Exploratory study of dealing with substances of concern in a product with an ex-ante LCA: a case of an LCD monitor.

Master's thesis project

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Exploratory study of dealing with substances of concern in a product with an ex-ante LCA: a case of an LCD monitor.

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Roelie van Breukelen

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Executive summary

Many products contain substances of concern (SoCs), posing risks to both human health and the environment. Addressing these substances aligns with the principles of a circular economy (CE) by either removing, reducing, or safely controlling them. Past attempts to substitute SoCs resulted in undesired trade-offs throughout the product lifecycle.

The Safe and Sustainable by Design (SSbD) approach, an extension of Safe by Design (SbD), prioritizes integrating safety considerations early in product development. Despite this, there is currently no tested SSbD approach for product designers aligning with CE principles. Bolaños Arriola et al. (2023) introduced the Safe and Circular Design (SCD) method tailored for product designers to address SoCs. However, the SCD method is yet to undergo practical testing and implementation.

This study aims to explore the implementation of the SCD method in replacing, reducing, or controlling a SoC in a liquid crystal display (LCD) monitor to fit within a CE framework. It is an exploratory study, evaluating the strategy and current technology's environmental impact, integrating life cycle assessment (LCA) with the SCD method to avoid unintended trade-offs.

In the first step of this study a literature review is done on possible SoCs within an LCD monitor. There is a scarcity of data and information on SoCs present in an LCD monitor and their location within an LCD monitor. In this study indium tin oxide (ITO) is selected as the SoC of this study due to its specific location and sufficient available data. ITO is the transparent conductive oxide (TCO) of an LCD monitor, and is potentially toxic for humans, animals, and the environment.

Furthermore, a literature review is done on possible strategies to avoid, reduce, or control ITO. Unfortunately, no reduce strategies are found, and there is a lack of control strategies at the pilot scale. Consequently, the study does not delve deeper into reduce and control strategies. While several avoid strategies are identified, their evaluation reveals challenges related to toxicity, material characteristics, and available inventory data. The evaluation underscores a significant lack of data and inconsistencies, leading to the selection of aluminium doped zinc oxide (ZnO:Al) as an avoid strategy primarily due to data availability, not its ideal characteristics.

An ex-ante LCA study is conducted on ITO film and ZnO:Al film. The results highlight that electricity consumption during the use phase of the LCD monitor significantly contributes to the environmental impacts of both films. The electricity consumption during the use phase of ZnO:Al is likely higher than that of ITO, resulting in a higher environmental impact for ZnO:Al. Furthermore, considering the cradle-to-gate perspective without electricity consumption in the use phase, ZnO:Al exhibits a higher environmental impact than ITO in most impact categories. Unfortunately, there are missing emission flows and characterization factors for the toxic substances in both alternatives, preventing a comprehensive evaluation of possible toxic trade-offs. However, based on the findings of this ex-ante LCA study, is it assumed that ZnO:Al cannot be utilised without incurring unwanted trade-offs in other impact categories.

The application of the SCD method to the LCD monitor case revealed both insights and challenges. Challenges included issues with terminology, a lack of information and toxicity data, and the absence of emission flows and characterization factors for the LCA study. However, the SCD method also provided valuable guidance in gathering information about SoCs and developing strategies for ITO. Specific challenges within the study were attributed to the SCD method, such as overlap between steps. Additionally, challenges were encountered in this study due to the absence of a design team or communication with the product client.

The study concludes that the application of the SCD method to the LCD monitor case has yielded valuable insights, while at the same time highlighting the overall lack of data and the necessity for multidisciplinary teams. The study introduces some alterations to further refine and enhance the SCD method. It is advisable to assess the effectiveness of this method in other case studies, preferably across a wide range of cases. To improve S(S)bD studies, organisations, companies, and governments should enhance data availability and transparency regarding product components and toxicity. Efforts should focus on filling gaps in emission flows and characterization factors for SoCs in LCA studies. In conclusion, enhancing data availability and multidisciplinary collaboration are crucial for ensuring safer and more sustainable product development.

List of Acronyms and Initialisms

AgNW	Silver nanowire network
ALCA	Attributional Life Cycle Assessment
CSS	Chemicals Strategy for Sustainability
CE	Circular Economy
CF	Colour Filter
CRM	Critical Raw Material
CRT	Cathode Ray Tube
ECHA	European Chemicals Agency
FFS	Fringe-Field Switching
IE	Industrial Ecology
IPS	In-Plane Switching
ISO	International Organization for Standardization
LC	Liquid Crystal
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LED	Light Emitting Diodes
NWA	Dutch Research Agenda (Nationale Wetenschapsagenda)
MVA	Multi-domain Vertical Alignment
PEF	Product Environmental Footprint
PWB	Printed Wiring Board
OECD	Organisation for Economic Co-operation and Development
OPV	Organic photovoltaic
RA	Risk Assessment
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation, and Restriction of Chemicals
RIVM	Dutch National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu)
RoHS	Restriction of Hazardous Substances
SbD	Safe-by-Design
SCD	Safe and Circular Design
SoC	Substance of Concern
SSbD	Safe and Sustainable by Design
SVHC	Substance of Very High Concern
TCO	Transparent Conductive Oxide
TFT	Thin Film Transistor
TN	Twisted Nematic
ZZS	Zeer Zorgwekkende stoffen (Dutch term voor SVHC)
pZZS	potential ZZS

List of Chemical Abbreviations

Al_2O_3	Aluminium oxide
APCs	Aminopolycarboxylate chelants
BBP	Butyl benzyl phthalate
BPA	Bisphenol A
BTBPE	1,2-bis(2,4,6-tribromophenoxy)ethane
DBP	Dibutyl phthalate
DEHP	Bis(2-ethylhexyl) phthalate
DIBP	Diisobutyl phthalate
$InCl_3$	Indium (III) chloride
$In(NO_3)_3$	Indium (III) nitrate
$In(OH)_3$	Indium (III) hydroxide
ITO	Indium tin oxide
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ether
PBDEs	Polybrominated diphenyl ethers
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene):poly-(styrenesulfonate)
PFAS	Poly- and perfluoroalkyl substances
SnF_2	Tin (II) fluoride
SnO_2	Tin (IV) oxide
SnO_2:F	Fluorine doped tin oxide
TBBP-A	Tetrabromobisphenol-A
ZnO	Zinc Oxide
ZnO:Al	Aluminium doped Zinc oxide
ZnO:Ga	Gallium doped Zinc oxide
$Zn(OH)_2$	Zinchydroxide

Glossary

Term	**Definition**	**Source**
Substance of Concern (SoC)	“*chemical pollution, which includes persistent, as well as readily degradable chemicals released at local to regional scales, which in aggregate threaten ecosystem and human viability.”* (as a guidance)	Diamond et al. (2015, p. 1)
Safe-by-design (SbD)	"*The SbD (Safe-by-Design, Safer-by-Design, or Safety-by-Design) concept refers to identifying the risks and uncertainties concerning humans and the environment at an early phase of the innovation process so as to minimize uncertainties, potential hazard(s) and/or exposure. The SbD approach addresses the safety of the material/product and associated processes through the whole life cycle: from the Research and Development (R&D) phase to production, use, recycling and disposal.*“	Organisation for Economic Co-operation and Development (2020, p. 15)
Safe Sustainable by Design (SSbD)	“*a pre-market approach to chemicals that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco) toxic, persistent, bio-accumulative or mobile. Overall sustainability should be ensured by minimising the environmental footprint of chemicals in particular on climate change, resource use, ecosystems and biodiversity from a lifecycle perspective.*”	European Commission (2020a, p. 4).
Risk assessment (RA)	*“Risk assessment is a process which entails some or all of the following element: hazard identification, effects assessment, exposure assessment and risk characterization“*	van Leeuwen and Vermeire (2007, p. 2)
Life Cycle Assessment (LCA)	“*compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle*".	ISO 14040
Ex-Ante LCA	*“performing an environmental life cycle assessment of a new technology before it is commercially implemented in order to guide R&D decisions to make this new technology environmentally competitive as compared to the incumbent technology mix.”*	van der Giesen et al. (2020, p. 2)

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1. Introduction

1.1 Background

The current linear economic system, characterised by a 'take, make, use and dispose' approach, relies on abundant, easily accessible resources and energy. This model has been the primary driver of industrial advancement, resulting in substantial economic growth (Ellen Macarthur Foundation, 2015). However, this economic framework has exerted unsustainable pressure on the Earth's ecosystem, leading to unsustainable resource use, pollution, greenhouse gas emissions, and various other emissions (Ellen Macarthur Foundation, 2013).

Recognising the need for a substantial shift towards a more sustainable, resource-efficient, climate-neutral, and environmentally friendly economy, the European Union (EU) has articulated a dedicated agenda for transitioning towards a Circular Economy (CE) (European Commission, 2020b). In a CE, the primary objective is the continuous reuse of materials and the minimisation of waste (Ellen Macarthur Foundation, 2015).

However, it is important to acknowledge the presence of substances in products and materials that pose risks to human health and the environment, commonly referred to as substances of concern (SoCs) or hazardous substances (European Environment Agency, 2018). One example is polyfluorinated substances (PFAS) found in items like cookware, clothing, furniture, and food packaging. PFAS can have detrimental effects on human development, reproduction, immune function, and may harm the liver (Centers for Disease Control and Prevention, 2022). In the context of a CE, the reuse of products and materials containing SoCs can be challenging, given the inherent risks they pose to human and environmental health (Safe-by-Design, n.d.).

Safe-by-Design (SbD) is an approach that prioritizes integrating safety considerations for both human health and the environment early in the development of, for instance, new products, materials, and chemicals. The precise definition of the SbD approach was not well-established until more recently. According to the Organisation for Economic Co-operation and Development (OECD), SbD is described as follows: "*The SbD (Safe-by-Design, Safer-by-Design, or Safety-by-Design) concept refers to identifying the risks and uncertainties concerning humans and the environment at an early phase of the innovation process so as to minimize uncertainties, potential hazard(s) and/or exposure. The SbD approach addresses the safety of the material/product and associated processes through the whole life cycle: from the Research and Development (R&D) phase to production, use, recycling and disposal.*“ (Organisation for Economic Co-operation and Development, 2020, p. 15).

An extension of the Safe-by-Design (SbD) approach is the Safe and Sustainable by Design (SSbD) approach, as introduced by the EU Chemicals Strategy for Sustainability (CSS) (European Commission, 2020a). The CSS defines SSbD as: “*a pre-market approach to chemicals that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco) toxic, persistent, bio-accumulative or mobile. Overall sustainability should be ensured by minimising the environmental footprint of chemicals in particular on climate change, resource use, ecosystems and biodiversity from a lifecycle perspective.*” (European

Commission, 2020a, p. 4). In other words, SSbD is exclusive for chemicals and aims to minimize any unintended trade-offs with other non-chemical impact categories that are not directly connected to the SoC (Caldeira et al., 2022; Guinée et al., 2022). In this study, the SSbD approach will be utilized on products.

Various tools and approaches are utilized in the SbD and SSbD framework to assess the safety and sustainability of new products, such as Risk Assessment (RA) and Life Cycle Assessment (LCA) (Salieri et al., 2021). RA involves assessing both quantitatively and qualitatively the risk that arises from exposure to specific pollutants, considering their actual or potential presence and their potential impact on human health and/or the environment (Guinée et al., 2022). Van Leeuwen gives the following definition for RA: *"Risk assessment is a process which entails some or all of the following element: hazard identification, effects assessment, exposure assessment and risk characterization"* (van Leeuwen & Vermeire, 2007, p. 2). In this study, only the hazard identification aspect of RA is conducted, an extensive RA is beyond the scope of this study.

LCA is a method that evaluates the environmental impact of products at each stage of their lifecycle, ranging from raw material extraction to end-of-life disposal (Guinée, 2002). Ex-ante LCA is a modified version of LCA that utilizes diverse data sources to project the potential environmental impact of an emerging technology. This projection is based on likely scenarios of the technology's performance at full operational scale. Ex-ante LCA then compares this projection to the environmental impact of the incumbent technology at the same point in time (Cucurachi et al., 2018).

