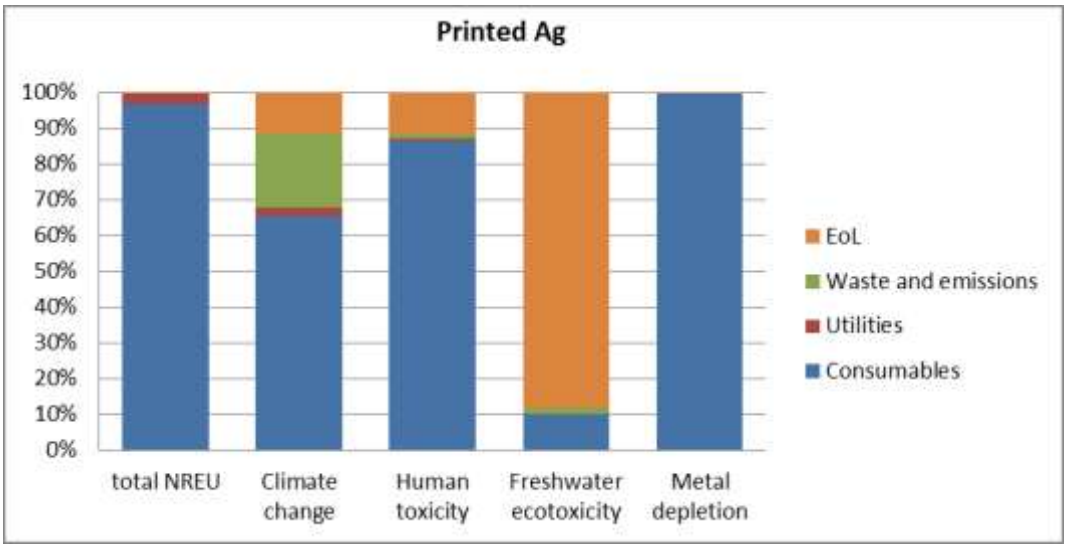

Figure 14. Contributions per life cycle stage for Printed Ag.

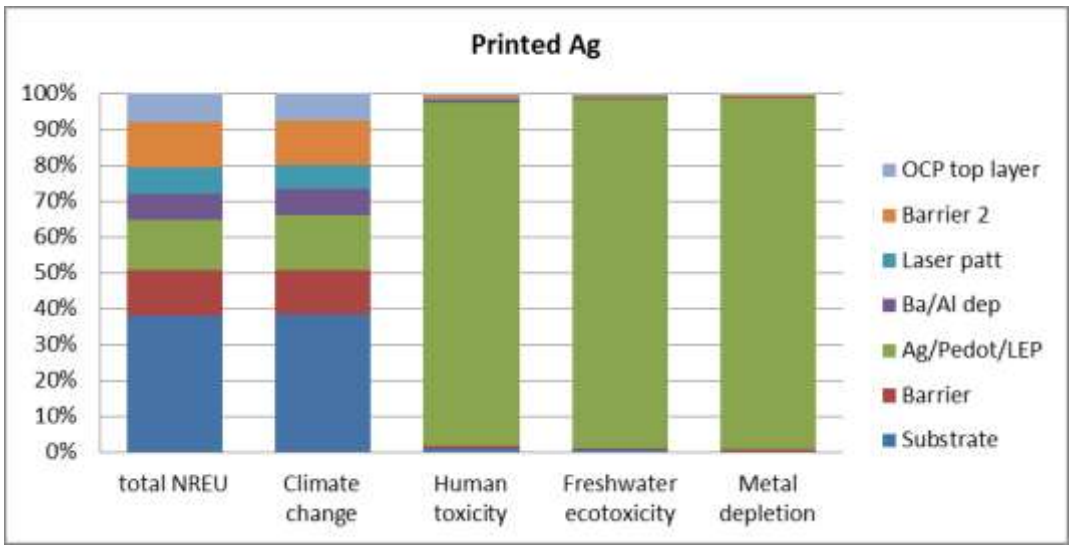

Figure 15. Contributions per machine for Printed Ag.

Embedded

For the Embedded design, again the consumables have large contributions. The relatively larger contribution in the waste and emissions stage is caused by the use of a temporary substrate and the PET liners of the lamination adhesive, which are both incinerated after use. The use of the temporary substrate and the adhesive also explain the large contribution of the transfer/etch machine.

The larger end of life impact on freshwater ecotoxicity is caused by the nickel from the NiCr deposition step. After incineration, the nickel mainly ends up in landfill, from which it leaches into groundwater. (This effect does not show for the Fast2light design, which also contains a NiCr layer, because of the dominance of the gold use in that design.)

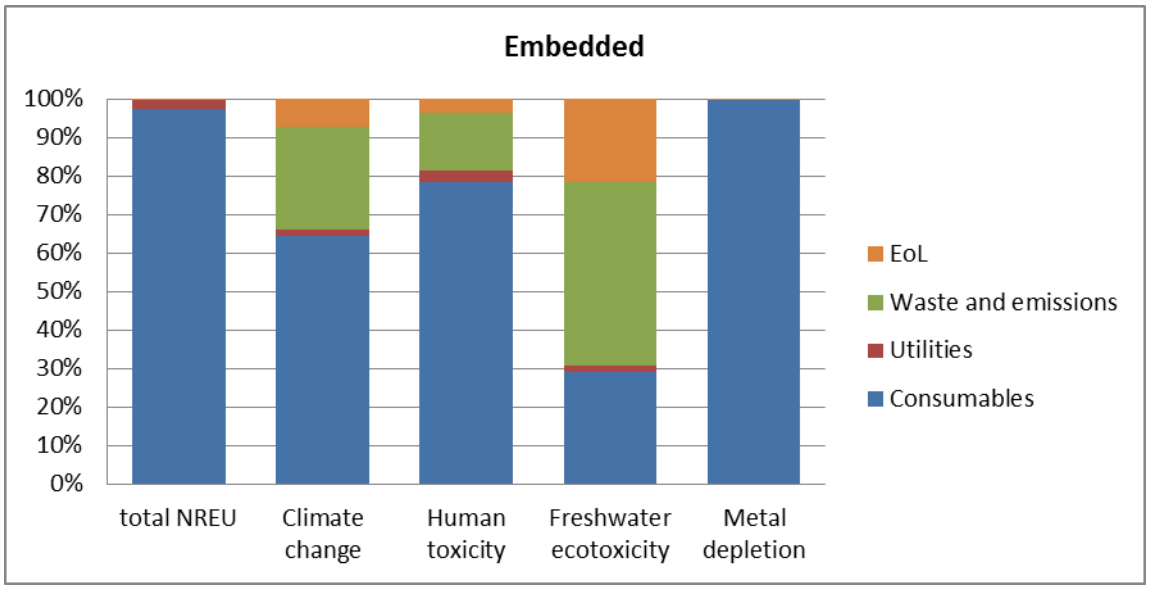

Figure 16. Contributions per life cycle stage for Embedded.

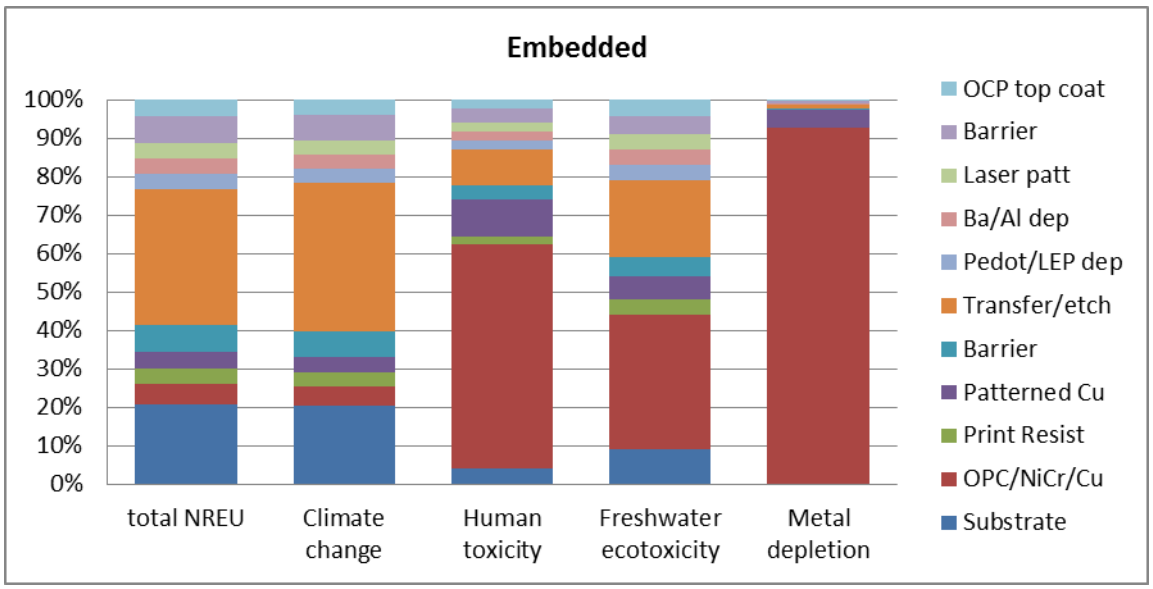

Figure 17. Contributions per machine for Embedded.

Printed Cu

The contributions for the Printed Cu design are similar to those for Printed Ag, with the exception of the end of life impacts associated with silver use. The impacts of copper are lower than those of silver on all indicators, but it is still the largest contributor to metal depletion and human toxicity. The toxicity impacts of copper result from toxic chemical use for the extraction of copper from ores.

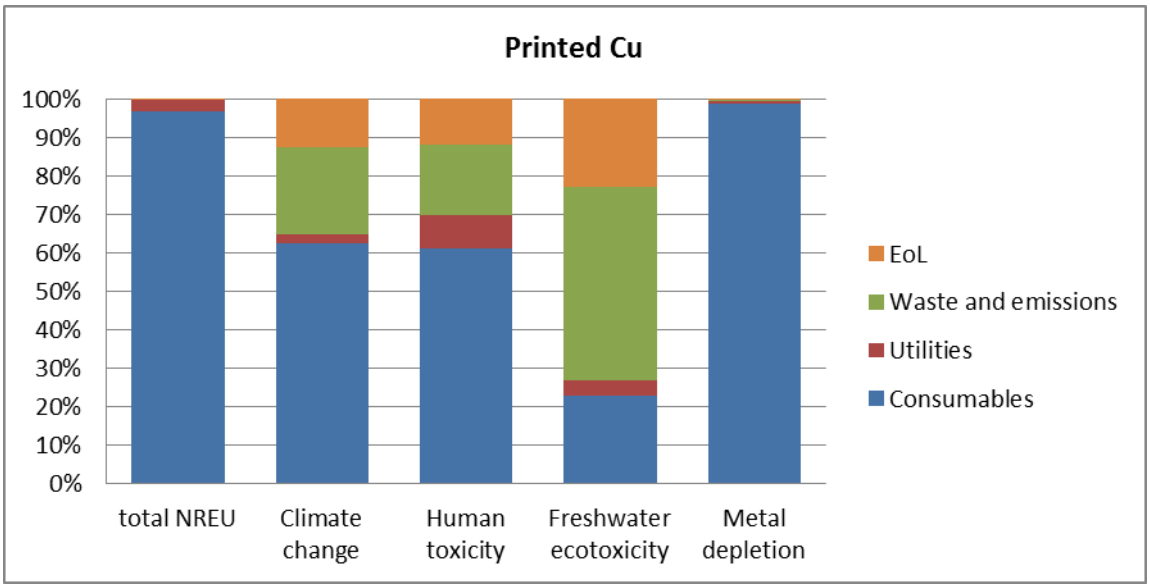

Figure 18. Contributions per life cycle stage for Printed Cu.