In SbD and SSbD studies the design part is not yet widely applied (Guinée, 2023). Thus, SbD and SSbD studies so far are more on "Sustainable" and "Safe". This might be partly because the "by design" can be interpreted as molecular, process and/or product design. Additionally, Guinée et al. (2022) underscore the confusing usage of the terms "chemical," "material," and "product" in S(S)bD research. The authors stress the need for interdisciplinary collaboration, precise definitions of terms, and explicit delineation of life cycle boundaries in forthcoming S(S)bD publications to ensure a comprehensive understanding and successful prevention of regrettable substitutions.

1.2 Problem definition

As discussed above, many products contain SoCs that pose risks to both human health and the environment. These substances need to be either removed from products, reduced, or safely controlled to align with the principles of a CE. However, replacing, reducing, or safely managing these substances presents a complex challenge.

Until recently, there is no S(S)bD approach available for product designers that facilitates the creation of safe products aligning with the principles of a CE and has undergone testing and implementation in real-world scenarios. Bolaños Arriola et al. (2023) are developing a method to address SoCs in products, specifically designed for product designers, the Safe and Circular Design (SCD) method. However, this method has not yet been tested and implemented in practical, real-world settings.

1.3 Knowledge gap

In this section, we delve into the knowledge gap of this study. The main gap is that no study has been conducted using the SCD method. Therefore, what kind of insights the method could provide and whether it is feasible and applicable in practice are still unknown. Additionally, the specific challenges that may arise and how to address them are yet to be determined. Finally, the method has not been combined with an extensive (ex-ante) LCA study yet, only with a screening LCA.

1.4 Research aim

The primary aim of this study is to test and implement the SCD method studying the specific case of an LCD monitor. The research aims to provide insights from an exploration to replace, reduce or control a SoC in a product to fit in an CE by applying and testing the SCD method.

The secondary aim of this study is to assess both the strategy and the current technology in terms of environmental impact, ensuring that no unintended trade-offs occur in other impact categories. Thus, the SCD method will be explored with the implementation of an extensive LCA study.

1.5 Research questions

The research questions presented in this study have been carefully formulated in direct response to both the identified knowledge gap within the field and the aim of this study.

1.5.1 Main research question

Which insights can be obtained by applying the SCD method through the case of an LCD monitor on the European market, exploring a range of possible strategies to replace, reduce or control a SoC that aim to lower the risks to the environment and human health as well as its life cycle environmental impacts?

1.5.2 Sub-research questions

1. What are possible SoCs in an LCD monitor and where are these SoCs located within an LCD monitor?
2. Which SoC can serve as an example for this study, considering data availability, and what is its harm to human health and the environment?
3. What are possible strategies to replace, reduce or control the selected SoC in an LCD monitor, and which strategy will be selected for this study?
4. What are the life cycle environmental impacts of an LCD monitor including the selected SoC and the strategy for the selected SoC?
5. Does the chosen strategy offer a replacement or controls the selected SoC in an LCD monitor without unwanted trade-offs in other impact categories?

1.6 Industrial Ecology, scientific and societal relevance

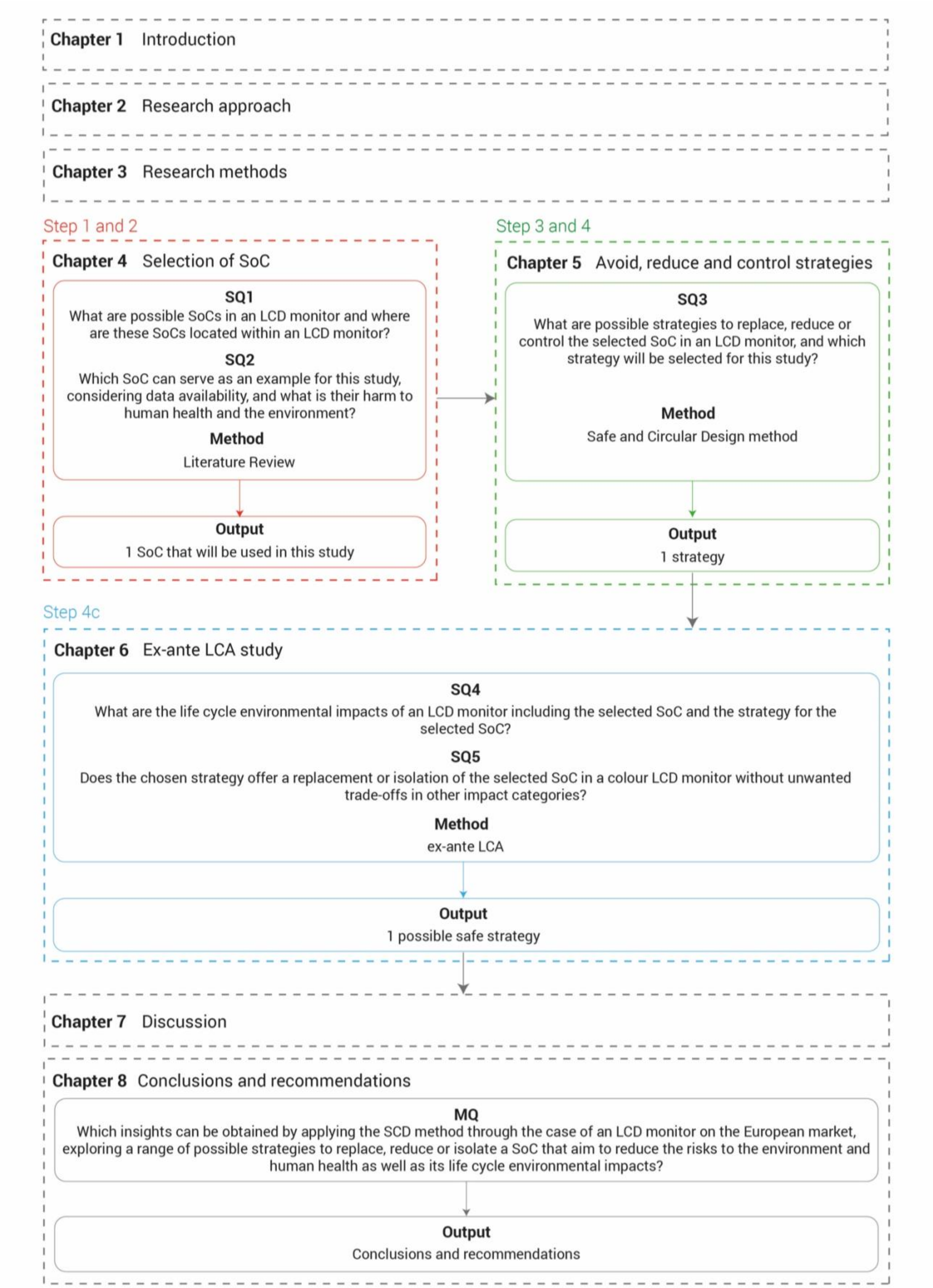
Industrial ecology (IE) delves into the systemic interactions between society, the economy, and the environment (ISIE, n.d.). Industrial ecology aims to establish a harmonious relationship between the ecological and human systems, ultimately delivering comprehensive sustainability benefits, including social, environmental, and economic (Awan, 2022).

In the context of IE, the aim of this study is to provide insights from an exploration to replace, reduce or control a SoC in an LCD monitor to fit in an CE by applying and testing the SCD method. Hereby, this study will assess both the strategy and the current technology in terms of environmental impact, ensuring that no unintended trade-offs occur in other impact categories. Moreover, the evaluation and refinement of the SCD method have wider implications beyond just LCD monitors, playing a role in the development of products designed with safety and circularity in mind.

From a societal perspective, the significance of this study is rooted in its potential to improve the LCD monitor's detrimental impact on both human well-being and the environment. Additionally, the evaluation and further development of the SCD method serve a broader purpose beyond LCD monitors, contributing to the development of products that are safely and circularly designed. Moreover, the scientific significance is notable as it fills a crucial knowledge gap and contributes new insights to the scientific field.

1.7 Thesis outline

The research flow diagram shown in Figure 1 outlines the structure of the thesis and its methods for addressing the sub-questions and main research question. It also outlines the steps of the SCD method that are implemented in this study. Firstly, Chapters 2 and 3 delve into the research approach and methods. In chapter 4, a literature review is undertaken to address the first two sub-research questions. Following this, a SoC is selected for the remainder of the study. Chapter 5 involves the generation of potential strategies to replace, reduce, or control the chosen SoC, addressing the third sub-research question. Within this chapter, a specific strategy is chosen for an ex-ante LCA. In Chapter 6, the ex-ante LCA is conducted on the selected SoC and strategy, providing answers to the last two sub-research questions. The chapters 7 and 8 involve a critical discussion of the research, the presentation of recommendations, and a conclusion.



SQ1
What are possible SoCs in an LCD monitor and where are these SoCs located within an LCD monitor?

SQ2
Which SoC can serve as an example for this study, considering data availability, and what is their harm to human health and the environment?

Method
Literature Review

Output
1 SoC that will be used in this study

SQ3
What are possible strategies to replace, reduce or control the selected SoC in an LCD monitor, and which strategy will be selected for this study?

Method
Safe and Circular Design method

Output
1 strategy

SQ4
What are the life cycle environmental impacts of an LCD monitor including the selected SoC and the strategy for the selected SoC?

SQ5
Does the chosen strategy offer a replacement or isolation of the selected SoC in a colour LCD monitor without unwanted trade-offs in other impact categories?

Method
ex-ante LCA

Output
1 possible safe strategy

MQ
Which insights can be obtained by applying the SCD method through the case of an LCD monitor on the European market, exploring a range of possible strategies to replace, reduce or isolate a SoC that aim to reduce the risks to the environment and human health as well as its life cycle environmental impacts?

Output
Conclusions and recommendations

Figure 1. Research flow diagram

2. Research approach

In this chapter, the research approach of this study is discussed. Additionally, a definition for SoC is given that will be used throughout this study, along with an introduction for the case.

2.1 LCD monitor case

To apply and test the SCD method, a case is selected. This choice is made to offer practical insights derived from efforts to replace, reduce, or control an SoC by applying the SCD method. This study supports the Dutch Research Agenda (NWA) project coordinated by TU Delft, aiming to establish a practical S(S)bD approach for designing safe products aligning with CE principles. The NWA project encompasses various cases. One of these cases is an LCD monitor, which is used for this study.

Chapter 1 formulated the primary research question and its sub-questions. To answer these research questions, a semi-quantitative approach is employed, taking a design-oriented and modelling approach. The semi-quantitative approach is chosen due to expected data scarcity. Additionally, a design-oriented approach is needed since this study explores the SCD method that is intended for product designers. Furthermore, a modelling approach is necessary due to the implementation of an ex-ante LCA study.

2.2 Definition of SoC

In this study, it is imperative to establish a definition for SoC that will be used in this study. This is particularly significant due to the varied definitions and terminologies used in practice and existing literature.

As discussed by Bolaños Arriola et al. (2022), different institutions such as the European Chemicals Agency (ECHA) and the Dutch National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu, RIVM) employ varying definitions for SoC.

ECHA defines substances with potential harmful effects on human health and the environment as Substances of Very High Concern (SVHCs). These substances meet the criteria outlined in Article 57 of the REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) regulation. These criteria encompass substances that cause cancer, mutagenesis, harm to the developing foetus, and those that are persistent and bio-accumulative in nature (ECHA, 2016).

RIVM also provides a definition for SVHCs (known as "Zeer Zorgwekkende stoffen" or ZZS in Dutch). In this definition, substances are classified as SVHC when they meet the REACH criteria and also include substances from other European legislation and treaties, such as the Persistent Organic Pollutants (POP) regulation (RIVM, n.d.-a). RIVM provides a list for the ZZS that are classified in these regulations, the ZZS list (RIVM, 2023b). Additionally, RIVM maintains a potential ZZS (pZZS) list, consisting of substances that are likely to meet the ZZS criteria but have not yet been identified as such (RIVM, n.d.-b).

Consequently, multiple definitions of SVHCs exist, with also no single, broadly accepted definition for SoCs. Bolaños Arriola et al. (2022) found that these definitions tend to focus on specific toxicity criteria, which may not encompass a broader range of potential pollutants that are of importance in a CE. To address this, Bolaños Arriola et al. (2022) chose to use the definition of chemical pollution as guidance. Diamond et al. (2015, p. 1) gives the following definition for chemical pollution: "*chemical pollution, which includes persistent, as well as readily degradable chemicals released at local to regional scales, which in aggregate threaten ecosystem and human viability.*" Rockström et al. (2009, p. 18) adds: "*Primary types of chemical pollution include radioactive compounds, heavy metals, and a wide range of organic compounds of human origin. Chemical pollution adversely affects human and ecosystem health, …".* The definition of chemical pollution was by Bolaños Arriola et al. (2022) considered appropriate within the context of CE as it accommodates a wider range of human-made compounds (e.g., PFAS) that could be released from products, accumulate in ecosystems, and have adverse effects on human health and the environment. Moreover, this definition recognizes that SoCs may not only be intentionally added but could also be formed during product use or at the end of a product's life cycle. This includes substances released by products that have not yet been classified or identified as SoC or emerging contaminants (Bolaños Arriola et al., 2022). In this study, the definition of Diamond et al. (2015, p. 1) for SoC will be used as guidance.

2.2.1 Restriction of Hazardous substances (RoHS) in EU

The Restriction of Hazardous Substances (RoHS) Directive (2011/65/EU), an EU regulation, restricts the usage of specific hazardous chemicals in electrical and electronic devices (European Union, 2023). Currently, the RoHS Directive prohibits ten substances: butyl benzyl phthalate (BBP), dibutyl phthalate (DBP), diisobutyl phthalate (DIBP), lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDEs). Unless specified otherwise, all items containing electrical or electronic components must adhere to these regulations (European Commission, 2022). Therefore, any LCD monitor sold and used in the EU must comply with RoHS Directive 2011/65/EU.

2.3 Introduction to LCD monitors

In this section, an introduction is provided for the case of this study. This includes an overview of the technology employed in an LCD monitor, along with an identification of the prior research. This specifically encompasses research on SoCs in an LCD monitor and LCA studies conducted on this product.

2.3.1 Technology of LCD monitors

Human lifestyles have been progressively but significantly altered by display technology, which is now universally acknowledged as essential to the modern world (Chen et al., 2018). Friedrich Reinitzer, an Austrian botanist, identified an intermediate state of matter between isotropic liquid and lattice-structured crystal in 1888, more than a century ago. For many years, this condition, subsequently known as liquid crystal (LC), was just a curiosity until useful uses for the technology started to emerge (Kim & Song, 2009). Since the late 1960s, when it became clear that there were numerous display applications, liquid crystal research has become increasingly popular. This has drawn the attention of numerous scientists, who have contributed significantly to the technologies that have enabled the spectacular success of liquid crystal displays (LCDs) (Kim & Song, 2009). Nowadays, LCDs are used in different kinds of applications like computer monitors, televisions, smartphones, tablets and data projectors (Chen et al., 2018).

Since LC materials don't emit light, the display screen must typically be illuminated by a backlight device (Chen et al., 2018). The backlight of the first LCD monitors was a compact fluorescent light. The usage of light emitting diodes (LEDs) began in the early 2010s. With LEDs, illumination can be dynamically altered, allowing for a wider dynamic range in images (Kawamoto, 2012). As well as the absence of mercury and improved energy efficiency (A.R. Balkenende, personal communication, January 16, 2024)

Figure 2 shows a schematic diagram of a thin-film transistor (TFT) LCD (Chen et al., 2018). Between a TFT substrate and a colour filter (CF) substrate, the LC layer is injected. The panel's outer faces are covered with two polarizers (also called analyzer in Figure 2) that are orthogonally oriented (Kim & Song, 2009).

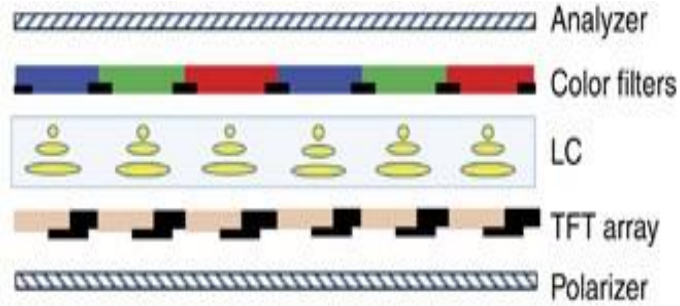


Figure 2. Schematic diagram of an LCD (Chen et al. 2018)

2.3.2 Prior research on LCD monitor

In this section, the prior research on the chosen case, an LCD monitor, is discussed. This specifically covers research on SoCs within an LCD monitor and LCA studies carried out on this product. In an LCD monitor several SoCs are present, such as flame retardants and heavy metals, including lead, chromium, and cadmium (Andooz et al., 2022; Gautam et al., 2022; Groß et al., 2008; Kolias et al., 2014; Savvilotidou et al., 2014; Sun et al., 2016; Yeom et al., 2018). These SoCs should be replaced, reduced, or controlled to make the product safer for human health, the environment, and to better align with a CE. Furthermore, possible strategies that replace, reduce, or control the SoCs in an LCD monitor should be assessed on their environmental impact, ensuring that no unwanted (toxic) trade-offs arise.

While existing literature acknowledges the presence of SoCs in such monitors (Groß et al., 2008; Lim & Schoenung, 2010; Savvilotidou et al., 2014; Tyagi & Chatterjee, 2013; Yeom et al., 2018), comprehensive and detailed information on these SoCs remains limited.

Numerous LCA studies have been done on LCD monitors, some of which compare different kind of monitors, like cathode ray tube (CRT) and LCD monitors (Bhakar et al., 2015; Hischier & Baudin, 2010; Socolof et al., 2005). There are studies that concentrate on computer monitors or TV screens (Duan et al., 2009; Song et al., 2013; Thomas et al., 2012). Furthermore, several studies dive into the end-of-life phase of LCD monitors or only the LCD panels (Noon et al., 2011; Yu et al., 2019). A few studies delve into comparative LCAs of different techniques for indium recovery from old LCDs (Amato et al., 2017; Dodbiba et al., 2012). Nevertheless, while several studies briefly allude to SoCs, most do not provide any specific details.

Thus, existing literature does not offer sufficient in-depth information regarding SoC in LCD monitors. Furthermore, there is an absence of (ex-ante) LCA studies focused on novel designs or alternatives for SoCs in the context of LCD monitors.

3. Research methods

In this chapter, the methods that will be used are explained. These methods are SCD, LCA and ex-ante LCA.

3.1 Safe and Circular Design method

The SCD method by Bolaños Arriola et al. (2023) aims to align with the CE principles, safeguard human health and the environment, and assist designers in addressing SoC in products. It is intended for the early stages of the design process of a new product to prevent or control SoC(s) (design), or to assess and reconsider existing products with SoC(s) (redesign). While certain steps provide basic guidance on integrating quantitative data when applicable, it primarily is a qualitative method. It is an iterative method, allowing designers to refine their work with each cycle.

This method comprises of four distinct steps, as illustrated in Figure 3, outlining the content of each step. All the steps are discussed below, based on the report and paper by Bolaños Arriola et al. (2022, 2023).

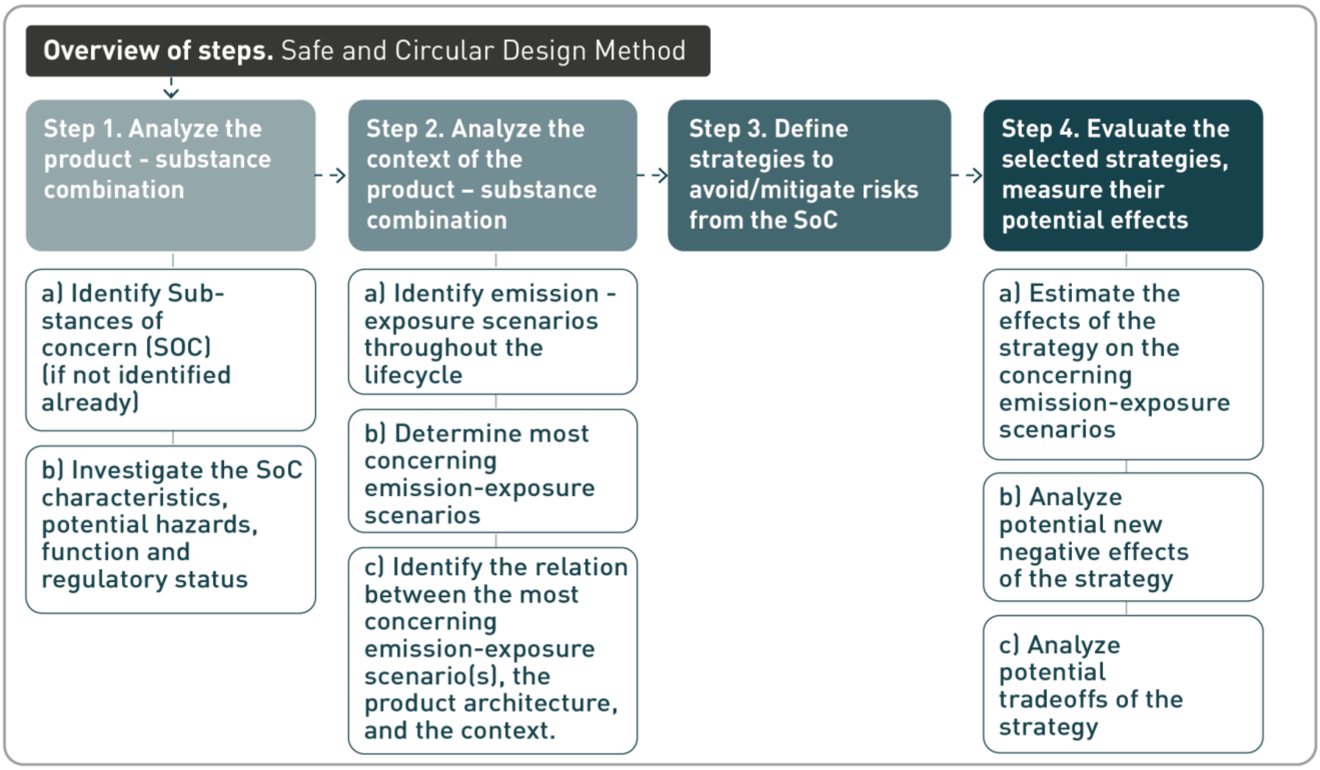
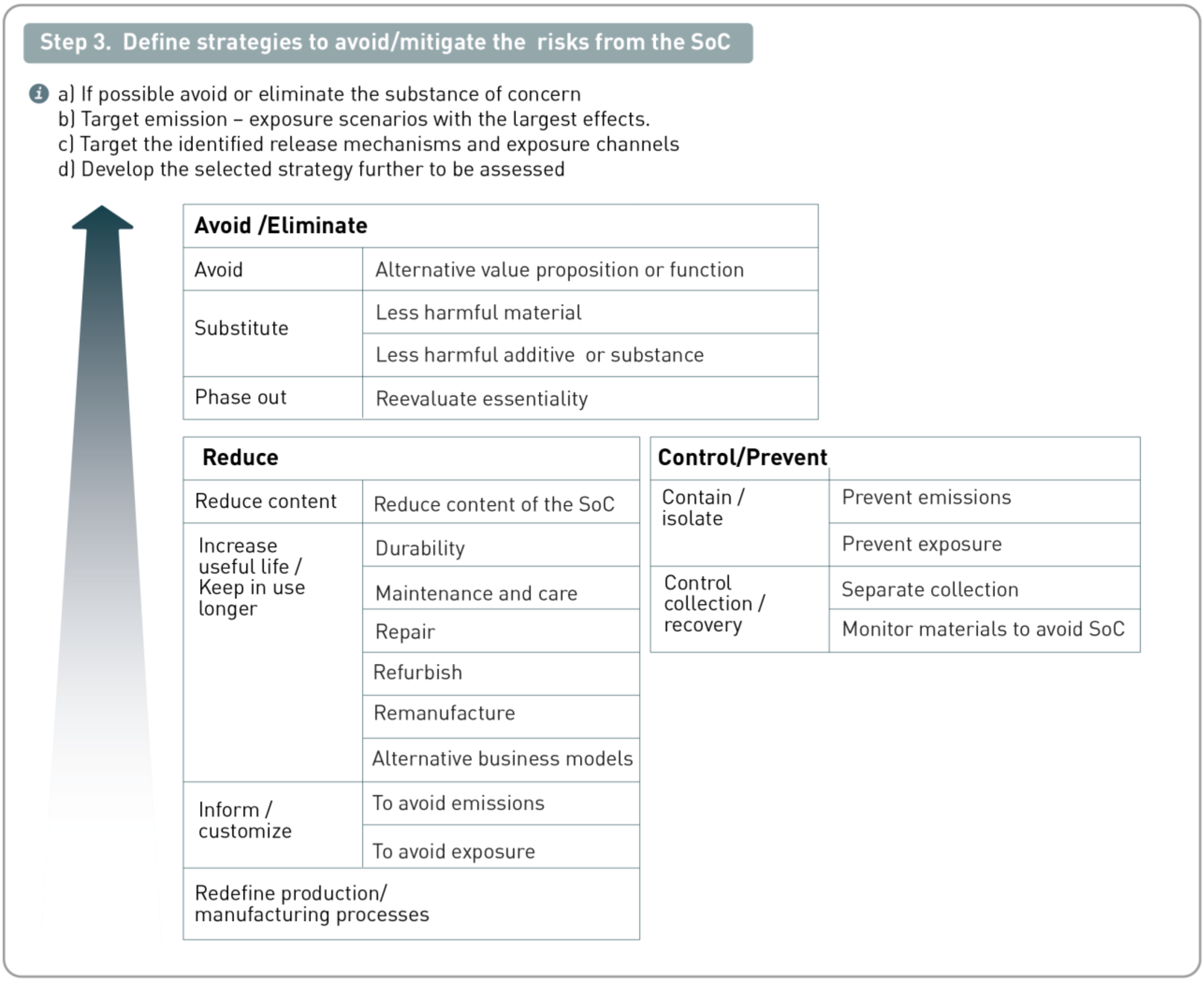