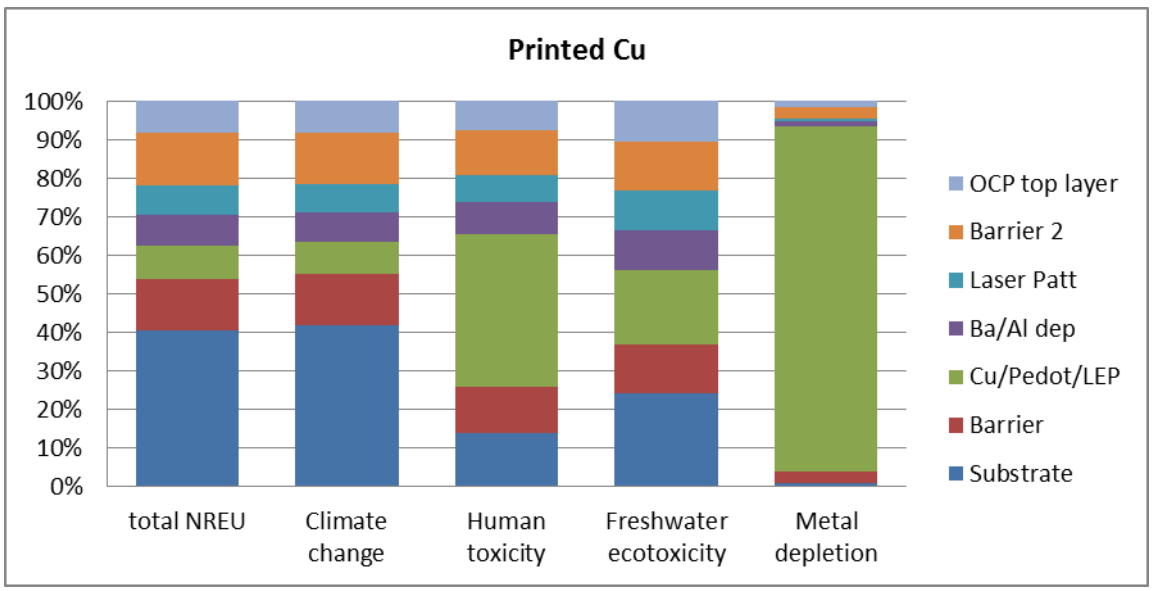

Figure 19. Contributions per machine for Printed Cu.

Top Emission

The top emission design uses the same Ag nano paste as Printed Ag, causing high impacts on freshwater ecotoxicology in the end of life stage, and on human toxicity and metal depletion from consumable use. On NREU and climate change, the liquid glass machine has high contributions because it contains a temporary substrate transfer step, identical to the one in the embedded design. The high waste and emission impact on climate change is also caused by the transfer from the temporary substrate.

Because the aluminium substrate is considerably thinner than the PET substrates (35 microns and 125 microns respectively), the contributions of the aluminium substrate are smaller than those of PET substrates even though the impacts per kg are larger for aluminium on most indicators (see paragraph 4.4.3 for a more detailed comparison of different substrates).

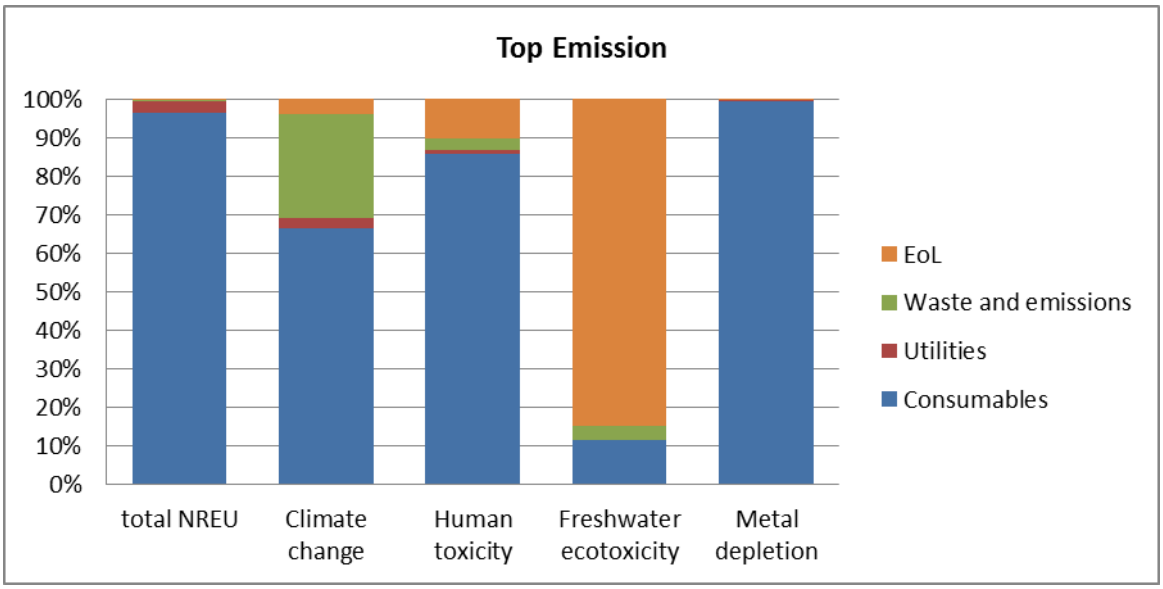

Figure 20. Contributions per life cycle stage for Top Emission.

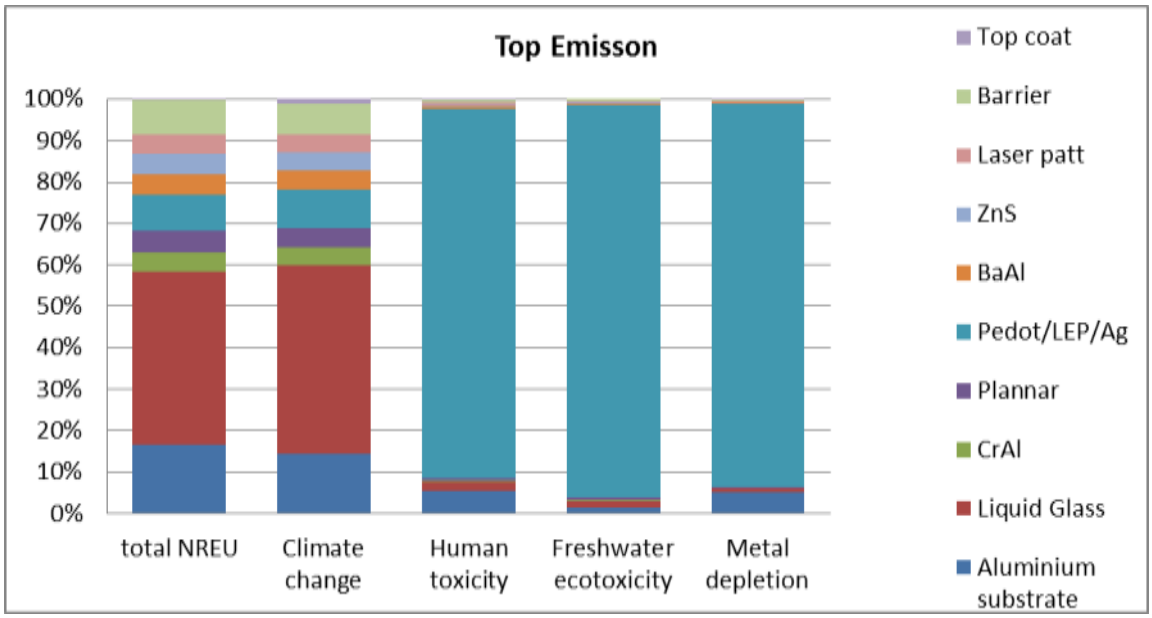

Figure 21. Contributions per machine for Top Emission.

4.4.2.2 Contribution of liner foils

In between all machines, an LDPE liner foil is used and discarded immediately after use (processes **Error! eference source not found.** and **Error! Reference source not found.**). Because the OLED designs require 7 to 11 different machines, the contributions of these foils can be quite significant. Table 3 below shows that the contributions of the liner foil processes can contribute up to 46% to total NREU and 44% to climate change. In absolute terms, the contributions of liner foils to Printed Ag and Printed Cu are equal, but relatively the contributions are higher for Printed Cu due to the lower total impacts of Printed Cu. The high contribution to freshwater ecotoxicity for Embedded and Printed Cu is explained by the overall low impact on this indicator for these designs. Even though liner foils do not contain metal, the use of liner foils does contribute to metal depletion. This is caused by the use of metal in the production chain of the plastics, e.g. for machinery and logistics. Because the liner foils occur in between machines, designs using more machines are affected more by this.

Table 4 shows that recycling of the foils reduces the impacts significantly.

With LDPE incineration

Table 3. Contributions of liner foils with LDPE incineration

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Fast2Light					
Total OLED	2.2E+00	1.4E-01	6.7E-01	8.9E-03	1.0E-01
Total liners	1.0E+00	6.4E-02	6.9E-03	5.1E-04	2.6E-04
Contribution	46%	44%	1%	6%	0%
Printed Ag					
Total OLED	1.6E+00	1.1E-01	1.8E-01	1.7E-02	2.1E-02
Total liners	6.7E-01	4.3E-02	4.6E-03	3.4E-04	1.8E-04
Contribution	42%	40%	3%	2%	1%
Embedded					
Total OLED	2.9E+00	2.0E-01	4.1E-02	1.5E-03	2.3E-02
Total liners	1.1E+00	7.1E-02	7.7E-03	5.7E-04	2.9E-04
Contribution	38%	35%	19%	38%	1%
Printed Cu					
Total OLED	1.5E+00	9.9E-02	1.2E-02	5.7E-04	4.1E-03
Total liners	6.7E-01	4.3E-02	4.6E-03	3.4E-04	1.8E-04
Contribution	45%	43%	37%	60%	4%
Top Emission					
Total OLED	2.5E+00	1.8E-01	1.9E-01	1.8E-02	2.3E-02
Total liners	1.0E+00	6.4E-02	7.0E-03	5.1E-04	2.7E-04
Contribution	41%	36%	4%	3%	1%

With LDPE Recycling

Table 4. Contributions of liner foils with LDPE Recycling.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Fast2Light					
Total OLED	1.4E+00	9.0E-02	6.7E-01	8.5E-03	1.0E-01
Total liners	1.7E-01	9.8E-03	3.7E-03	8.5E-05	2.4E-04
Contribution	13%	11%	1%	1%	0%
Printed Ag					
Total OLED	1.0E+00	7.1E-02	1.7E-01	1.7E-02	2.1E-02
Total liners	1.2E-01	6.6E-03	2.5E-03	5.7E-05	1.6E-04
Contribution	11%	9%	1%	0%	1%
Embedded					
Total OLED	2.0E+00	1.4E-01	3.7E-02	1.0E-03	2.3E-02
Total liners	1.9E-01	1.1E-02	4.1E-03	9.4E-05	2.7E-04
Contribution	10%	8%	11%	9%	1%
Printed Cu					
Total OLED	9.4E-01	6.3E-02	1.0E-02	2.8E-04	4.1E-03
Total liners	1.2E-01	6.6E-03	2.5E-03	5.7E-05	1.6E-04
Contribution	12%	10%	24%	20%	4%
Top Emission					
Total OLED	1.9E+00	1.4E-01	1.8E-01	1.7E-02	2.1E-02
Total liners	1.8E-01	1.0E-02	3.9E-03	8.7E-05	2.4E-04
Contribution	9%	7%	2%	1%	1%

4.4.2.3 Five OLEDs compared

Table 5 and Figure 22 show the results for the cradle to factory gate and end of life phases added together, for five selected indicators. The results show that for all indicators, the Printed Cu design has the lowest impacts. For climate change and NREU, both printed OLED designs (Printed Ag and Printed Cu) have the lowest impacts, and Embedded has the highest impacts. The difference between the two printed designs is entirely explained by the difference between copper and silver use, since the designs are identical except for the anode materials. On all indicators, copper has lower impacts.

For human toxicity and metal depletion, the Fast2Light OLED has highest impacts due to the Au incorporated; for freshwater ecotoxicity, the Printed Ag and Top emission OLEDs have highest impacts due to the use of Ag. Embedded has high climate change impacts due to the use of the temporary substrate and the high contribution of liner foils.