Figure 3. Steps of SCD method (Bolaños Arriola et al., 2023)

The first step involves an analysis of the product-substance combination. Initially, in this step, possible SoCs are identified and comprehensively described. This includes detailing the potential hazards, characteristics, role within the product, and its regulatory status. Information about a SoC can often be sourced from the ECHA database.

The subsequent step entails an examination of the context surrounding the product-substance combination. This involves identifying potential emission and exposure scenarios across the product's lifecycle. Following this, prioritization of these scenarios and lifecycle stages is conducted based on their severity in terms of impact on human health and the environment. In cases where sufficient data is available, a RA can be performed. These emissions and exposure scenarios are strongly linked to the product's design, forming an initial step towards the selection and specification of a strategy.

The third step involves the definition or selection of strategies to address the findings from the initial two steps. Preferably, consideration is given to strategies aimed at avoiding or eliminating the SoC. If it is not feasible to avoid or eliminate the substance, exploration of reduction and control/prevention strategies is recommended. The method also offers suggestions for these strategies, as depicted in Figure 4.



Step 3. Define strategies to avoid/mitigate the risks from the SoC

ℹ a) If possible avoid or eliminate the substance of concern
b) Target emission – exposure scenarios with the largest effects.
c) Target the identified release mechanisms and exposure channels
d) Develop the selected strategy further to be assessed

Avoid /Eliminate	
Avoid	Alternative value proposition or function
Substitute	Less harmful material
	Less harmful additive or substance
Phase out	Reevaluate essentiality

Reduce	
Reduce content	Reduce content of the SoC
Increase useful life / Keep in use longer	Durability
	Maintenance and care
	Repair
	Refurbish
	Remanufacture
	Alternative business models
Inform / customize	To avoid emissions
	To avoid exposure
Redefine production/ manufacturing processes	

Control/Prevent	
Contain / isolate	Prevent emissions
	Prevent exposure
Control collection / recovery	Separate collection
	Monitor materials to avoid SoC

Figure 4. Step 3, List of possible design strategies to deal with SoC in products. (Bolaños Arriola et al., 2023)

In the fourth step, the generated strategies are evaluated. Firstly, a (qualitative) assessment is made to determine how much the selected strategy or strategies will reduce, maintain, or potentially increase the level of concern associated with the identified emission-exposure scenarios. This assessment allows for identifying areas that may require improvement and further attention. Secondly, consideration is given to the potential adverse consequences that the strategy might introduce during the product's lifecycle, including the possibility new risks and increased environmental impacts. Finally, the potential drawbacks of the strategy are contemplated, which may encompass reduced product performance and elevated production costs, among other factors.

The SCD method is intended for use by a team of product designers and experts in a company context. However, in this research this was not the case. Thus, In this research, the first two steps are addressed through an extensive literature review. Furthermore, the third and fourth steps are tackled by means of a literature review. Additionally, the fourth step consist of analysing potential trade-offs of the strategy (step 4c). This can be conducted with an (ex-ante) LCA study, which will be the case in this study. The methods of an LCA study and ex-ante LCA study will be discussed in the following sections. The SCD method can also be combined with a comprehensive RA, but this falls outside the scope of this study.

3.1.1 Limitations

Bolaños Arriola et al. (2022) emphasize the significance of collaboration between product designers and other stakeholders, such as LCA researchers. Regrettably, practical constraints and time limitations prevent the involvement of stakeholders in this project. Nevertheless, the researcher possesses a unique background in both product design and LCA research, which should mitigate the limitation of lacking stakeholder involvement.

Another limitation could be the collection of essential data for the analysis of product-substance combinations, exposure scenarios, toxicity data, harmonized toxicity assessments, emissions, and the effects of strategies.

3.2 LCA

In this study, the method LCA is implemented in the SCD method. The method LCA is explained in this section. Chapter 6, where the LCA study is conducted, provides the methodological details of this study.

In ISO 14040, LCA is defined as the “*compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle*" (ISO, 2006). LCA is a method for analysing the environmental impact of products at every stage of their life cycle. From resource extraction to production of materials, the product itself, use of the product, and management of the product after it is discarded (in other words, ‘from the cradle to the grave’). The term ‘product system’ refers to the entire system of unit processes involved in a product’s life cycle (Guinée, 2002).

An LCA study is divided into four phases (see Figure 5) as defined by ISO 14040/14044 standards (ISO, 2006). These four phases are the goal and scope definition, the inventory analysis, impact assessment and interpretation. Each phase is discussed in the text below, based on ISO 14040/14044 (ISO, 2006) and the handbook of LCA (Guinée, 2002).

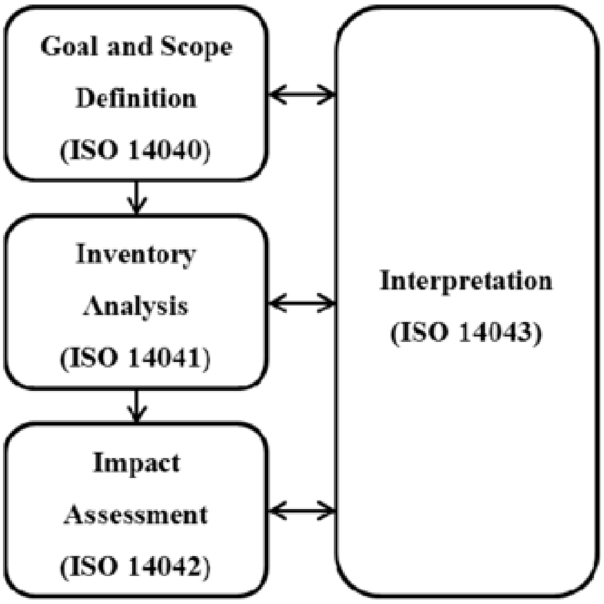


Figure 5. LCA general framework (ISO, 2006)

3.2.1 Goal and scope definition

In this phase, the initial decisions that establish the working plan for the entire LCA is made. Consequently, the goal and scope definition are the base of the research.

The goal of the LCA study will consists of the aim of the LCA study, the application of the findings, the practitioner, the stakeholders, the research's commissioner and initiator, the stakeholders, and the target audience of the study's results.

In the scope of the LCA study, key decisions are made to shape the study, including considerations like the study's temporal (e.g. desired age of data under 15 years), geographical (e.g. the Netherlands), and technological coverage (e.g. best available technology, the level of sophistication (e.g. detailed), and the focus on environmental impacts.

Lastly, the definitions of function, functional unit, alternative(s), and reference flows are given. The functional unit specifies the main function or functions that a product system performs and how much of these should be considered in the planned LCA study. It will serve as the foundation for choosing one or more substitute product systems that might carry out this function(s). The functional unit makes it possible to define reference flows for each system and to regard them as functionally equivalent.

3.2.2 Inventory analysis

The Inventory analysis phase involves establishing the product system(s), which includes defining system boundaries (between the economy and the environment, in relation to cut-off and with other product systems) creating flow diagrams with unit processes, gathering data for these processes, conducting allocation for multifunctional processes, and finalizing calculations. The main result of this phase is the inventory table, that includes all the environmental in- and outflows of the system related to the functional unit for each reference flow such as kilograms of carbon dioxide, cubic meters of natural gas, and more.

LCA data can be modelled in many different software, for instance, you have CMLCA (Heijungs, 2012), Activity Browser (Steubing et al., 2020) and OpenLCA. Furthermore, databases like ecoinvent can be used. For this study, the OpenLCA software is chosen. OpenLCA is chosen because of its open-source nature.

3.2.3 Impact assessment

The phase known as Life Cycle Impact Assessment (LCIA) involves further processing and evaluation and aggregation of the inventory results in terms of societal preferences and environmental impacts. In order to do this, a list of relevant impact categories to consider is defined, and models are chosen by the practitioner to link the environmental interventions to appropriate category indicators for these impact categories. In the characterization stage, the actual modelling results are calculated, and an optional normalisation is used to show the proportion of the modelled outcomes in a global or regional total. In order to account for the societal preferences of the many effect categories, the category indicator findings might finally be aggregated and weighted.

3.2.4 Interpretation

In this phase, the overall conclusions are drawn, and all the choices and assumptions are made during the analysis and the results of the analysis are evaluated in terms of robustness and soundness. Conclusions are generated based on contribution and sensitivity analyses, and these outcomes are utilised to develop recommendations for changes.

3.2.5 Limitations

The limitations of an LCA study stem from its broad approach. It can't assess local impacts, doesn't fully consider future changes, focuses on physical aspects (lack of market mechanisms), and doesn't cover economic and social factors. It relies on technical assumptions, data availability can be a problem, and it informs decisions but doesn't make them (Guinée, 2002).

Additionally, there are several limitations associated with LCA within the SCD method. For instance, many SoCs lack characterization factors for human toxicity and ecotoxicity impacts. Furthermore, LCA databases often lack characterization factors and emission flows on SoCs that are relatively well-understood, especially if they constitute a minor portion of the product composition. These limitations should be closely monitored during the study. When no data can be found, assumptions should be made.

3.3 Ex-ante LCA

Most LCA studies carried out in the last twenty years have been ex-post studies, focusing on existing and established technologies. This is primarily due to the requirement for sufficient data for fore- and background processes to perform an LCA study. Nevertheless, making adjustments to technical systems that are already in use is quite expensive (Cucurachi et al., 2018). This is referred to as the Collingridge dilemma: assessment of a technology is easier when technologies are well-established, but the expenses associated with making changes are high. Conversely, assessing early-stage technologies is challenging, but making modifications is less expensive (Kudina & Verbeek, 2019). The use of LCA in an ex-ante way allows for the assessment of potential policy changes, verification of environmental sustainability claims and support for early design improvements and wise financial choices (Cucurachi et al., 2018). van der Giesen et al. (2020, p. 2) define ex-ante LCA as *“performing an environmental life cycle assessment of a new technology before it is commercially implemented in order to guide R&D decisions to make this new technology environmentally competitive as compared to the incumbent technology mix.”*

In an ex-ante LCA emerging technologies, typically still in the experimental or pilot phase, can be compared to the established incumbent technology within the current technological landscape (Cucurachi et al., 2018). The aim of an ex-ante LCA study is to provide structure and enable informed discussions on design choices and potential future scenarios for new technologies. Consequently, the outcomes of an ex-ante LCA study should not be viewed as a final conclusion (van der Giesen et al., 2020).

Van der Giesen et al. (2020) mention that the distinctions between ex-ante and ex-post LCA do not primarily lie in the overall LCA framework, but rather in how specific phases and steps are executed. This includes defining the intended use of emerging technologies, establishing the functional unit, creating the flowchart, and projecting the technology's future and related data. Consequently, to conduct an ex-ante LCA study, the same framework of ISO 14044 and its standard LCA phases is employed.

3.3.1 Challenges

Ex-ante LCA studies have several unique challenges. The primary hurdle lies in the scarcity of data, both for background and foreground processes (Cucurachi et al., 2018). These studies involve high uncertainty, particularly concerning the temporal development of and life cycle inventory data for the emerging technology. The modelling process must be consistent across various product systems and consider the evolution of both foreground and background future systems (van der Giesen et al., 2020). Background data from existing LCI databases often lacks representativeness, and the absence of characterization factors for certain environmental impact categories further complicates the analysis. Additionally, conducting ex-ante LCA requires greater stakeholder participation and interdisciplinary collaboration (van der Giesen et al., 2020). Addressing these challenges is vital in harnessing ex-ante LCA's potential to provide insights into emerging technologies' environmental impacts and guide R&D, business decisions, and investment choices. Thus, these challenges should also be considered during this study.

4. Selection of SoC for this study

In this chapter, the first two steps of the SCD method are conducted, each encompassing sub steps that will be discussed in the following sections. Initially, a literature review is conducted to identify potential SoCs present in an LCD monitor. Following this, the SoC that will be used in this study is chosen, what will be based on data availability for the purposes of this study. Furthermore, the exposure and emission scenarios of the chosen SoC are discussed.

4.1 Literature research on possible SoCs in LCD monitor

First, research is done on the possible SoCs that are present in an LCD monitor. Unfortunately, there is no contact with experts in the market that could provide information on the SoCs present in an LCD monitor. Thus, a literature review is conducted to identify the possible SoCs in an LCD monitor and to specify the SoC focused on in this study. Which will address the first sub-research question: *What are possible SoCs in an LCD monitor, and where are these SoCs located within an LCD monitor?*

4.1.1 Method

To facilitate this literature review, initial keywords have been defined. In the literature, various terms are employed to refer to SoCs, and these have all been included as keywords. Table 1 provides a clear overview of these keywords, which are utilized in various combinations using ‘AND’ and ‘OR’ operators. Additionally, some analyses may utilize only a subset of the identified keywords. The search engines employed for this research are Google Scholar and Web of Science. The keyword combinations used, and the resulting outcomes are presented in Appendix C. Furthermore, a filter was employed to limit the results to studies published within the last 15 years.

Table 1. Keywords literature review SoCs in LCD monitor.

Liquid Crystal Display	**Substances of concern**	**Monitor**
LCD	Substances of very high concern	Screen
	Hazardous substances	Personal Computer
	Toxic materials	Computer
	Toxic compounds	
	Toxic metals	
	Toxic substances	
	Chemical hazards	
	Brominated flame retardants	
	Flame retardants	

Despite using numerous different keywords and combinations, only limited research concerning SoCs in an LCD monitor was discovered. No single study was identified that comprehensively discusses all the SoCs within an LCD monitor. In order to expand the scope of the search and identify additional studies addressing SoCs in an LCD, it was decided to include search combinations that omitted the keyword 'monitor' and its synonyms. Additionally, to broaden the search scope and discover additional relevant studies on SoCs in an LCD, an alternative approach was formulated. This approach involved searching for articles that provide comprehensive details about all the components and materials used in an LCD (monitor). It was anticipated that such articles might also provide information about potential SoCs in an LCD (monitor). Consequently, an additional set of keywords was introduced, as detailed in Table 2, which are utilized in various combinations using ‘AND’ and ‘OR’ operators. Additionally, some analyses may utilize only a subset of the identified keywords. The same search engines are used, and the outcomes are documented in Appendix C.

Table 2. Extra keywords literature review SoCs in LCD monitor.

Liquid Crystal Display	Components	Monitor
LCD	Bill of materials	Screen
	Construction	Personal Computer
	Materials	Computer

The abstracts, titles, and keywords of papers were read and assessed for their suitability. Studies were chosen for inclusion in this research based on the following search criteria:

- The paper had been published within the last 15 years;
- It focused (partly) on an LCD or LCD monitor;
- It mentions substances that could be SoC(s) in an LCD or LCD monitor.

4.1.2 SoCs in LCD monitor

Numerous studies mention the metals present in an LCD monitor (Andooz et al., 2022; Gautam et al., 2022; Kolias et al., 2014; Pabo & Plamthottam, 2012; Savvilotidou et al., 2014; Tyagi & Chatterjee, 2013; Yeom et al., 2018). The majority of these studies exclusively focus on the LCD display (without electronics and housing), with only one study specifically addressing an LCD monitor (Kolias et al., 2014). There is no study found that mentions the possible SoCs that could be generated during the life cycle of the LCD monitor.

These studies exhibit differences in identifying the metals within an LCD monitor. For example, copper is mentioned by six references, but cadmium is only mentioned by one reference. This difference could arise due to differences between monitors, but this remains unclear. Table 3 provides a summary of the mentioned metals and indicates which studies confirm their presence in an LCD monitor. While some metals are referenced in multiple studies, others are mentioned in just one study. Notably, not all metals will be present in the LCD monitor in their metallic form; some will exist as oxides (A.R. Balkenende, personal communication, February 5, 2024).

Table 3. Mentioned metals in LCD monitor with sources.

Metal	Sources
Aluminium (Al)	Gautam et al. (2022); Kolias et al. (2014); Savvilotidou et al. (2014); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Antimony (Sb)	Lim and Schoenung (2010)
Arsenic (As)	Kolias et al. (2014); Lim and Schoenung (2010); Savvilotidou et al. (2014); Yeom et al. (2018)
Barium (Ba)	Lim and Schoenung (2010); Yeom et al. (2018)
Beryllium (Be)	Yeom et al. (2018)
Cadmium (Cd)	Yeom et al. (2018)

Chromium (Cr)	Kolias et al. (2014); Lim and Schoenung (2010); Savvilotidou et al. (2014); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Cobalt (Co)	Lim and Schoenung (2010); Yeom et al. (2018)
Copper (Cu)	Gautam et al. (2022); Kolias et al. (2014); Lim and Schoenung (2010); Savvilotidou et al. (2014); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Gold (Au)	Yeom et al. (2018)
Indium (In)	Andooz et al. (2022); Gautam et al. (2022); Pabo and Plamthottam (2012); Tyagi and Chatterjee (2013)
Iron (Fe)	Gautam et al. (2022); Kolias et al. (2014); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Lead (Pb)	Kolias et al. (2014); Lim and Schoenung (2010); Yeom et al. (2018)
Manganese (Mn)	Yeom et al. (2018)
Mercury (Hg)	Kolias et al. (2014); Lim and Schoenung (2010)
Molybdenum (Mo)	Lim and Schoenung (2010); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Nickel (Ni)	Kolias et al. (2014); Lim and Schoenung (2010); Savvilotidou et al. (2014); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Palladium (Pd)	Yeom et al. (2018)
Selenium (Se)	Yeom et al. (2018)
Silver (Ag)	Lim and Schoenung (2010); Yeom et al. (2018)
Tantalum (Ta)	Tyagi and Chatterjee (2013)
Tin (Sn)	Andooz et al. (2022); Gautam et al. (2022); Kolias et al. (2014); Pabo and Plamthottam (2012); Savvilotidou et al. (2014); Tyagi and Chatterjee (2013); Yeom et al. (2018)
Titanium (Ti)	Tyagi and Chatterjee (2013); Yeom et al. (2018)
Tungsten (W)	Tyagi and Chatterjee (2013)
Vanadium (V)	Yeom et al. (2018)
Zinc (Zn)	Gautam et al. (2022); Kolias et al. (2014); Savvilotidou et al. (2014); Yeom et al. (2018)

These studies typically do not specify the precise locations of metals within an LCD monitor. Kolias et al. (2014) have categorized their findings into various parts of the LCD monitor, such as the plastic housing and the printed wiring board (PWB), yet they do not provide a more detailed breakdown of metal locations. Tyagi and Chatterjee (2013) provide a more detailed location of several metals. Thereby, two metals, indium, and tin, are assigned a specific location. These metals are employed in a transparent conductive oxide (TCO) called indium tin oxide (ITO), which is situated on both sides of the LC on two glass substrates (Andooz et al., 2022). Figure 6 shows the basic construction of an LCD and where the ITO film is located.

In the literature, various other substances present in an LCD monitor are mentioned, as indicated in Table 4. Some of these substances are flame retardants used in plastics (TBBP-A, PBDEs, and BTBPE), while others are used to enhance the flexibility of plastic components (DEHP, BBP, and DBP). As a result, these substances can be found in the plastic constituents of the LCD monitor. Tyagi and Chatterjee (2013) identify several different kinds of silicone and photopolymers/binders that are present in an LCD monitor. Notably, each of these substances is only mentioned in a single article.

Furthermore, in these studies, there is a lack of clarity regarding the specific model of the LCD monitor under assessment. Sun et al. (2016) only notes that the monitor they examined was manufactured in China in 2005. Consequently, it remains unclear whether these substances are commonly present in all LCD monitors or if they are exclusive to the specific models employed in these studies.

Table 4. Other SoCs present in LCD monitor with sources.

Substance	**Source**
Tetrabromobisphenol-A (TBBP-A)	Groß et al. (2008)
Bis (2-ethylhexyl) phthalate (DEHP)	Groß et al. (2008)
Butyl benzyl phthalate (BBP)	Groß et al. (2008)
Dibutylphthalate (DBP)	Groß et al. (2008)
Polybrominated diphenyl ethers (PBDEs)	Sun et al. (2016)
1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE)	Sun et al. (2016)
Different kinds of silicone	Tyagi and Chatterjee (2013)
Several photopolymers/binders	Tyagi and Chatterjee (2013)

This literature review has revealed a scarcity of information relating to SoCs within an LCD monitor. Consequently, providing an in-depth response to the research question *What are possible SoCs in an LCD monitor, and where are these SoCs located within an LCD monitor?* proved unfeasible. There are more studies found on metals in an LCD monitor than other substances like flame retardants. Furthermore, there is limited knowledge regarding the precise locations of SoCs within the LCD monitor and whether they are universally found in all LCD monitors. Notably, two metals, indium, and tin, have been mentioned in multiple articles with specific information about their location within the product, as they are utilised in ITO.

4.2 Selection of SoC

This subchapter comprises step 1a of the SCD method, which involves identifying the SoC. Additionally, it includes step 1b, which entails describing the substance characteristics, potential hazards, function in the product, and regulatory status. Moreover, step 2a is conducted at the end of this subchapter, which involves identifying the emission exposure scenarios throughout the lifecycle. This section will answer the following sub-research question: *Which SoC can serve as an example for this study, considering data availability, and what is its harm to human health and the environment?*

Before making the decision on which SoC to focus on in this study, two things must be considered. Firstly, it is crucial to determine the availability of adequate data and information on the chosen SoC for following steps of the study. This is particularly crucial given the exploratory nature of this study. Secondly, understanding the precise location of the SoC within the LCD monitor is of importance, as it will enable the generation and design of strategies in the later stages of this study. It is noteworthy that these selection criteria differ from those of the SCD method. Whereas the SCD method selects an SoC based on its highest potential toxicity, in this case, alternative selection criteria are utilised. This is because without the specific location of the SoC and adequate data, the remaining steps of the SCD method cannot be tested and implemented.

As mentioned in the previous section, there is a limited amount of information available regarding SoCs within an LCD monitor. The studies exhibit inconsistencies in identifying the substances present in an LCD monitor. Consequently, it becomes challenging to determine whether the mentioned substances are universally present in all monitors or exclusive to the specific models under examination. For this reason, substances within plastic components are not selected, nor are substances mentioned in only one study.