Table 5. Results on selected environmental impact categories for cradle to factory gate + end of life (per MLm-h)

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**kg CO_2 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg Fe eq**
Fast2Light	2.2E+00	1.4E-01	6.7E-01	8.9E-03	1.0E-01
Printed Ag	1.6E+00	1.1E-01	1.8E-01	1.7E-02	2.1E-02
Embedded	2.9E+00	2.0E-01	4.1E-02	1.5E-03	2.3E-02
Printed Cu	1.5E+00	9.9E-02	1.2E-02	5.7E-04	4.1E-03
Top Emission	2.5E+00	1.8E-01	1.9E-01	1.8E-02	2.3E-02

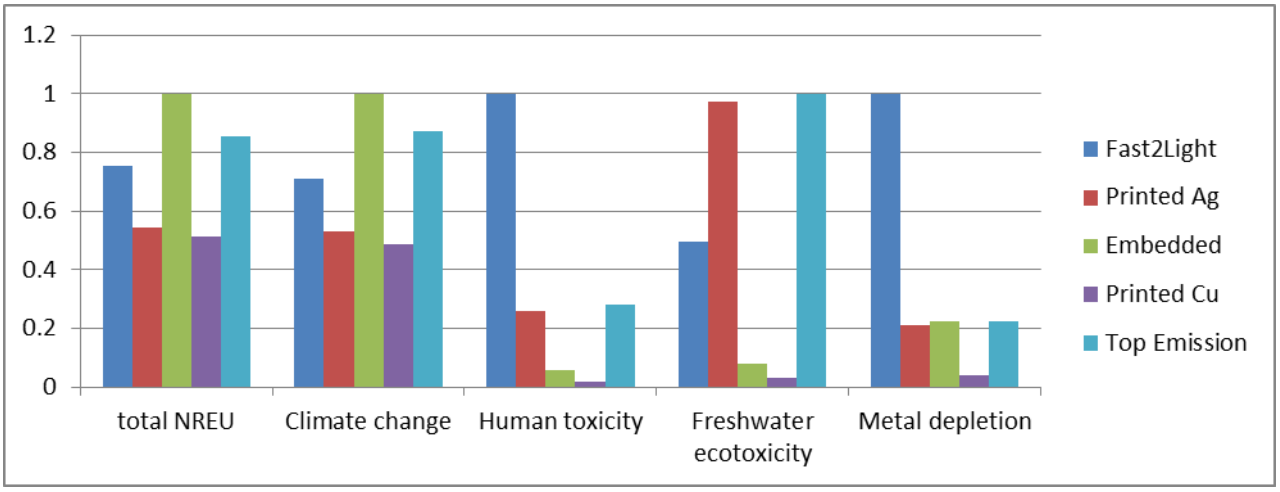

Figure 22. Five OLEDs compared.

4.4.3 Metal and PET substrates compared

Table 6 and Figure 23 compare the results for the different substrates assessed. For the metal substrates, two thicknesses are included.

The results show that for substrates of the same thickness, the PET substrate has the lowest environmental impacts, even when the bottom barrier is included in the comparison. When metal substrates of 35 micron thickness are compared, the metal substrates have lower impacts on climate change and NREU, but higher impacts on the other categories.

The copper substrate has slightly lower impacts on climate change and NREU, but on the other categories the aluminium substrate has significantly lower impacts.

Table 6. Results for PET and aluminium substrates

		total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
		MJ	**kg CO_2 eq**	**kg 1,4-DB eq**	**kg 1,4-DB eq**	**kg Fe eq**
PET (125 µm)	Substrate	1.2E+01	7.9E-01	3.3E-02	2.6E-03	6.9E-04
	Barrier	3.9E+00	2.5E-01	2.8E-02	1.4E-03	2.3E-03
	Total	1.5E+01	1.0E+00	6.1E-02	4.0E-03	3.0E-03
Aluminium (35 µm)	Total	7.9E+00	4.9E-01	2.0E-01	4.9E-03	2.3E-02
Aluminium (125 µm)	Total	2.3E+01	1.6E+00	6.9E-01	1.7E-02	8.0E-02
Copper (35 µm)	Total	7.6E+00	4.2E-01	6.7E+00	8.1E-02	6.1E+00
Copper (125 µm)	Total	2.2E+01	1.3E+00	2.4E+01	2.9E-01	2.2E+01

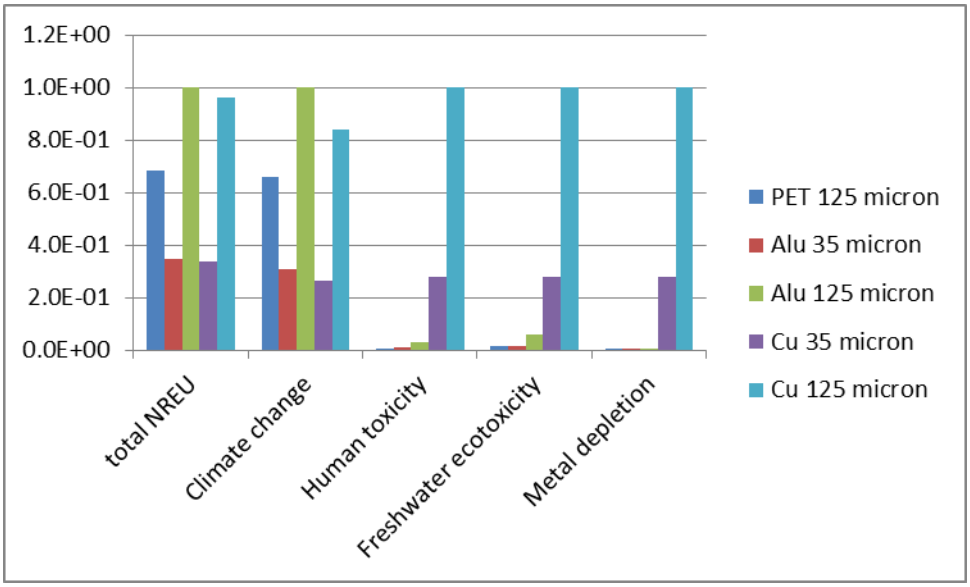

Figure 23. Metal and PET substrates compared

4.4.4 Sensitivity analysis

4.4.4.1 Sensitivity to total yield

The sensitivity of the end results to the assumed total yield is given in the graphs below (Figure 24 - Figure 28). The results show that for all impacts, the results are sensitive to the assumed total yield. This is to be expected because the inventoried amounts of materials, consumables and waste production are all affected by the total yield. Therefore, all curves show the expected 1/total yield relationship. Because the fraction non-yield is recycled more effectively than the working OLEDs, for the categories where metal use is important the sensitivity is somewhat less than would be expected from the 1/total yield relation. This is indicated for the Fast2Light and Printed Ag OLEDs by the dashed line in Figure 25 and Figure 27.

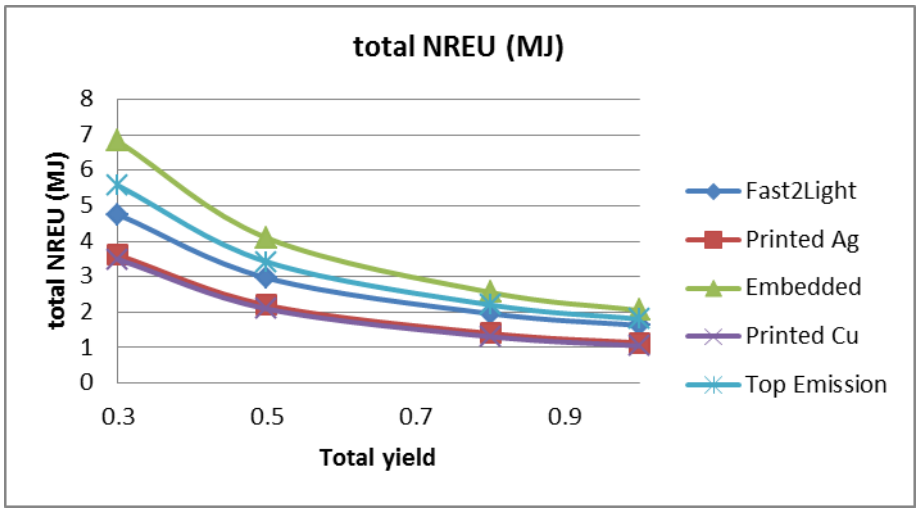

Figure 24. Sensitivity of NREU to Total yield.

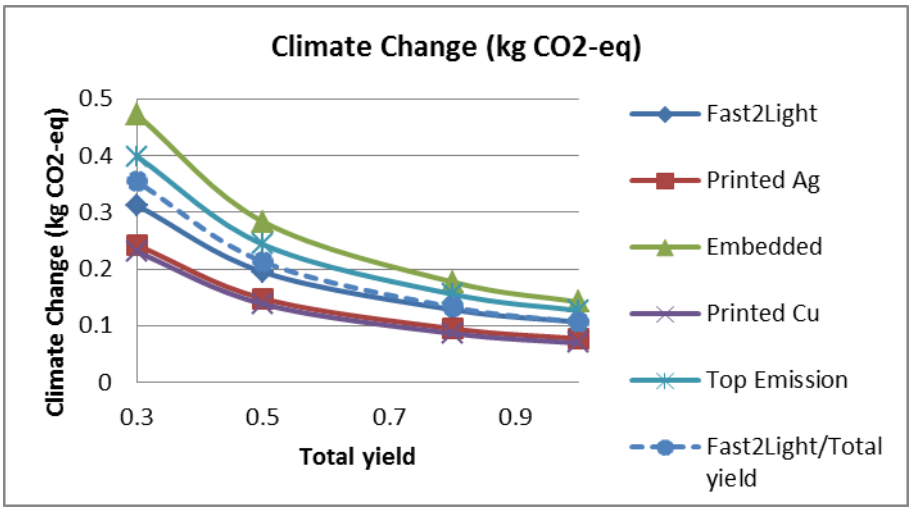

Figure 25. Sensitivity of Climate Change to Total yield. The dashed line indicates the 1/total yield relation that is to be expected for Fast2Light.

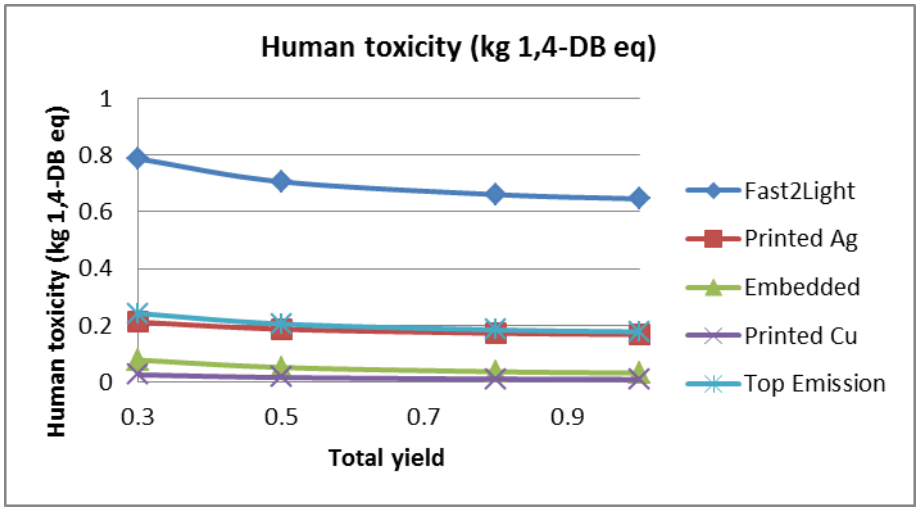

Figure 26. Sensitivity of Human toxicity to Total yield.

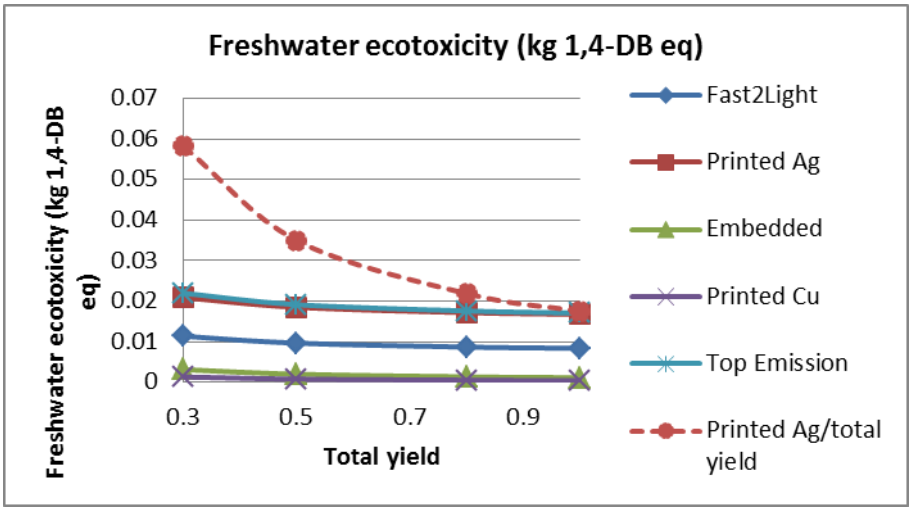

Figure 27. Sensitivity of Freshwater ecotoxicity to Total yield. The dashed line indicates the 1/total yield relation that is to be expected for Printed Ag.