Multiple metals remain as potential SoCs for this study. Particularly, two of these metals, tin, and indium as components of ITO. Since tin and indium are present as ITO in an LCD, ITO would be a possible SoC for this study. ITO has a well-defined location within an LCD monitor. Consequently, an examination was conducted to determine if sufficient data could be retrieved for each step of the study. Table 5 demonstrates that there is data and information available for each step of the SCD method, which could make ITO a suitable SoC for this study.

Table 5. Data availability for every step of the study

Step	Source	Data
Step 3 and 4	Minami (2008)	Gives several substitutions for ITO.
	Varanytsia et al. (2016)	Alternative aluminium zinc oxide (AZO) and gallium zinc oxide (GZO)
	Way et al. (2019)	Alternative fluorine doped tin oxide (FTO)
	Wang et al. (2018)	Recovering of ITO from LCD waste with flotation
	Choi et al. (2014)	Recovering of ITO from LCD waste with electrochemical and acid treatment
Step 4c	Kawajiri et al. (2022)	Inventory data of alternative zinc oxide (ZnO) and ITO
	Rao et al. (2021)	Partly Inventory data on FTO
	Sarialtin et al. (2020)	Partly Inventory data on FTO
	ecoinvent	Inventory data and background processes for the LCA

ITO has been selected as the SoC for this study. Firstly, the precise location of ITO within an LCD monitor is known. Moreover, there is an abundance of data and information accessible for the remaining steps of the study. Lastly, ITO is not limited to its use in LCDs; it is also employed in various other products, like solar cells (Dong et al., 2019; Txintxurreta et al., 2021), potentially broadening the relevance of the results of this research to a wider market.

4.2.1 Introduction Indium tin oxide

Unlike some metals, indium doesn't exist independently in ore; rather, it is obtained as a by-product from specific sulphide ores of zinc, copper, and lead, usually in relatively small quantities (Hasegawa et al., 2013). Primary indium production is chiefly dominated by China (38%), followed by the Republic of Korea (30%), Japan (11%), and Canada (11%) (Akcil et al., 2019).

The EU Commission has classified indium as a critical raw material (CRM) due to its enduring strategic importance for the EU manufacturing industry. This classification suggests that there may be a potential supply risk of indium in the near future. Additionally, the price of indium has experienced fluctuations due to actions taken by countries with indium reserves. For these reasons, numerous studies have been conducted to recover indium from industrial waste (Hasegawa et al., 2013). Furthermore, extensive research is being conducted to explore alternative materials that can replace ITO (Kawajiri et al., 2022).

Indium finds application in a variety of products, including flat panel displays, batteries, and solar panels (Akcil et al., 2019; Schwarz-Schampera, 2014). More than 80% of the worldwide indium production is dedicated to the manufacturing of ITO (Akcil et al., 2019; Wang et al., 2018). ITO serves as a transparent conductive oxide (TCO) in flat panel displays and LCDs. ITO is the most widely used TCO due to its exceptional properties, such as high optical transparency in the visible spectrum, high electrical conductivity, good chemical stability and high infrared reflectance (Her & Chang, 2017; Sun et al., 2016; Txintxurreta et al., 2021). Consequently, ITO has been widely used in various products, including photoelectric devices, display panels, photovoltaic cells, thin-film sensors, and organic light-emitting diodes (Dong et al., 2019; Txintxurreta et al., 2021).

ITO is primarily composed of indium (III) oxide (90 wt%) and tin (IV) oxide (10 wt%) (Akcil et al., 2019; Wang et al., 2018). Various production methods can be employed to generate ITO films, including magnetron sputtering, pulsed laser deposition, chemical vapour deposition, spray pyrolysis , radio frequency sputtering, sol-gel processing, and electron beam deposition (Dong et al., 2019; Her & Chang, 2017; Txintxurreta et al., 2021). Among these methods, sputtering (with target) is the most commonly used technique for producing ITO due to its rapid growth rate, reliability, and precise control over film characteristics (Her & Chang, 2017).

An LCD monitor has two ITO coatings, both of which are applied onto glass substrates. One of these ITO coatings functions as a common electrode and is deposited on the CF layer, typically having a thickness ranging from 125 to 150 nm. The other ITO coating is patterned on the TFT to serve as a transparent pixel electrode, essential for controlling each sub-pixel of an LCD, with a thickness typically falling within the range of 20-50 nm (Lippens et al., 2012; Wang et al., 2018). Figure 6 illustrates the basic construction of an LCD and indicates the specific locations of the ITO coatings.

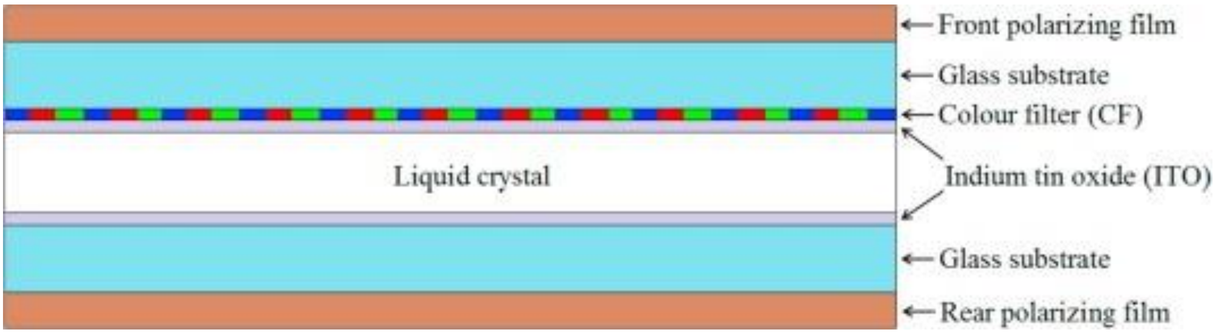


Figure 6. Basic construction of an LCD (Wang et al., 2018)

4.2.2 Material characteristics of Indium tin oxide

This section discusses the material characteristics of ITO. As previously mentioned, ITO possesses exceptional properties, including high optical transparency in the visible spectrum, high electrical conductivity, good chemical stability, and high infrared reflectance (Her & Chang, 2017; Sun et al., 2016; Txintxurreta et al., 2021). According to Arvidsson et al. (2016), the optical transparency of ITO ranges from 79% to 90% in the visible spectrum. Fang et al. (2002) states that the light transmittance of ITO is 90%. Lastly, Kawajiri et al. (2022) mentions that the light transmittance of ITO exceeds 85%. It is assumed, that the best material characteristics can be achieved with mass production, thus the optical transparency of ITO is 90%.

Several different values of resistivity of ITO are found in literature. Dondapati et al. (2013) and Fischer et al. (2018) mention that ITO has a resistivity close to 1,0 x 10^{-4} Ωcm. According to Farhan et al. (2013) is the resistivity of ITO 7,5 x 10^{-4} Ωcm when it is produced with ion-assisted deposition at room temperature. Also, for the resistivity of ITO is assumed that the best value can be reached with mass production, thus the resistivity of ITO is 1,0 x 10^{-4} Ωcm.

According to A.R. Balkenende, the lifespan of ITO film is not determining the lifespan of an LCD monitor (personal communication, November 29, 2023). This means that the lifespan of an LCD monitor is most commonly shorter than that of an ITO film. The lifespan of an LCD monitor depends on how it is used and its quality (AKB, 2022). If the monitor is not turned off when it is not used, the technical lifespan is about 3 to 5 years (Editorial Team, 2020). However, when a monitor is turned off when it is not used, the lifespan can be up to 10 to 20 years (AKB, 2022; Editorial Team, 2020). Kawajiri et al. (2022) assumed a lifespan of 10 years for an LCD TV. It is assumed that the lifespan of an LCD monitor is about the same.

4.2.3 Toxicity Indium tin oxide

In this section, step 2a of the SCD method is executed, involving the identification of emissions and exposure scenarios across the product-substance combination. This is also part of step 1b of the SCD method, namely the detailing the potential hazard of ITO.

The emissions and exposure of ITO will most likely only take place during the manufacturing of ITO and in the end-of-life of an LCD monitor. During the use phase is the ITO safely enclosed in the LCD in a monitor (A.R. Balkenende, personal communication, November 29, 2023). In this section, the emissions and exposures of ITO, that are found, are discussed divided into human, animal, and environmental hazards.

Human hazards

Pabo and Plamthottam (2012) noted that until the early 1990s, indium compounds were considered non-hazardous due to the limited information and research available on their impact on human health and animals. Furthermore, they summarized the available data on the toxicity of indium compounds in humans during the production of ITO. The most important findings are discussed in this section.

Between 2003 and 2010, studies reported 10 cases of lung disease related to occupational exposure to ITO, with three fatalities in Japan and the US (Omae et al., 2011). Inhaling industrial ITO exposure has been linked to lung diseases (Chonan et al., 2007; Hamaguchi et al., 2008; Homma et al., 2003; Lison et al., 2009; Nakano et al., 2009), including cholesterol clefts, granulomas, pulmonary alveolar proteinosis, interstitial fibrosis, and emphysema (Cummings et al., 2010; Cummings, Nakano, et al., 2012) . The type of indium exposure affects workers differently, with elemental indium identified as a likely toxic component of ITO (Cummings, Suarthana, et al., 2012; White & Hemond, 2012). Indium, when inhaled, persists in the human body for an extended period (mean of 4,6 years), indicating the potential for long-term health impacts from indium inhalation exposure (Chonan et al., 2007). Even after withdrawal from exposure, Hoet et al. (2012) noted that indium levels in the plasma and urine of workers in a metallurgical setting remained elevated for years. This suggests an ongoing risk of pulmonary and systemic diseases beyond the exposure period. The exposure media of indium and ITO is through air (Pabo & Plamthottam, 2012).

Bomhard (2018) conducted comprehensive research on the toxicity of indium oxide, which highlights the increasing occupational exposure to indium oxide leading to health hazards such as lung diseases predominantly reported among workers in Korea and Japan. Additionally, Bomhard (2016) conducted research on the toxicity of ITO which indicates various lung-related effects, but conclusive information about potential harm to other organs is lacking. Bomhard (2016) also emphasizes that more research should be done to the toxicity of ITO, particularly concerning the solubility of ITO in biological fluids, potential genotoxicity, and the development of lung tumours in rodents exposed to ITO.

As previously discussed, there are various production techniques for ITO. However, the above cited articles do not specify if the mentioned emissions and exposures apply uniformly across all production methods or are specific to particular techniques. Notably, some articles refer to ITO (sputtering) targets, indicating that it is about the magnetron or radio frequency sputtering production techniques (Bomhard, 2016, 2018; Chonan et al., 2007; Omae et al., 2011; White & Hemond, 2012). In this study, it is assumed that the emissions and exposures are associated with the sputtering production technique.

Moreover, an examination of emissions and exposure scenarios for the end-of-life of an LCD monitor, including ITO, has been conducted. Studies assessing the toxicity of e-waste sites, as reviewed by Pabo and Plamthottam (2012), were conducted prior to LCD monitors becoming a significant component of the e-waste stream (Brigden et al., 2005; Brigden et al., 2008; Ha et al., 2009). Consequently, the measured indium levels are likely attributed mostly to cell phones. It is plausible that concentrations have increased now that a greater number of LCD monitors are reaching the end of their useful life. Nevertheless, indium concentrations were already found in the air, hair of workers and dust (Pabo & Plamthottam, 2012).

As LCDs become prevalent at informal e-waste sites, the rise in indium concentrations is expected, according to Pabo and Plamthottam (2012). Worker exposure during LCD dismantling may cause varying degrees of lung damage. Indium could impact soil, food, and water, posing a high risk to humans, especially given its evolving recognition as a toxicant. The potential risk at informal e-waste sites depends on how LCD screens are managed (Pabo & Plamthottam, 2012).