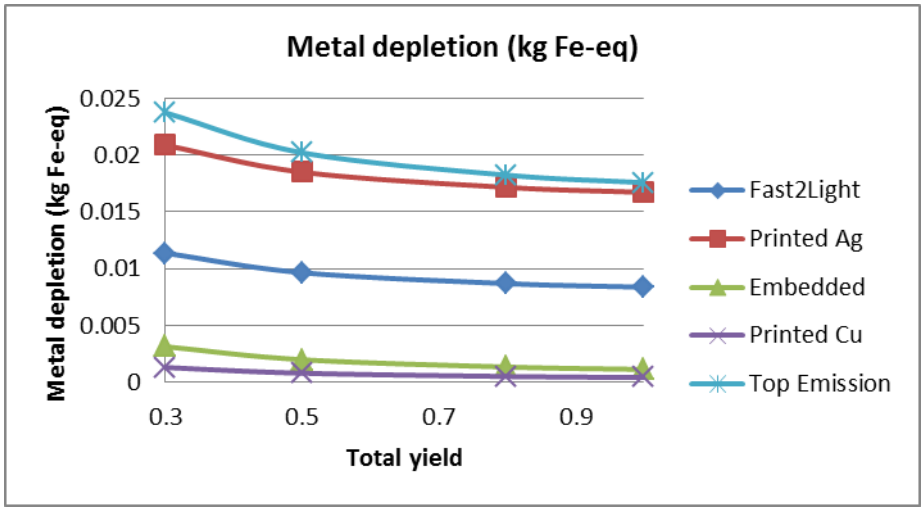

Figure 28. Sensitivity of Metal depletion to Total yield.

4.4.4.2 Sensitivity to recycle rate

The sensitivities of the end results to the assumed recycle rate are illustrated in the graphs below (Figure 29 - Figure 33). On NREU and climate change, the results show little to almost no sensitivity to the assumed recycle rates. This is explained by the low contributions that the metals have on these impacts, and the relatively small difference between primary and secondary metals.

On human toxicity the results for Fast2Light are highly sensitive to the recycle rate. This is because the production of primary gold has high human toxicity impacts compared to secondary gold. For freshwater ecotoxicity the analysis shows that higher recycling of the silver avoids its emission in the end of life phase, thus reducing the impacts significantly.

Different designs have different sensitivities to the assumed recycle rates. For NREU and climate change this does not lead to different prioritization between the designs. For human toxicity, freshwater ecotoxicity and metal depletion, higher recycle rates make the differences between the designs smaller. Extremely high recycle rates diminish the end of life impacts of nano silver, making them competitive with the other designs. At recycle rates above 95% the impact of the silver anode designs becomes lower than the impact of the Embedded OLED, but the difference remains small. A scenario with recycle rates as high as 95% are unlikely, because the metallic yield of the smelting processes alone is about 95%. A recycle rate of 95% would therefore require perfect collection and pre-processing rates.

The Printed Ag and Top Emission designs have different sensitivities because for the Top Emission design, recycling of the aluminium substrate is assumed.

For metal depletion, low recycle rates favour the Embedded and printed Cu designs compared to the printed silver designs. Higher recycle rates make the better performing anode of the Embedded design less important and therefore the printed designs perform better at recycle rates around 30% and higher.

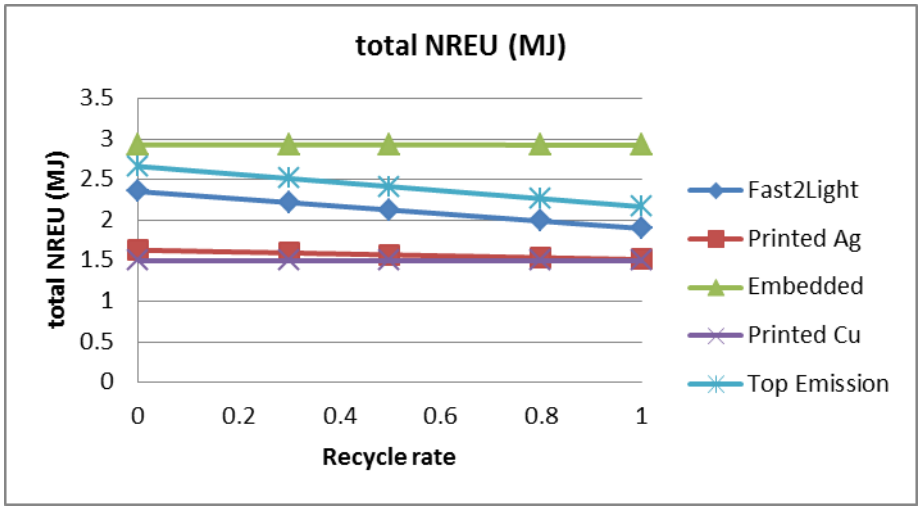

Figure 29. Sensitivity of NREU to recycle rate.

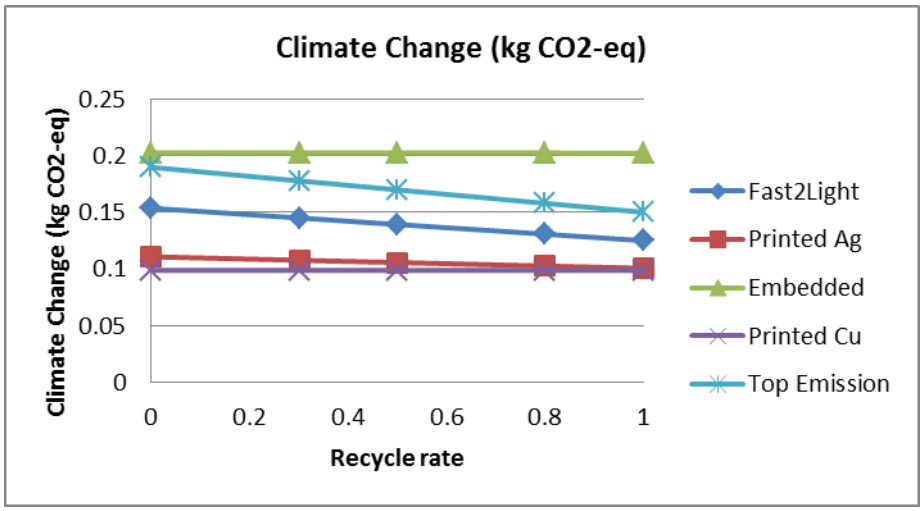

Figure 30. Sensitivity of Climate Change to recycle rate.

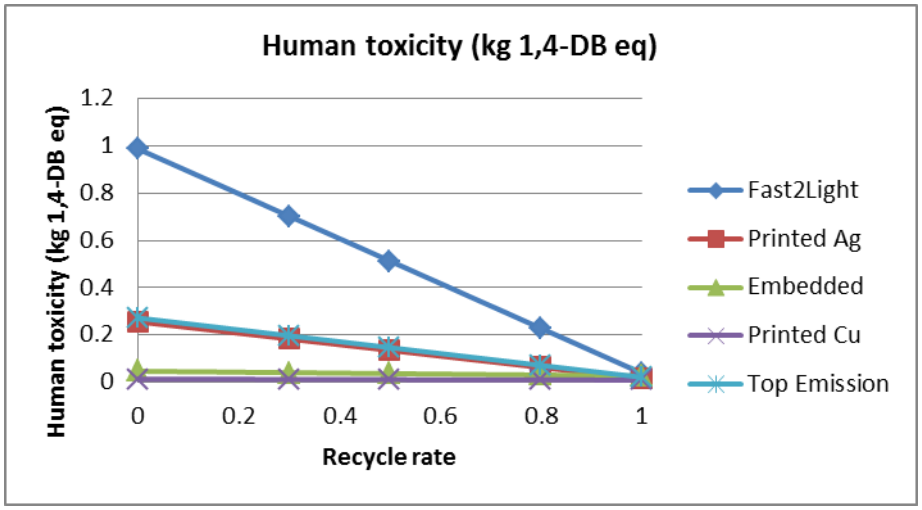

Figure 31. Sensitivity of Human toxicity to recycle rate.

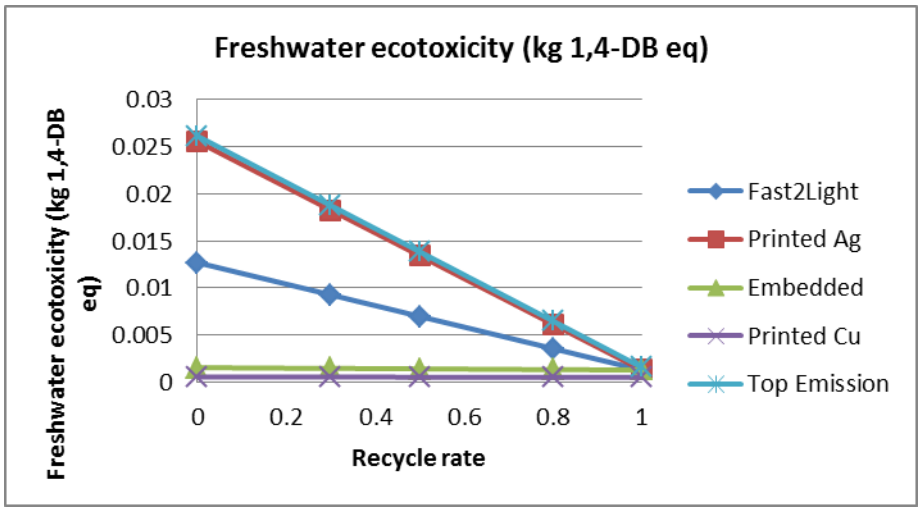

Figure 32. Sensitivity of Freshwater ecotoxicity to recycle rate.

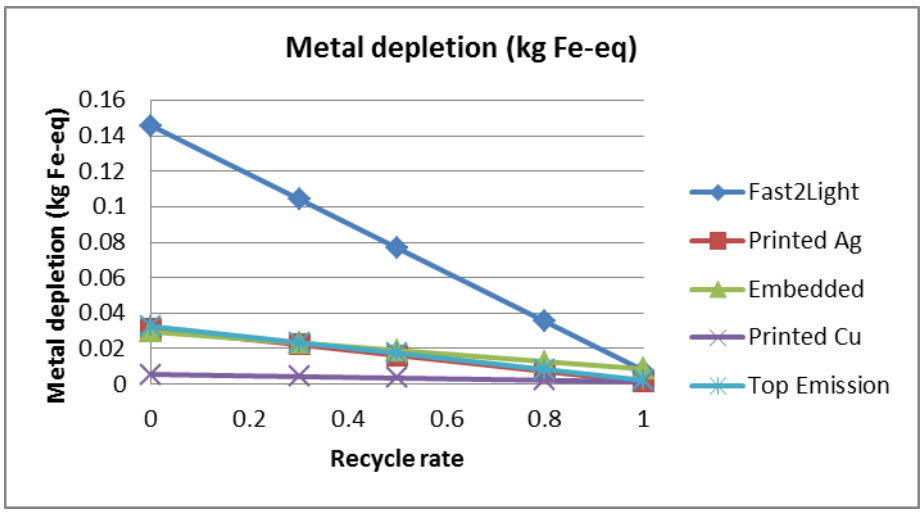

Figure 33. Sensitivity of Metal depletion to recycle rate.

4.4.5 Conclusions

4.4.5.1 Overall conclusions

From the environmental assessment the following conclusions can be drawn:

- In the entire life cycle, electricity use in the use phase has by far the largest contribution on all impacts. This is common to all lighting technologies. Therefore, any change made to the designs of the OLEDs to reduce environmental impacts should above all not diminish their luminous efficacy.
- When the use phase is not considered, the assessment shows that the use of consumables has the highest contributions to the impacts, except for the end of life phase of silver use.
- Substrates and liner foils cause high environmental impacts for all OLED designs due to their high material contributions.
- The contributions of liner foils are very high in all OLED designs. Even when recycling of the LDPE foils is considered, the contribution to climate change can be as high as 11% (for the Fast2Light OLED).
- The use of an aluminium substrate for the Top Emission design has slightly lower impacts on NREU and climate change impacts. The avoidance of the use of a bottom barrier also lowers the impacts. This reduction is entirely compensated by the use of the temporary substrate.
- The part of silver that is not recycled eventually ends up for a large fraction in aquatic environments. The high ecotoxicity associated with these silver emissions makes silver anode OLEDs particularly unsuitable for municipal waste incineration and landfilling. Only in scenarios where unrealistically high recycling rates are assumed designs using silver have ecotoxicity impacts comparable to the other designs.
- The use of gold has very high impacts on all indicators due to high energy use in the mining and extraction and the use of toxic chemicals in the extraction of primary gold.
- The contribution of utilities (electricity, water and nitrogen gas) is very low to all environmental impacts. Therefore, the results are not affected significantly by the number of machines calculated in the process flows.

4.4.5.2 Comparison of five different designs

From the comparison of five different designs the following conclusions can be drawn:

- On all impact categories, the Printed Cu design shows the lowest environmental impacts. This is explained by the low amount of process steps and the low impacts associated with copper as compared to gold and silver.
- The Printed Ag design also has low impacts on most impact categories, except for human toxicity, freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity and urban land occupation (see also appendix E), where the end of life fate of the silver used causes high impacts.
- The difference between Printed Ag and Printed Cu is explained entirely by the difference between copper and silver use, since the designs are identical except the anode material.
- Sensitivity analysis shows that assuming different total process yields does affect the designs differently, but does not change the order in which the different designs score.
- The comparison shows that designs using many process steps (and therefore many machines) have larger impacts, due to the high contributions of liner foils. This favours the Printed designs compared to the other designs, which are more complex and use more machines.
- Other causes of larger impacts are the use of temporary substrates (Embedded, Top Emission) and gold use (Fast2Light).

5 Environmental risk of nano silver in printed electronics

5.1 Introduction

The nano materials development and production field is growing rapidly. Nano materials are being used in a wide variety of products, e.g. textiles, cosmetics, medical devices, water treatment technologies and food packaging. [9] Nano materials often show unique and considerably different chemical, physical and biological properties compared with their bulk and ionic counterparts. It is these unique properties that make nanomaterial science a promising field of research, but they also complicate the assessment of their environmental impacts. Researchers have identified many obstacles that stand in the way of a good understanding of the eco toxicological effects of nano materials. One of them, as pointed out by many researchers, is the lack of definition of a 'nano' material itself. The prefix 'nano' refers to the unit nanometre, 10^{-9} meter. Therefore, nano materials typically are defined as 'having one or more dimension on the scale between 1 and 100 nanometre. This definition is somewhat arbitrary and does not necessarily coincide with the threshold between 'normal' and 'nano' physico-chemical properties. [9] [13] [32]

Much research has already been performed on the potential toxicology of these materials. However, many different sizes and configurations of nano silver particles fit this definition and combined with the lack of systematic standard methodologies, data interpretation and generalization is difficult. [13] [33] [34] The methods used today for toxicity assessment are developed with the assessment of chemicals in mind; the unique properties that distinguish nano materials from their bulk material counterparts are at the same time the properties that pose challenges to toxicity assessment. [35] [36] [37] The same problems arise with developing regulatory requirements for these materials. [32] Therefore, knowledge on eco toxicological properties and environmental fate, but also development of regulation is lagging behind the continuous development of new materials and application techniques. [32] [38]

To understand the life cycle impacts of nano silver and copper, a good understanding of the environmental fate and ecological exposure is essential. Again the lack of definition, numerous different types of nano materials and lack of standardized methodology, combined with a lack of information on production and use of nano particles stand in the way of developing this knowledge. [39] Due to their small size, nano materials cannot be easily detected, making it difficult to monitor potential exposure routes. [13]

Due to the above described difficulties with assessing the ecotoxicology and environmental fate of nano silver, it is not possible to quantify the environmental impacts of accidental or intentional release of these particles to the environment. Because of these problems, this part of the research will take a somewhat different approach. As proposed by e.g. Shatkin (2008) and by Wardak et al. (2008), the methods of environmental risk assessment and life cycle assessment can be combined. Combining the two methods makes it possible to give an indication of whether environmental problems are to be expected, and where in the OLED life cycle they will arise. The main drivers that may require more detailed analysis can be identified, without quantifying the impacts. [12] [13]

After this introduction, this chapter follows the environmental risk assessment methodology as described in section 2.2. First, an exposure assessment is performed in which the life cycle of the nano pastes is described and potential exposure routes are identified (paragraph 5.2). In turn, a literature survey is undertaken to determine whether silver nanoparticles are expected to have a negative effect on humans, animals or ecosystems (paragraph 5.3).

5.2 The nano silver Life Cycle

Nanoparticles can be released into the environment during synthesis, during incorporation into product goods, during the use phase of these goods and during recycling or disposal of these goods. [34] [40] This

paragraph describes the life cycle of nano silver used for OLED production in order to determine potential exposure routes of silver nanoparticles used in OLED manufacturing.

5.2.1 Production of nano silver

There are several ways to produce nano silver and copper pastes, which can be characterized either as 'top down' or 'bottom up'. In top down methods, bulk silver is converted into powder by physical processes (e.g. pulsed wire evaporation or laser ablation). In bottom up processes, a chemical or biochemical process is used to grow particles of metallic silver suspension from metal salts (chemical precipitation). A silver salt is reduced by a reducing agent. The size of the particles can be controlled by the choice of reducer and by adding stabilizing or capping agents, which also prevent further agglomeration of the particles. [34] [41] [42]

A 2010 review shows that most silver nanoparticles (> 96%) are produced by a bottom up process. Of them, 83% are made by the reduction of silver nitrate ($AgNO_3$), most often (80%) in a water solution. This is explained by the relatively low cost of silver nitrate and water compared to the alternatives. Examples of other commonly used salts are silver acetate ($AgC_2H_3O_2$), silver perchlorate ($AgClO_4$) and silver sulphate (Ag_2SO_4). Alternative solvents may be ethanol, dimethylformamide, ethylene glycol and toluene. A reducing agent is used to provide the free electrons needed to reduce the silver ions. Sodium borohydride ($NaBH_4$) and citrate are used most commonly, but reduction by irradiation, micro-organisms and amines are also common. As stabilizing agents, citrate, polyvinyl pyrrolidone and amines are encountered most, but again other chemicals can be used as well. [41]

The exact processes used for nano silver and copper paste production are regarded highly confidential and therefore it is not possible to use real industry data. It is also not possible to receive data on waste and emissions resulting from these processes. From the MSDS of the pastes currently used by Holst Centre can be concluded that the complexing agent currently used is organic. [43]

This leaves many uncertainties regarding the production process. Composing an LCA, in more detail than the one done in chapter 4 of this report is therefore not possible. What can be said about the production phase is that it is likely that the anions left as a by-product from the reduction process are likely to be nitrate, known as a drinking water pollutant and known to cause eutrophication when released in high concentrations into surface waters. From stoichiometry it can be concluded that for every mole of silver, at least one mole of nitrate will be released, or from their relative molar masses, for one kg of silver, at least 1.75 kg of nitrate will be released.

It can be expected that the conversion of silver ions into silver nanoparticles will not always be 100%, Tolaymat et al. found that up to about 30% of the initial silver ions may not make it into the final nano silver product, and has to be dealt with in waste treatment, be reused or be released into the environment. [41]

5.2.2 Application of nano silver paste

The metal pastes are used in the studied OLEDs in a rotary screen printing process. Per OLED (58,5 x 58,5 cm), $8{,}04*10^{-4}$ kg is applied on the device, and another 5% is wasted.

After application, the printed structure is exposed to several processes in order to fix the materials onto the substrate and ensure good conductivity. First, the organic thinner (a-terpineol) is evaporated out of the ink. Also, the capping agent which was used to prevent coagulating of the nanoparticles is removed. After that, the particles are sintered by a thermal or photonic curing process. After sintering, the particles are bonded to each other. The degree into which the particles are bonded depends amongst other things on the curing time and a temperature used, and is therefore an engineering consideration. At the moment, no definitive answer can be given to the question of whether the silver should be regarded as bulk or as nano material after the sintering step. [7] [44]

5.2.3 OLED use phase

In the use phase, the silver is entirely encapsulated by the device and with normal use it can be expected that no silver particles are released from the device.

5.2.4 End of Life phase

The end of life fate of the metals in the OLED depends on the end of life fate of the device. When the OLED is recycled for its precious metal content, mechanical separation techniques such as shredding and grinding

are used. [21] [45] These processes cut the devices into small pieces, exposing the printed silver lines at the edges. At the moment, no studies have been published on whether significant amounts of nano particles will be released from this process, but a similar scenario has been studied for the case of carbon nano tubes in Lithium-ion batteries. They found that carbon nano tubes occurred in the dust created by these mechanical separation processes, which were not completely removed by the facilities exhaust filters. [40] It has to be mentioned that the carbon nano tubes in Lithium-ion batteries occur in larger amounts, and that they are not sintered to form coagulated structures as is the case with nano silver in printed electronics.

The case for incineration has been studied by Roes et al. They showed that the incineration of silver nanoparticles in MSWI plants is likely to result in the formation of primary and secondary nano objects, which can be expected to be released into the environment along with the flue gasses. [46]

5.3 Effect assessment

This paragraph will give an outline of current literature published on the (eco)toxicity of silver nanoparticles, it is not meant to be a complete literature review.

Even though silver is known to cause serious acute effects on humans in high doses, it is considered relatively harmless to humans under normal circumstances. Silver has been used for its antibacterial properties in medical applications for several decades, without causing serious adverse effects to humans. [34] [47] However, Silver ions are known to cause adverse effects on humans and ecosystems and as a result, silver has been classified as an environmental hazard on the EEC 1976 Dangerous Substance Directive List II (76/464/EEC) and the US EPA priority pollutant list in 1977. [34] [42]

One of the main questions in nano materials toxicology is if and how the toxicological properties of the bulk or ionic materials can be translated to their nano counterparts. There are several reasons to expect a size dependency of the toxicology of particles. Particle size is a limiting factor for the accessibility to the body's organs and tissues. Also, particle size limits the accessibility to cells and cell compartments. Finally, surface/size ratio increases with decreasing particle size, therefore increasing surface reactivity. [48] Nano particles have been proposed to be used as carrier for targeted drug delivery, e.g. for crossing the blood-brain barrier. In the same way, other contaminants may be adsorbed to nano-particles and thereby enter sensitive organs which are normally not receptive to those contaminants. [49]

5.3.1 Bioavailability and bioaccumulation

One of the reasons why bulk silver is considered relatively harmless is its limited bioavailability. Bioavailability is the amount of pollutant that an organism takes up from environmental media. Bioaccumulation is a measure of the potential for a pollutant to be retained by organisms after take-up. Together bioavailability and bioaccumulation are important factors in the risk assessment because availability and subsequent accumulation are usually precursors to toxicity. Silver nanoparticles are unlikely to be an exception to this generalisation. [34]

Silver nanoparticles have been shown to be able to penetrate into the cells of many types of organisms, e.g. zebra fish embryos and bacteria. [34] Another potential risk to organisms is in the form of silver ions. Dissolved silver ions have been shown to be persistent and bio accumulative in prokaryotes and freshwater and marine invertebrates and fish. The chemical properties of silver ions make them compatible for uptake via cell membrane ion transporters, similar to Na and Cu ions into cells. [34] [50] Silver nanoparticles may adsorb adsorbed by the outside of organism's cells where they start releasing high concentrations of ions which penetrate the cell and cause damage. [34]

5.3.2 Observed effects

In vivo research so far is scarce, but some studies have been done on bacteria, several invertebrates and on zebra fish and rainbow trout.