ECHA classifies tin, tin (IV) oxide and indium oxide as non-hazardous or non-toxic (ECHA, 2023k, 2023n, 2023o). Furthermore, information regarding the substance indium is not available in the ECHA database. ECHA categorizes ITO as a health hazard, highlighting its potential to cause cancer through inhalation, as well as severe eye irritation, respiratory irritation, skin irritation, and organ damage with prolonged or repeated exposure (ECHA, 2023l). ECHA does not state in which phase of the life cycle of ITO, during production or end-of-life, this hazard occurs or if this hazard is both for humans and animals. According to Pabo and Plamthottam (2012)

$InCl_3$, $In(NO_3)_3$ and $In(OH)_3$ can occur after the end-of-life of ITO. ECHA, states that $InCl_3$ can cause severe skin burns and eye damage, as well as harm organs upon prolonged or repeated exposure. Additionally, it has harmful effects on aquatic life with long-lasting consequences (ECHA, 2023m). ECHA has no hazards classified for $In(OH)_3$ (ECHA, 2023j). Furthermore, ECHA does not have any documentation for $In(NO_3)_3$. None of the mentioned substances appears on the ECHA list or ZZS list of RIVM (ECHA, 2023b; RIVM, 2023b). However, ITO has been added to the pZZS list of the RIVM (RIVM, 2023a).

Animal hazards
Several studies have been done on the toxicity of ITO for animals. Historical studies dating back to 1942 indicated haemorrhagic lesions in laboratory animals, while subsequent research demonstrated harm to the foetus during pregnancy and the development of abnormalities in an embryo or foetus (Pabo & Plamthottam, 2012). Bomhard (2016) emphasized that experimental animals exhibit lung damage, leading to inflammatory and fibrotic changes, as well as an increase in lung tumours. Bomhard (2018) further supported this, suggesting that the lung is a major target organ inducing inflammation, fibrosis, and lung tumours in rodents.

Nagano et al. (2011) confirmed inhalation-induced carcinogenicity and in rats chronic pulmonary lesions in rats and mice exposed to ITO, with hamsters developing pneumonia from ITO exposure (Tanaka et al., 2002). Omura et al. (2002) reported testicular damage in hamsters due to intratracheal instillations of ITO, linking it to indium absorption from dissolved ITO particles affecting the testis. However, the reproductive impacts were inconclusive (Pabo & Plamthottam, 2012).

Animal studies have indicated that the chemical form of indium plays a role in its distribution within the body, affecting which organs are affected by its accumulation. Soluble indium accumulates primarily in the liver, spleen, and other reticuloendothelial system organs, while ionic indium accumulates in the kidneys (Pabo & Plamthottam, 2012). It is assumed that this exposure most likely will happen at the end-of-life of an LCD monitor when the monitor is shredded and used as, for instance, filling for roads.

Environmental hazards
Finally, the environmental hazard of ITO is looked at. Several studies have been done on the indium levels in soil at recycling sites. According to Bridgen et al. (2005, 2008) are the indium levels below the detection limits. However, Ha et al. (2009) revealed elevated indium levels in soil and air at the e-waste recycling facilities. Fujimori et al. (2012) further demonstrates indium enrichment in dust at recycling facility. Suggesting an emerging trend of LCDs becoming a significant part of the e-waste stream (Pabo & Plamthottam, 2012).

With the anticipated increase in LCDs within e-waste, there is a concern that indium could deposit on soil, foods, and enter waterways, impacting aquatic organisms. While indium's low solubility implies a low to moderate aquatic threat, the potential for a moderate to high human threat exists due to the incomplete understanding of indium toxicity in humans (Pabo & Plamthottam, 2012).

In conclusion, there is a scarcity of data on the SoCs present in an LCD monitor or those that could be generated during its life cycle. Additionally, there is a shortage of toxicity data on the selected SoC. While there is some available data on the potential toxicity of ITO during production and at the end of its life, it remains limited. Furthermore, the potential probability of toxicity remains unclear. Nevertheless, even with this restricted data, it is possible to assume that ITO holds potential hazards for both humans and animals. This is demonstrated by cases such as lung disease observed in workers and animals due to exposure to ITO.

The emission and exposure scenarios of the manufacturing and end-of-life are not always clear, resulting in increased difficulty in generating and finding strategies for ITO. Since it is assumed that the use phase of ITO is safe, the focus during the generation and search for strategies will mainly be on the production and end-of-life of ITO.

Due to the limited data available on emission exposure scenarios, executing steps 2b and 2c of the SCD method proved unfeasible. Step 2b involves prioritising emissions exposure scenarios and lifecycle stages, which is almost unfeasible due to the scarcity of data. However, it can be assumed that production of ITO and its end-of-life have higher priority, as some data exists for these lifecycle stages. Additionally, step 2c, detailing emission exposure scenarios in connection to the product, was also unfeasible due to the lack of data.

5. Avoidance, reduction, and control strategies for ITO

In this chapter, the next two steps of the SCD method are conducted. This involves the third step of the method, which consists of defining or selecting strategies for ITO. Moreover, it involves the fourth step of the SCD method, which consist of evaluating the selected strategies and measure their potential effects. The fourth step comprises several sub steps. For example, step 4b involves analysing the potential negative effects of the strategy, which could introduce new risks for human health or the environment. This sub step is carried out in this chapter. Additionally, step 4c involves analysing potential trade-offs of the strategy. While this is partly addressed in the next chapter with the ex-ante LCA study, trade-offs could also relate to product performance, a topic discussed in this chapter.

Unfortunately, there is no contact with experts in the market who could provide information on possible strategies for ITO. Therefore, a literature review is conducted to identify possible strategies that could avoid, reduce, or control ITO in an LCD monitor. The following sections delve into the various identified strategies for ITO. Here, both steps 3 and 4 of the SCD method are addressed. This approach is taken because the evaluation of the identified strategies partly informs the selection of the strategy. The chosen strategy will undergo assessment in the next chapter, comparing it to the current technology, ITO, through an ex-ante LCA study. The sub-research question addressed in this chapter is: *What are possible strategies to replace, reduce or control the selected SoC in an LCD monitor, and which strategy will be selected for this study?*

5.1 Literature review to possible strategies

This section presents a literature review on potential strategies for replacing, reducing, or controlling ITO in an LCD monitor. According to Bolaños Arriola et al. (2022), there are three different kinds of strategies: avoidance, reduction, and control. Potential strategies for each category are identified in the literature review.

5.1.1 Method

This section covers the method used for this literature review. To streamline the review process, specific keywords were initially defined. Table 6 offers a comprehensive list of the specified keywords, which were used in different combinations. The research was conducted using Google Scholar and Web of Science search engines. The combinations of keywords and their corresponding outcomes are detailed in Appendix C. Additionally, a filter was applied to include only studies published within the last 15 years.

Table 6. Keywords literature review strategies for ITO

Indium tin oxide	**Liquid Crystal Display**	**Alternative**
ITO	Liquid Crystal	Reduce
	LCD	Recovery
		Replace
		Control
		Strategy
		Refurbish
		Reuse
		Remanufacture
		Contain
		Isolate
		Substitute
		Avoid
		Extraction

The abstracts, titles, and keywords of papers were read and assessed for their suitability. Studies were chosen for inclusion in this research based on the following search criteria:

- The paper had been published within the last 15 years;
- It focused (partly) on ITO in an LCD;
- It mentions a possible strategy to replace or avoid ITO;
- It mentions a possible strategy to reduce ITO;
- It mentions a possible strategy to control ITO.

5.2 Avoidance strategies

In this section, strategies that avoid the use of ITO are discussed, specifically, substitution strategies. Minami (2008) discusses several compounds that can serve as TCOs containing indium, such as indium zinc oxide (ZnO:In). It is noted that these alternatives may increase the resistivity of the TCO, furthermore some of these compounds are toxic as well. Additionally, indium is still present in these substances and as discussed in chapter 4.2.2 indium is one of the potentially toxic substances of ITO. For this reason, this study will not further explore the avoidance strategies that still contain indium.

Other strategies found in literature are the TCOs aluminium doped zinc oxide, gallium doped zinc oxide, fluorine doped tin oxide, graphene, silver nanowire networks and conducting polymers. These TCOs are briefly discussed, providing an overview of potential toxicity, material characteristics (electrical resistivity, light transmittance, and lifespan), and possible inventory data. To achieve a comprehensive understanding of potential toxicity of the TCOs, information is sought from literature, ECHA, and RIVM. The discussion of material characteristics and lifespan is essential, as it can influence the performance of the LCD monitor. For example, lower light transmittance may result in increased electricity consumption during the use of the LCD monitor. In case of a TCO, higher light transmittance is preferred, along with lower electrical resistivity. For this study, the optimal material characteristics of the TCOs are assumed, as mass production will be altered to achieve these material characteristics (A.R. Balkenende, personal communication, November 29, 2023). The material characteristics of the TCOs are therefore compared to best properties reported for ITO, i.e. light transmittance of 90% and electrical resistivity of 1×10^{-4} Ωcm.

Additionally, it is noted whether an alternative has inventory data or processes available in ecoinvent for potential follow-up ex-ante LCA study on that strategy.

5.2.1 Aluminium doped zinc oxide

As a replacement for ITO, zinc oxide (ZnO) has attracted much attention, especially to its desirable characteristics which include high transmittance, non-toxicity and lower cost (Eshaghi & Hajkarimi, 2014). ZnO can be used in combination with different dopant materials. Aluminium doped ZnO (ZnO:Al) is seen as one of the most promising TCO as an alternative to ITO (2 wt% Al_2O_3) (Yamamoto et al., 2011). Specifically, because aluminium lowers the resistivity of ZnO (Eshaghi & Hajkarimi, 2014). Below the material characteristics, possible toxicity, and available inventory data of ZnO:Al are discussed.

Material characteristics

The material characteristics of ZnO:Al depend on the production method and film thickness (Al-Ofi et al., 2012; Ayinde et al., 2019). According to Ayinde et al. (2019), the light transmittance of ZnO:Al is typically between 75% and 95%. Al-Ofi et al. (2012) notes that the light transmittance is approximately 90% for films with a thickness of 100-150 nm. Additionally, the light transmittance can vary from 75% to 85% for films with a thickness of 200-300 nm. Varanytsia et al. (2016) states that the average light transmittance of ZnO:Al is 92%-93% in the visible spectrum. Consequently, it is assumed that the light transmission of ZnO:Al is 95%

Various resistivities of ZnO:Al are mentioned in literature. According to Ayinde et al. (2019), the resistivity of ZnO:Al is between 0,07 Ωcm and 0,01 Ωcm. On the other hand, Dondapati et al. (2013) report that the resistivity of ZnO:Al is approximately $1,1 \times 10^{-3}$ Ωcm. Gao et al. (2014), however, state that the resistivity of ZnO:Al is $9,8 \times 10^{-4}$ Ωcm. For this study it is assumed that the resistivity of ZnO:Al is $1,0 \times 10^{-3}$ Ωcm.

No data have been found on the lifespan of ZnO:Al. Kawajiri et al. (2022) only mention that they assumed the lifespan to be 10 years when applied in an LCD TV. According to A.R. Balkenende, the lifespan of ZnO:Al should not limit the lifespan of an LCD monitor, indicating that it is higher than that of an LCD monitor (personal communication, November 29, 2023).

Toxicity

In this section, the toxicity of ZnO:Al is researched. Additionally, the toxicity of several substances is discussed, including ZnO and Al_2O_3, as they are used during the production of ZnO:Al. Furthermore, zinc hydroxide ($Zn(OH)_2$) is discussed because this substance can be generated after the end of the life of ZnO:Al (A.R. Balkenende, personal communication, November 21, 2023).

Literature suggests that ZnO is non-toxic without elaborated argumentation Ayinde et al., 2019; Barasheed et al., 2013; Eshaghi & Hajkarimi, 2014; Fang et al., 2002; Shui et al., 2009; Swami et al., 2023). However, ECHA's database reveals multiple documentations of ZnO when the keyword "zinc oxide" is employed (ECHA, 2023c). Interestingly, one of the documents asserts that ZnO poses a substantial toxic risk to aquatic life, with potentially long-lasting effects (ECHA, 2023p). Moreover, ZnO may present hazards if ingested, inhaled, or upon repeated or prolonged exposure, potentially causing harm to internal organs. It can also impact fertility and the health of unborn children (ECHA, 2023p). ECHA describes the products and areas in which ZnO is present, mentioning electrical and electronic equipment (ECHA, 2023q). It is assumed that ZnO in ZnO:Al is largely the same as ZnO mentioned by ECHA; however, there could be differences in emission mechanisms (A.R. Balkenende, personal communication, November 21, 2023). It's worth noting that ZnO is not listed in the ZZS list or pZZS list of the RIVM, nor does it feature in the list of SVHC provided by ECHA (ECHA, 2023b; RIVM, 2023a, 2023b).