One of the main environmental concerns regarding nano silver particles is its high bioavailability and toxicity to bacteria. There is considerable evidence that silver nanoparticles exhibit antibacterial activity. [34] [50] This raises concern for the possibility that the release of silver nanoparticles disrupts important biochemical processes such as carbon and nitrogen cycling. [50]

Most of the studies on fish show that silver nanoparticles affect early life stage development of zebra fish embryos. Particles also accumulate on the gills, inducing oxidative stress. Threshold concentrations at which these effects occur vary, which may be caused by experimental setup parameters or different particle behaviour. In general, it can be concluded that juvenile zebra fish are more susceptible to silver nanoparticles than to equal concentrations of silver nitrate (AgNO3). [34]

Problems with generalisation of observed effect studies are the dependency of toxicity to shape and size of the used nanoparticles. This is illustrated by a study comparing the effects of silver nanowires, spherical nanoparticles and silver micro particles, which showed no effect for the spherical particles, but strong toxicity for the nano wires. [51] A study compared the effects of silver nanoparticles (<100 nm) to silver non-nanoparticles (>100 nm) on drosophila eggs. They showed lower toxicity of nanoparticles. [52] In the case of aquatic invertebrates, some studies show enhanced silver nanoparticle toxicity as compared to silver ions, but others show less toxicity. The differences in toxicity may be explained by different capping agents used. [34] [53]

5.4 Regulatory developments

As mentioned earlier, regulation regarding nano materials is lagging behind the technical developments. It is, therefore, important for users of nanotechnology to not only follow the technical developments, but also to keep an eye on the development of new regulations. This lagging behind of regulation is actually quite common for new technologies. [54] In the case of nano materials it is expected that the above described difficulties in assessing environmental risks of the materials will cause extra difficulties in development of regulations. Two of the big questions regarding the regulation of nano materials are those of whether nano materials are to be considered a new material or not (the ‘newness’ discussion), and whether the existing framework for the regulation of chemicals should be adapted to include nano materials, or a new framework is necessary for the regulation of nano materials. [32]

At the moment, most governments seem to choose to adapt existing regulations, already applied to other chemicals. In the EU, this means that nano materials are regulated by the European Union’s Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation. [55] The REACH regulation requires for each chemical being manufactured in quantities over one tonne per year to be registered at the European Chemicals Agency (ECHA) in Helsinki.

The above described difficulties regarding ‘newness’ of nano materials have been recognized by the Dutch RIVM (Netherlands National Institute for Public Health and the Environment). In a case study testing the suitability of current REACH regulations for the registration of nano silver, they concluded that one of the main issues arises with the ‘one substance - one registration’ principle. Silver is already registered in the bulk form. At the moment it is not clear whether nano silver should be treated as a different, new substance and thus should be registered separately. The same goes for the distinction between different shapes and sizes of nano materials. [56]

Apart from the REACH regulation, other European regulations may prove relevant for nano materials in the future. In 2009 the European Parliament Committee on the Environment, Public Health, and Food Safety (ENV Committee) proposed adding long multi-walled carbon nanotubes and nano silver to the list of materials restricted from use in electric and electronic equipment by the Restriction of Hazardous Substances (RoHS) Directive, which already restricts the use other substances such as lead and mercury. The European Parliament did not vote in favour of banning these nano materials. [57] Instead, the 2011 recast of the directive contains a passage mentioning nano materials in a more general sense. It now states that ‘As soon as scientific evidence is available, and taking into account the precautionary principle, the restriction of other hazardous substances, including any substances of very small size or with a very small internal surface structure (nanomaterials) which may be hazardous due to properties relating to their size or structure, and their substitution by more environmentally friendly alternatives which ensure at least the same level of protection of consumers should be examined.’. [58]

5.5 Conclusions

Silver nanoparticles are likely to be emitted into the environment with the production of nano-pastes and in the production processes using these pastes for the manufacturing of OLEDs. After sintering and encapsulation nanoparticles are less likely to be emitted, but small amounts may be released in the end of life stage of the OLED. Further research and measurement at actual production plants should be done to make more detailed assessment possible.

The discussion on the ecotoxicity of silver nanoparticles is far from settled. Many studies on the potential toxicity of nano materials have been conducted, but the versatile nature of nano materials makes generalisation and the development of dose-response relations difficult. There are however studies that show increased toxicity compared to bulk and ionic silver in specific cases.

The possibility of increased toxicity has also been recognized by regulatory bodies, e.g. by the explicit mentioning of nano materials in the 2011 RoHS recast by the European Parliament. It is not unlikely that in the near future the use of nano materials in electronics will be subjected to more stringent regulation under the RoHS regulation.

6 Overall conclusions and recommendations

Even though no large scale production of OLED lighting devices on foil exists at the moment, the environmental impacts of five different OLED designs have been assessed. The production of these devices uses many processes and materials that had not been analysed before, complicating the assessment. Much important information on material and energy consumption of the production processes was retrieved from the cost of ownership calculations from Holst Centre. This made it possible that the production and end of life stages of the life cycle were assessed in great detail. Additional information on the end of life impacts of these materials could be calculated using the municipal solid waste incineration model developed by the Swiss Centre for Life Cycle Inventories. This shows that Life Cycle Assessment in an early stage of development is possible and can contribute to the sustainable development of new technologies at Holst Centre.

The assessment and comparison of different plastic substrate materials using publicly available information was not possible. Producers of these materials could not be convinced to cooperate with the assessment; therefore no definite conclusions could be drawn from the research. Further research on the subject should be done in cooperation with the producers of these materials. The assessment did show that an aluminium substrate performed slightly better than a PET substrate, but that the difference was entirely offset by the use of the temporary substrate in the Top Emission OLED design.

The literature study on the potential environmental risks of nano silver use in printed electronics above all showed that the discussion on the potential eco toxicity of nano silver is far from settled. There are reasons to expect increased eco toxicity of silver nanoparticles as compared to bulk and ionic silver. It is likely that the emission of silver particles occurs in the life cycle of OLED devices. Therefore, it is possible that the environmental impacts are underestimated in this study. Users of the materials should keep a close eye on the development of scientific knowledge on the subject, but also on legislation regulating the use of these materials.

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A Process flow charts of the studied OLEDs (confidential)

The content of this appendix is confidential and is therefore removed from this version of the report.

B Appendix to the inventory assessment (confidential)

The content of this appendix is confidential and is therefore removed from this version of the report.

C Inventory assessment of different substrate materials

C.1 Introduction

For the production of OLED lighting several options are available for the choice of substrate material. The choice of substrate material is usually based on material properties and cost information. This appendix describes the information that could be found on different substrate materials using publicly available data.

Table C - 1 gives the materials that are analysed, plus some additional information. In theory, the mechanical properties of the materials can be used to determine the required thickness of the films, but in practice films are being produced industrially in only a limited number of thicknesses. Therefore, all plastic substrates are assumed to be 125 µm thick. For the aluminium and copper substrates, 35 µm thickness is assumed.

Table C - 1 Information on different substrate materials

Material	***Transparent***	***Thickness (µm)***	***kg/m^2***
Poly(ethylene terephthalate) (PET)	Yes	125	1.75E-01
Poly(ethylene naphthalate) (PEN)	Yes	125	1.70E-01
Polyether ether ketone (PEEK)	Yes	125	1.70E-01
Polyimide (PI)	Yes	125	1.82E-01
Poly carbonate (PC)	Yes	125	1.50E-01
Aluminium	No	35	9.5E-02
Copper	No	35	3.1E-01

For the environmental assessment, LCA methodology as described in chapter 5 will be used. As a functional unit, one square metre of substrate material is used.

As will become clear in the following paragraphs, not for all of the above materials a complete inventory assessment could be done. For most of the materials, no complete information on their production could be found, or some of the materials used for their production are unknown in LCA databases. The information that is available is given in this inventory assessment for future reference. For the impact assessment, only those materials are compared for which a complete inventory could be done, which are PET and aluminium (see paragraphs **Error! Reference source not found.** and 4.4.3).

C.2 Poly(ethylene terephthalate) (PET)

Table C - 2 Inventory for PET substrate

	Amount(kg/m^2)	***Reference***
PET film	1.75E-01	[73]

C.3 Poly(ethylene naphthalate) (PEN)

PEN is a polyester polymer of ethylene glycol and dimethyl-2,6-naphthalenedicarboxylate (2,6-NDC). 2,6-NDC is produced by esterification of methanol and naphthalene dicarboxylic acid (2,6-NDA). 2,6-NDA is

produced by oxidation of dimethyl naphthalene (DMN), DMN is produced by the alkenylation of ortho-xylene and butadiene. [80] See Figure 1 below.

Further details on the production process could not be found. Therefore, data on process yields, energy use and waste and emission production is missing. The numbers in table Table C - 3 are derived from the relative molar masses of the used materials, 100% process yields are assumed.

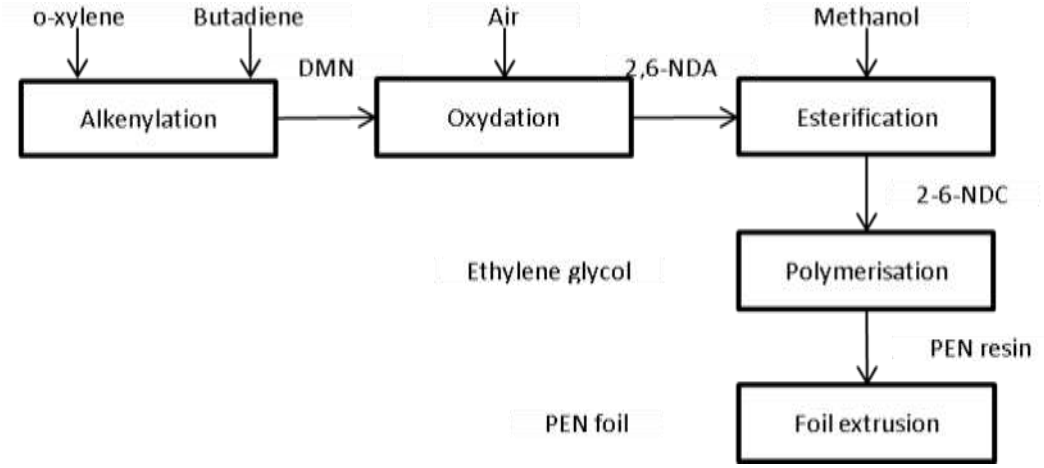

Figure 34. Process chain for PEN foil production

Table C - 3 Inventory for PEN foil (incomplete)

Material/process	***Amount (kg/m^2)***	***Reference***
o-xylene[1]	6.89E-02	[65]
Butadiene	3.51E-02	[73]
Methanol	3.56E-02	[65]
Ethylene glycol	3.44E-02	[65]
Film extrusion	1.70E-01	[62]

1 The isomers ortho-, meta- and para-xylene are products of the same reaction and then separated by distillation, data for 'xylene' is used

C.4 Polyether ether ketone (PEEK)

PEEK is the polymer from sodium bisphenolate and 4,4'-diluorobenzophenone. Sodium bisphenolate is produced from sodium carbonate and hydroquinone, hydroquinone is produced from benzene and propylene (industry data).4,4'-difluorobenzene is produced from p-fluorobenzoyl chloride and fluorobenzene. Fluorobenzene is produced from HF and aniline. [81] See Figure 35 below. No information could be found on the production of p-fluorobenzoyl chloride.

Further details on the production process could not be found. Therefore, data on process yields, energy use and waste and emission production is missing. The numbers in Table C - 4 are derived from the relative molar masses of the used materials, 100% process yields are assumed.

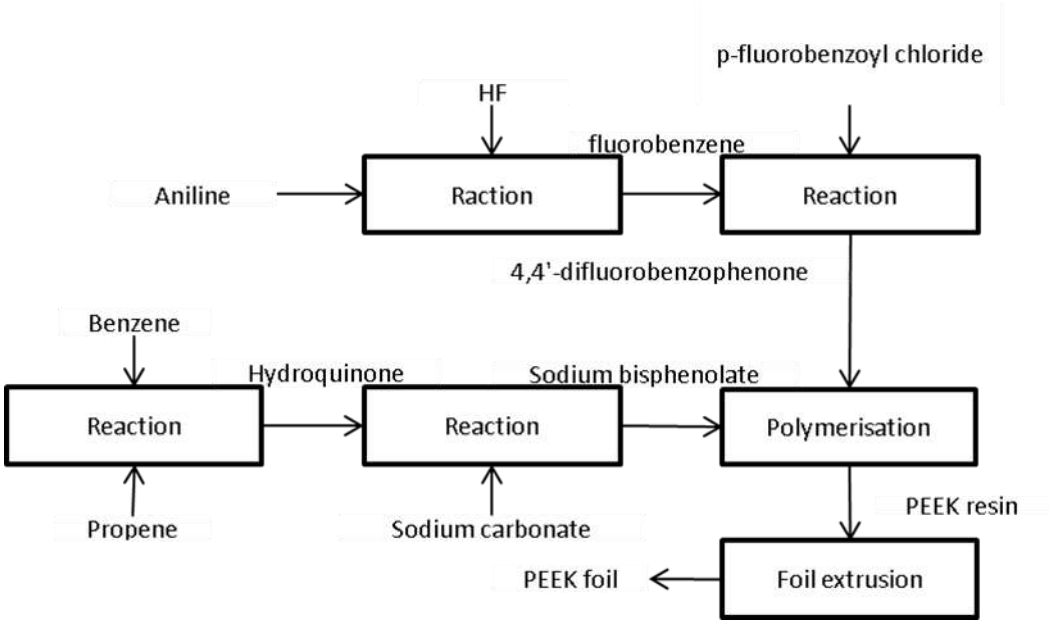

Figure 35. Process chain for PEEK foil production

Table C - 4 Inventory for PEEK (incomplete)

Material/process	***Amount (kg/m^2)***	***Reference***
Benzene	3.94E-02	[62]
Propene (propylene)	2.12E-02	[62]
Sodium carbonate	4.84E-02	[65]
Aniline	4.70E-02	[65]
HF	1.01E-02	[63]
p-fluorobenzoyl chloride	7.24E-02	No data
Film extrusion	1.70E-01	[62]

C.5 Polyimide (PI)

The used polyimide film is known under the brand name Kapton. Its chemical name is poly(4,4'-oxydiphenylene-pyromellitimide). It is produced by the condensation of pyromellitic dianhydride and 4,4'-oxydiphenylamine.

For both pyromellitic dianhydride and 4,4'-oxydiphenylamine, no further information on production processes could be found. No life cycle impact assessment based on this information is possible.

C.6 Poly carbonate (PC)

Most polycarbonate materials are produced by the reaction of bisphenol A and phosgene. [82]

C.7 Aluminium

Table C - 5 Inventory for aluminium substrate

Material/process	***Amount (kg/m^2)***	***Reference***
Aluminium	9.5E-02	[67]
Aluminium sheet rolling	9.5E-02	[79]

C.8 Copper

Table C - 6 Inventory for copper substrate

Material/process	***Amount (kg/m^2)***	***Reference***
Copper	3.1E-01	[67]
Copper sheet rolling	3.1E-01	[79]

D Results from MSWI inventory analyses

D.1 Silicon incineration

Table D - 1

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Silicon		air	high population density	kg	2.33E-03
Silicon		water	river	kg	2.12E-04
Silicon		water	ground-, long-term	kg	8.68E-02
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	3.49E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	1.97E+00
residual material landfill facility	CH	waste management	residual material landfill	unit	3.53E-10
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	1.69E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
cement, unspecified, at plant	CH	construction materials	binder	kg	6.77E-02
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	1.69E-01
transport, freight, rail	RER	transport systems	train	tkm	6.77E-03
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	8.88E-02

D.2 Nitrogen incineration

Table D - 2

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Nitrogen oxides		air	high population density	kg	3.18E-02
Ammonia		air	high population density	kg	7.92E-04
Dinitrogen monoxide		air	high population density	kg	4.22E-03
Cyanide		air	high population density	kg	9.00E-04
Nitrate		water	river	kg	1.28E-02
Nitrate		water	ground-, long-term	kg	3.59E-02
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	7.87E-11
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	4.43E-02
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	kg	2.69E-03
quicklime, milled, packed, at plant	CH	construction materials	additives	kg	4.77E-04
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	kg	1.90E-06
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	3.17E-06
transport, freight, rail	RER	transport systems	train	tkm	1.27E-01
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	1.25E-02
ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	kg	5.05E-02
natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	MJ	4.92E+00
titanium dioxide, production mix, at plant	RER	chemicals	inorganics	kg	1.44E-03
chromium oxide, flakes, at plant	RER	chemicals	inorganics	kg	2.95E-05

D.3 OCP incineration

Table D - 3

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	2.23E-04
Carbon dioxide, fossil		air	high population density	kg	2.18E+00
Methane, fossil		air	high population density	kg	6.38E-06
BOD5, Biological Oxygen Demand		water	river	kg	2.25E-05
COD, Chemical Oxygen Demand		water	river	kg	4.01E-05
TOC, Total Organic Carbon		water	river	kg	1.64E-05
DOC, Dissolved Organic Carbon		water	river	kg	1.64E-05
BOD5, Biological Oxygen Demand		water	ground-, long-term	kg	4.84E-03
COD, Chemical Oxygen Demand		water	ground-, long-term	kg	1.48E-02
TOC, Total Organic Carbon		water	ground-, long-term	kg	5.86E-03
DOC, Dissolved Organic Carbon		water	ground-, long-term	kg	5.86E-03
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	8.05E-12
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	4.53E-03
residual material landfill facility	CH	waste management	residual material landfill	unit	4.31E-12
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	2.07E-03
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	kg	6.46E-07
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	1.08E-06
cement, unspecified, at plant	CH	construction materials	binder	kg	8.28E-04
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	2.07E-03
transport, freight, rail	RER	transport systems	train	tkm	8.39E-05

transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	3.06E-04
disposal, municipal solid waste, 22.9% water, to municipal incineration	CH			kg	1.00E+00

D.4 Ni incineration

Table D - 4

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Nickel		air	high population density	kg	4.32E-08
Nickel, ion		water	river	kg	6.27E-04
Nickel, ion		water	ground-, long-term	kg	9.36E-01
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	2.04E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	1.15E+00
residual material landfill facility	CH	waste management	residual material landfill	unit	2.62E-10
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	1.26E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
cement, unspecified, at plant	CH	construction materials	binder	kg	5.04E-02
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	1.26E-01
transport, freight, rail	RER	transport systems	train	tkm	5.04E-03
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	5.34E-02

D.5 Cr incineration

Table D - 5

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Chromium		air	high population density	kg	7.39E-08
Chromium VI		water	river	kg	3.26E-02
Chromium, ion		water	river	kg	3.19E-03
Chromium VI		water	ground-, long-term	kg	1.06E-01
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	1.18E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	6.65E-01
residual material landfill facility	CH	waste management	residual material landfill	unit	1.65E-09
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	7.92E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	kg	1.27E-04
iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	kg	3.88E-02
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	2.12E-04
cement, unspecified, at plant	CH	construction materials	binder	kg	3.17E-01
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	7.92E-01
transport, freight, rail	RER	transport systems	train	tkm	9.01E-02
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	7.90E-02

D.6 Cu incineration

Table D - 6

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Copper		air	high population density	kg	7.38E-06
Copper, ion		water	river	kg	4.06E-05
Copper, ion		water	ground-, long-term	kg	8.08E-01
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	1.78E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	1.00E+00
residual material landfill facility	CH	waste management	residual material landfill	unit	5.20E-10
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	2.49E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	kg	2.81E-05
iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	kg	8.56E-03
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	4.69E-05
cement, unspecified, at plant	CH	construction materials	binder	kg	9.98E-02
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	2.49E-01
transport, freight, rail	RER	transport systems	train	tkm	2.29E-02
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	5.61E-02

D.7 ISO incineration

Table D - 7

	Location	*category*	*subcategory*	*unit*	*amount*

Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	2.23E-04
Carbon dioxide, fossil		air	high population density	kg	2.82E+00
Methane, fossil		air	high population density	kg	6.38E-06
Nitrogen oxides		air	high population density	kg	2.62E-03
Ammonia		air	high population density	kg	6.53E-05
Dinitrogen monoxide		air	high population density	kg	3.48E-04
Cyanide		air	high population density	kg	7.41E-05
BOD5, Biological Oxygen Demand		water	river	kg	2.91E-05
COD, Chemical Oxygen Demand		water	river	kg	5.19E-05
TOC, Total Organic Carbon		water	river	kg	2.13E-05
DOC, Dissolved Organic Carbon		water	river	kg	2.13E-05
Nitrate		water	river	kg	1.05E-03
BOD5, Biological Oxygen Demand		water	ground-, long-term	kg	6.27E-03
COD, Chemical Oxygen Demand		water	ground-, long-term	kg	1.92E-02
TOC, Total Organic Carbon		water	ground-, long-term	kg	7.59E-03
DOC, Dissolved Organic Carbon		water	ground-, long-term	kg	7.59E-03
Nitrate		water	ground-, long-term	kg	2.96E-03
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	1.69E-11
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	9.51E-03
residual material landfill facility	CH	waste management	residual material landfill	unit	5.59E-12
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	2.68E-03
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	kg	2.22E-04
quicklime, milled, packed, at plant	CH	construction materials	additives	kg	3.93E-05
hydrochloric acid, 30% in H2O,	RER	chemicals	inorganics	kg	3.57E-07

at plant					
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	5.95E-07
cement, unspecified, at plant	CH	construction materials	binder	kg	1.07E-03
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	2.68E-03
transport, freight, rail	RER	transport systems	train	tkm	1.06E-02
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	1.42E-03
ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	kg	4.15E-03
natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	MJ	4.05E-01
titanium dioxide, production mix, at plant	RER	chemicals	inorganics	kg	1.19E-04
chromium oxide, flakes, at plant	RER	chemicals	inorganics	kg	2.43E-06

D.8 Ba incineration

Table D - 8

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Barium		air	high population density	kg	1.00E-03
Barium		water	river	kg	1.38E-04
Barium		water	ground-, long-term	kg	8.88E-01
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	1.76E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	9.90E-01
residual material landfill facility	CH	waste management	residual material landfill	unit	2.61E-10
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	1.25E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01

cement, unspecified, at plant	CH	construction materials	binder	kg	5.00E-02
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	1.25E-01
transport, freight, rail	RER	transport systems	train	tkm	5.00E-03
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	4.71E-02

D.9 Al incineration

Table D - 9

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Aluminum		air	high population density	kg	1.56E-03
Aluminum		water	river	kg	8.32E-05
Aluminum		water	ground-, long-term	kg	7.40E-01
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	2.41E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	1.35E+00
residual material landfill facility	CH	waste management	residual material landfill	unit	5.72E-10
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	2.75E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
cement, unspecified, at plant	CH	construction materials	binder	kg	1.10E-01
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	2.75E-01
transport, freight, rail	RER	transport systems	train	tkm	1.10E-02
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	7.06E-02

D.10 Ag incineration

Table D - 10

	Location	*category*	*subcategory*	*unit*	*amount*
Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Silver		air	high population density	kg	1.30E-05
Silver, ion		water	river	kg	1.19E-04
Silver, ion		water	ground-, long-term	kg	6.30E-01
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	1.18E-09
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	6.61E-01
residual material landfill facility	CH	waste management	residual material landfill	unit	8.60E-10
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	4.13E-01
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	kg	2.01E-04
iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	kg	6.12E-02
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	3.35E-04
cement, unspecified, at plant	CH	construction materials	binder	kg	1.65E-01
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	4.13E-01
transport, freight, rail	RER	transport systems	train	tkm	1.09E-01
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	5.89E-02

D.11 ZnS incineration

Table D - 11

	Location	*category*	*subcategory*	*unit*	*amount*

Carbon monoxide, biogenic		air	high population density	kg	1.35E-04
Carbon monoxide, fossil		air	high population density	kg	8.82E-05
Methane, biogenic		air	high population density	kg	3.86E-06
Methane, fossil		air	high population density	kg	2.53E-06
Sulfur dioxide		air	high population density	kg	1.40E-03
Zinc		air	high population density	kg	1.10E-05
Sulfate		water	river	kg	1.60E-01
Zinc, ion		water	river	kg	1.23E-04
Sulfate		water	ground-, long-term	kg	8.25E-01
Zinc, ion		water	ground-, long-term	kg	1.04E-02
municipal waste incineration plant	CH	waste management	municipal incineration	unit	2.50E-10
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	kg	1.00E+00
slag compartment	CH	waste management	municipal incineration	unit	8.15E-10
process-specific burdens, slag compartment	CH	waste management	municipal incineration	kg	4.58E-01
residual material landfill facility	CH	waste management	residual material landfill	unit	2.37E-09
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	kg	1.14E+00
Heat, waste		air	high population density	MJ	4.44E-01
Heat, waste		water	river	MJ	7.31E-02
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	kWh	1.44E-01
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	MJ	8.39E-01
sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	kg	1.20E-01
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	kg	3.21E-04
iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	kg	7.00E-02
chemicals inorganic, at plant	GLO	chemicals	inorganics	kg	5.36E-04
cement, unspecified, at plant	CH	construction materials	binder	kg	4.56E-01
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	kg	1.14E+00
transport, freight, rail	RER	transport systems	train	tkm	3.92E-01
transport, lorry 20-28t, fleet average	CH	transport systems	road	tkm	1.16E-01

E Appendix to the results section

E.1 All results for cradle to factory gate + end of life

Table E - 1 All results for cradle to factory gate + end of life

Environmental impact category	*Unit*	*Fast2Light*	*Printed Ag*	*Embedded*	*Printed Cu*	*Top Emission*
Non renewable, fossil	**(MJ)**	5.5E+01	3.9E+01	7.9E+01	3.8E+01	9.8E+01
Non-renewable, nuclear	**MJ**	7.0E+00	4.8E+00	9.5E+00	4.6E+00	1.1E+01
Non-renewable, biomass	**MJ**	1.0E-04	6.6E-05	1.3E-04	6.3E-05	1.0E-04
total NREU	**MJ**	6.2E+01	4.4E+01	8.9E+01	4.2E+01	1.2E+02
Renewable, biomass	**MJ**	1.0E+00	6.5E-01	1.2E+00	6.2E-01	9.7E-01
Renewable, wind, solar, geothe	**MJ**	5.3E-02	3.2E-02	5.6E-02	3.0E-02	4.9E-02
Renewable, water	**MJ**	1.4E+00	1.0E+00	1.5E+00	9.0E-01	1.7E+00
Total REU	**MJ**	2.5E+00	1.7E+00	2.8E+00	1.6E+00	2.7E+00
Total Energy use	**MJ**	6.5E+01	4.6E+01	9.2E+01	4.4E+01	1.2E+02
Climate change	**(kg CO_2 eq)**	3.4E+00	2.5E+00	4.9E+00	2.3E+00	7.8E+00
Ozone depletion	**kg CFC-11 eq**	8.6E-08	5.2E-08	6.2E-08	3.9E-08	5.6E-08
Human toxicity	**(kg 1,4-DB eq)**	1.3E+01	3.4E+00	8.9E-01	2.9E-01	3.7E+00
Photochemical oxidant formation	**kg NMVOC**	1.3E-02	9.1E-03	1.7E-02	7.3E-03	2.9E-02
Particulate matter formation	**kg PM10 eq**	5.2E-03	4.2E-03	7.3E-03	3.2E-03	1.3E-02
Ionising radiation	**kg U235 eq**	2.7E-01	1.6E-01	2.7E-01	1.4E-01	2.3E-01
Terrestrial acidification	**(kg SO2 eq)**	1.9E-02	1.6E-02	2.9E-02	1.3E-02	4.9E-02
Freshwater eutrophication	**kg P eq**	7.8E-03	1.7E-03	6.0E-04	2.3E-04	1.7E-03
Marine eutrophication	**kg N eq**	4.2E-03	2.7E-03	4.9E-03	2.1E-03	9.4E-03
Terrestrial	**(kg 1,4-DB**	2.0E-04	1.4E-04	1.2E-04	6.1E-05	1.9E-04

ecotoxicity	**eq)**					
Freshwater ecotoxicity	**kg 1,4-DB eq**	1.7E-01	3.4E-01	3.1E-02	1.2E-02	3.6E-01
Marine ecotoxicity	**kg 1,4-DB eq**	1.6E-01	2.8E-01	3.1E-02	1.2E-02	3.1E-01
Agricultural land occupation	**m2a**	8.9E-02	6.0E-02	1.1E-01	5.7E-02	9.0E-02
Urban land occupation	**m2a**	5.4E-02	1.1E-02	5.2E-03	2.4E-03	1.2E-02
Natural land transformation	**m2**	3.2E-04	1.3E-04	1.3E-04	8.3E-05	1.4E-04
Water depletion	**m3**	1.8E-02	7.2E-03	1.0E-02	5.0E-03	1.3E-02
Metal depletion	**(kg Fe eq)**	1.9E+00	4.1E-01	4.4E-01	8.4E-02	4.2E-01
Fossil depletion	**kg oil eq**	1.3E+00	9.4E-01	1.9E+00	9.0E-01	2.5E+00
Human Health	**(DALY)**	1.5E-05	7.0E-06	9.4E-06	4.3E-06	1.7E-05
Ecosystems	**(species.yr)**	3.0E-08	2.1E-08	4.0E-08	2.0E-08	6.4E-08
Resources	**($)**	2.1E+01	1.5E+01	3.0E+01	1.4E+01	4.0E+01

Table E - 2 Results per life cycle stage

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Production phase	2.3E+00	1.2E-01	1.6E-01	2.1E-03	2.1E-02
Use phase	2.3E+02	1.1E+01	7.6E+00	1.5E-01	5.2E-01
EoL	2.7E-03	1.4E-02	2.0E-02	1.5E-02	1.2E-05

E.2 Results for Fast 2 Light

Table E - 3 Results per life cycle stage for Fast2Light

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Consumables	2.1E+00	9.5E-02	6.7E-01	8.2E-03	1.0E-01
Utilities	6.2E-02	3.5E-03	1.4E-03	2.9E-05	3.1E-05
Waste and emissions	2.5E-03	3.4E-02	3.5E-03	4.3E-04	1.7E-05
EoL	2.6E-03	1.2E-02	1.5E-03	2.2E-04	1.0E-05
Total	2.2E+00	1.4E-01	6.7E-01	8.9E-03	1.0E-01

Table E - 4 Results per machine for Fast2Light

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Substrate	6.1E-01	4.1E-02	1.7E-03	1.4E-04	3.6E-05
Barrier	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
NiCr dep	1.3E-01	8.2E-03	1.2E-02	2.9E-04	1.0E-02
Print Resist	1.2E-01	7.5E-03	8.1E-04	5.8E-05	3.3E-05
Cu/Au dep	4.7E-01	3.0E-02	6.5E-01	8.0E-03	8.9E-02
PEDOT/LEP dep	1.2E-01	7.5E-03	9.5E-04	6.0E-05	3.8E-05
Ba/Al dep	1.2E-01	7.7E-03	1.1E-03	5.9E-05	6.1E-05
Laser patt	1.2E-01	7.3E-03	8.6E-04	5.9E-05	3.1E-05
Barrier 2	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
OCP top layer	1.2E-01	8.1E-03	9.3E-04	6.0E-05	5.9E-05

E.3 Results for Printed Ag

Table E - 5 Results per life cycle stage for Printed Ag.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Consumables	1.5E+00	7.0E-02	1.5E-01	1.8E-03	2.1E-02
Utilities	4.5E-02	2.4E-03	1.1E-03	2.2E-05	2.4E-05
Waste and emissions	1.6E-03	2.2E-02	2.3E-03	2.8E-04	1.1E-05
EoL	2.6E-03	1.2E-02	2.0E-02	1.5E-02	1.0E-05
Total	1.6E+00	1.1E-01	1.8E-01	1.7E-02	2.1E-02

Table E - 6 Results per machine for Printed Ag.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Substrate	6.1E-01	4.1E-02	1.7E-03	1.4E-04	3.6E-05
Barrier	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
Ag/PEDOT/LEP	2.2E-01	1.7E-02	1.7E-01	1.7E-02	2.1E-02
Ba/Al dep	1.2E-01	7.7E-03	1.1E-03	5.9E-05	6.1E-05
Laser patt	1.2E-01	7.3E-03	8.5E-04	5.9E-05	3.1E-05
Barrier 2	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
OCP top layer	1.2E-01	8.1E-03	9.3E-04	6.0E-05	5.9E-05

E.4 Results for Embedded

Table E - 7 Results per life cycle stage for Embedded.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Consumables	2.9E+00	1.3E-01	3.2E-02	4.3E-04	2.2E-02
Utilities	6.3E-02	3.6E-03	1.3E-03	2.8E-05	3.0E-05
Waste and emissions	4.6E-03	5.4E-02	6.0E-03	7.0E-04	3.1E-05
EoL	2.9E-03	1.5E-02	1.5E-03	3.2E-04	1.2E-05
Total	2.9E+00	2.0E-01	4.1E-02	1.5E-03	2.3E-02

Table E - 8 Results per machine for Embedded.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Substrate	6.1E-01	4.1E-02	1.7E-03	1.4E-04	3.6E-05
OPC/NiCr/Cu	1.6E-01	1.0E-02	2.4E-02	5.2E-04	2.1E-02
Print Resist	1.2E-01	7.5E-03	8.1E-04	5.8E-05	3.3E-05
Patterned Cu	1.3E-01	8.2E-03	3.9E-03	9.1E-05	1.0E-03
Barrier	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
Transfer/etch	1.0E+00	7.8E-02	3.9E-03	3.0E-04	1.8E-04
PEDOT/LEP dep	1.1E-01	7.2E-03	8.3E-04	5.8E-05	3.1E-05
Ba/Al dep	1.2E-01	7.7E-03	1.1E-03	5.9E-05	6.1E-05
Laser patt	1.2E-01	7.3E-03	8.6E-04	5.9E-05	3.1E-05
Barrier	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
OCP top coat	1.2E-01	8.1E-03	9.3E-04	6.0E-05	5.9E-05

E.5 Results for Printed Cu

Table E - 9 Results per life cycle stage for Printed Cu.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Consumables	1.4E+00	6.2E-02	7.6E-03	1.3E-04	4.1E-03
Utilities	4.5E-02	2.4E-03	1.1E-03	2.2E-05	2.4E-05
Waste and emissions	1.6E-03	2.2E-02	2.3E-03	2.8E-04	1.1E-05
EoL	2.5E-03	1.2E-02	1.5E-03	1.3E-04	9.8E-06
Total	1.5E+00	9.9E-02	1.2E-02	5.7E-04	4.1E-03

Table E - 10 Results per machine for Printed Cu.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Substrate	6.1E-01	4.1E-02	1.7E-03	1.4E-04	3.6E-05
Barrier	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
Cu/PEDOT/LEP	1.3E-01	8.1E-03	5.0E-03	1.1E-04	3.7E-03
Ba/Al dep	1.2E-01	7.7E-03	1.1E-03	5.9E-05	6.1E-05
Laser Patt	1.2E-01	7.3E-03	8.5E-04	5.9E-05	3.1E-05
Barrier 2	2.0E-01	1.3E-02	1.5E-03	7.1E-05	1.2E-04
OCP top layer	1.2E-01	8.1E-03	9.3E-04	6.0E-05	5.9E-05

E.6 Results for Top Emission

Table E - 11 Results per life cycle stage for Top Emission.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Consumables	2.5E+00	1.2E-01	1.6E-01	2.0E-03	2.2E-02
Utilities	8.3E-02	4.7E-03	1.8E-03	3.7E-05	4.0E-05
Waste and emissions	4.3E-03	5.0E-02	5.6E-03	6.6E-04	2.9E-05
EoL	5.3E-03	6.9E-03	1.9E-02	1.5E-02	1.6E-05
Total	2.5E+00	1.8E-01	1.9E-01	1.8E-02	2.3E-02

Table E - 12 Results per machine for Top Emission.

	total NREU	***Climate change***	***Human toxicity***	***Freshwater ecotoxicity***	***Metal depletion***
	MJ	**(kg CO_2 eq)**	**(kg 1,4-DB eq)**	**kg 1,4-DB eq**	**(kg Fe eq)**
Substrate	4.1E-01	2.6E-02	1.0E-02	2.5E-04	1.2E-03
Liquid Glass	1.0E+00	8.0E-02	3.8E-03	3.0E-04	1.6E-04
CrAl	1.2E-01	7.4E-03	8.1E-04	5.8E-05	5.3E-05
Planar	1.3E-01	8.2E-03	1.3E-03	6.9E-05	4.2E-05
PEDOT/LEP/Ag	2.2E-01	1.7E-02	1.7E-01	1.7E-02	2.1E-02
BaAl	1.2E-01	7.9E-03	1.1E-03	6.0E-05	6.2E-05
ZnS	1.2E-01	7.8E-03	8.4E-04	5.8E-05	3.2E-05
Laser patt	1.2E-01	7.4E-03	8.9E-04	5.9E-05	3.2E-05
Barrier	2.1E-01	1.3E-02	1.6E-03	7.2E-05	1.2E-04
Top coat	5.5E-03	1.9E-03	7.4E-05	1.4E-06	1.6E-05

F Comparison with other lighting technologies (confidential)

The content of this appendix is confidential and is therefore removed from this version of the report.