According to A.R. Balkenende ZnO:Al can be converted to zinc hydroxide ($Zn(OH)_{2)}$ at the end of its life (personal communication, November 21, 2023). ECHA states that $Zn(OH)_2$ is very toxic to aquatic life with possible long-lasting effects (ECHA, 2023d). In the literature, no documentation on the toxicity of $Zn(OH)_2$ has been found. $Zn(OH)_2$ is also not listed on the ZZS or pZZS list of the RIVM or the list of SVHC of ECHA (ECHA, 2023b; RIVM, 2023a, 2023b).

Additionally, attention is directed towards the substance aluminium oxide (Al_2O_3), which is utilised in the production of ZnO:Al (Kawajiri et al., 2022). Also, for Al_2O_3 are there several documentations found in the ECHA database. One of these documents pertains to aluminium hydroxide (iChemical, No date). The other document discusses aluminium oxide and notes that the substance can be harmful if inhaled or ingested, and there are suspicions of its potential to cause cancer (ECHA, 2023e). This is remarkable, since Al_2O_3 can be found in many products that are used daily without noticeable effects related to toxicity. For instance, Al_2O_3 can be found on every aluminium surface (Sheasby et al., 2001). Notably, also aluminium oxide is absent from the ZZS list, pZZS list provided by the RIVM, as well as the list of SVHC maintained by ECHA (ECHA, 2023b; RIVM, 2023a, 2023b). No toxicity information on Al_2O_3 is found in literature. However, several studies have explored the toxicity of Al_2O_3 nanoparticles (Pakrashi et al., 2013; Park et al., 2016; Sadiq et al., 2011; Yousef et al., 2019; Zaitseva et al., 2018). It is unclear whether nanoparticles are also generated during the production of ZnO:Al. Nevertheless, Zaitseva et al. (2018) suggest that Al_2O_3 nanoparticles pose a significant potential hazard to human health.

Finally, the toxicity of ZnO:Al is examined. According to Kawajiri et al. (2022), ZnO:Al is considered non-toxic, although no detailed argumentation is provided. In contrast, ECHA indicates that ZnO:Al is potentially toxic to aquatic life with long-lasting effects (ECHA, 2023g). Notably, ZnO:Al is not listed on the ZZS or pZZS list of the RIVM or the list of SVHC of ECHA (ECHA, 2023b; RIVM, 2023a, 2023b). The conflicting information regarding the potential toxicity of ZnO, Al_2O_3, $Zn(OH)_2$ and ZnO:Al makes a final assessment challenging. However, given the low amount of Al_2O_3 in ZnO:Al, it is assumed to behave similarly to ZnO (A.R. Balkenende, personal communication, November 21, 2023).

Inventory data
In literature and the ecoinvent database, searches were conducted for inventory data of ZnO:Al for a potential ex-ante LCA study. Kawajiri et al. (2022) conducted an LCA study on ITO and the alternative ZnO:Al (made with magnetron sputtering), providing inventory data for the ZnO:Al system until the end-of-life. Additionally, Espinosa et al. (2011) carried out an LCA study on ZnO made with slot-die coating, providing production inventory data that could be useful. Moreover, the zinc oxide production process is available in ecoinvent.

5.2.2 Gallium doped zinc oxide

Gallium doped ZnO (ZnO:Ga) is another extensively researched TCO that could serve as an alternative to ITO (4 wt% Ga_2O_3) (Kawajiri et al., 2022; Yamamoto et al., 2011). Below, the material characteristics, possible toxicity, and available inventory data of ZnO:Ga are discussed.

Material characteristics

Varanytsia et al. (2016) declare that the average light transmittance of ZnO:Ga is 92%-93%, reaching a maximum of 95% in the visible spectrum. Yamamoto et al. (2012) mention a light transmittance range of 78% to 90% for ZnO:Ga. Fortunato et al. (2004) demonstrated that the light transmittance of ZnO:Ga falls between 80% and 90%. For this study, it is assumed that the light transmission of ZnO:Ga is 95%.

Similar resistivity values for ZnO:Ga are found in literature. Yamamoto et al. (2011) indicates that the resistivity of ZnO:Ga is approximately $2{,}4 \times 10^{-4}$ Ωcm. Fortunato et al. (2004) states that the lowest resistivity achieved, with a thickness of 1100 nm, is $2{,}6 \times 10^{-4}$ Ωcm. According to Yamada et al. (2006), the lowest resistivity is $2{,}2 \times 10^{-4}$ Ωcm with a film thickness of 179nm and 4% Ga_2O_3. For this study it is assumed that the best material characteristics can be achieved with mass production, thus a resistivity of $2{,}2 \times 10^{-4}$ Ωcm.

No data is found on the lifespan of ZnO:Ga. According to Shain et al. (2014), the lifespan of electronic devices can be extended due to the good adhesion contact of ZnO:Ga with glass. However, it remains unclear what the average lifespan of ZnO:Ga is and to what extent it contributes to the extension of the lifespan of electronic devices. Though, it is assumed that it is not limiting the lifespan of the LCD monitor (A.R. Balkenende, personal communication, January 16, 2024).

Toxicity

In this section, the toxicity of ZnO:Ga is investigated. The toxicity of various substances is examined, including Ga_2O_3, which is employed in the production of ZnO:Ga. ZnO, used in the production process, has already been discussed in the preceding section.

First, the substance gallium (III) oxide (Ga_2O_3), used in the production of ZnO:Ga (Yamamoto et al., 2011), is examined. ECHA indicates that Ga_2O_3 has no classified hazards (ECHA, 2023h). Notably, Ga_2O_3 is not found in the SVHC list of ECHA or the ZZS list or pZZS list of the RIVM (ECHA, 2023b; RIVM, 2023a, 2023b). However, Wolff et al. (1988) mention that inhaled Ga_2O_3 particles exhibit significant toxicity, emphasizing the need to restrict workplace exposures. Bomhard (2020) reviewed all the available data on toxicity of Ga_2O_3 and concludes not a lot of data is available on this. Nevertheless, Bomhard (2020) concludes that the acute toxicity of Ga_2O_3 is rather low.

ZnO:Ga can be converted to zinc hydroxide and gallium hydroxide ($Ga(OH)_2$) at the end of its life (A.R. Balkenende, personal communication, November 27, 2023). ECHA has documented the substance $Ga(OH)_2$; however, the documentation is empty of information pertaining to the substance's possible toxicity (ECHA, 2023a). Furthermore, $Ga(OH)_2$ is not listed on the ZZS or pZZS list of the RIVM or the list of

SVHC of ECHA (ECHA, 2023b; RIVM, 2023a, 2023b). Thus, the toxicity of $Ga(OH)_2$ is unclear.

Finally, the substance ZnO:Ga is investigated. It appears that the ECHA database does not contain any information on ZnO:Ga. Furthermore, ZnO:Ga is not present in the SVHC list of ECHA or the ZZS list or pZZS list of the RIVM (ECHA, 2023b; RIVM, 2023a, 2023b). Moreover, there is no literature found on the toxicity of ZnO:Ga. Consequently, because of the conflicting data regarding the toxicity of ZnO, Ga_2O_3 and ZnO:Ga, it remains unclear if ZnO:Ga is potentially toxic or not.

Inventory data
No LCA study is found on ZnO:Ga in literature. Consequently, no inventory data is available. However, Espinosa et al. (2011) conducted an LCA study on ZnO made with slot-die coating, providing inventory data of the production. In ecoinvent only the production process of ZnO and gallium are available.

5.2.3 Fluorine doped tin oxide

Another alternative to ITO mentioned in the literature is fluorine-doped tin (IV) oxide (SnO_2:F) (2 wt% - 12 wt%) (Banyamin et al., 2014; Rizki et al., 2022; Way et al., 2019). Below, the material characteristics, possible toxicity, and available inventory data of SnO_2:F are discussed.

Material characteristics
Various data on the light transmission of SnO_2:F is found in literature. The material characteristics of SnO_2:F can be influenced by the way the film is produced. Ramírez-Amador et al. (2019) reports that the light transmission of SnO_2:F can reach 80-90% in the visible spectrum when produced using the Pneumatic Spray Pyrolysis (PSP) technique. Banyamin et al. (2014) indicates that the light transmission of SnO_2:F averages around 83% when it is made with magnetron sputtering. For this study, it is assumed that the light transmission of SnO_2:F is 90%.

Also, for SnO_2:F different values of resistivity are found in literature. According to Banyamin et al. (2014), the resistivity of SnO_2:F can reach up to $6{,}7 \times 10^{-3}$ Ωcm. According to Rizki et al. (2022), the resistivity of SnO_2:F ranges from 22 Ωcm to $0{,}5 \times 10^{-3}$ Ωcm, depending on the amount of dopant material used and the deposition time. For this study, it is assumed that the resistivity of SnO_2:F is $0{,}5 \times 10^{-3}$ Ωcm.

Besides several attempts, in literature there is no information found on the lifespan of SnO_2:F. However, it is assumed that it is not limiting the lifespan of the LCD monitor (A.R. Balkenende, personal communication, January 16, 2024).

Toxicity
SnO_2:F is produced using tin (IV) oxide (SnO_2) and tin (II) fluoride (SnF_2) powder targets (Banyamin et al., 2014). As discussed in section 3.2.2, ECHA indicates that SnO_2 is non-hazardous (ECHA, 2023o). Furthermore, SnO_2 is not listed in the ZZS or pZZS lists of the RIVM or ECHA's list of SVHC (ECHA, 2023b; RIVM, 2023a, 2023b). Moreover, several publications state that SnO_2 is non-toxic (He et al., 2022; Tran et al., 2015; Wu et al., 2022).

Regarding SnF_2, a search for its potential toxicity is conducted. According to Tran et al. (2015), SnF_2 is non-toxic, without detailed argumentation. Furthermore, no other literature corroborates this finding. Furthermore, SnF_2 is not present in the ECHA database and is not listed in the ZZS or pZZS lists of the RIVM or ECHA's SVHC list (ECHA, 2023b; RIVM, 2023a, 2023b).

Lastly, an examination of the toxicity of SnO_2:F is carried out. There is limited information in the literature regarding the toxicity of SnO_2:F. Abbas et al. (2014) assert that SnO_2:F is non-toxic, and Boutet et al. (2002) suggest that SnO_2:F is among the least toxic TCOs. No additional information is available. Furthermore, SnO_2:F is not found in the ECHA database, the ZZS or pZZS lists of the RIVM, or ECHA's SVHC list (ECHA, 2023b; RIVM, 2023a, 2023b). Thus, it is concluded that SnO_2:F is non-toxic. Especially, given the low amount of SnF_2 in SnO_2:F, it is assumed to behave similarly to SnO_2. However, it should be stated that only a small amount of data is available, which means that SnO_2:F could still be toxic.

Inventory data

Several LCA studies have been found on SnO_2:F. Rao et al. (2021) conducted an LCA study on high-performance monocrystalline perovskite solar cells. In these solar cells, SnO_2:F on glass is utilised. Nevertheless, they do not provide the inventory data for the production of SnO_2:F on glass. Sarialtin et al. (2020) performed a comparative LCA study on perovskite solar cells. In this case, SnO_2:F glass is employed. However, their input includes liquid fluorine instead of SnF_2 and tin instead of SnO_2. They obtained their inventory data from Espinosa et al. (2015). Nonetheless, they do not specify whether the SnO_2:F in their model is genuinely manufactured using liquid fluorine and tin or if this is an assumption. No other inventory data for the SnO_2:F product system is found. Nevertheless, SnO_2 is accessible in ecoinvent, but SnF_2 is not.

5.2.4 Graphene

Another replacement of ITO that is mentioned in literature, is graphene (or nanostructured carbon) (Xu & Liu, 2016). Below, the material characteristics, possible toxicity and available inventory data of graphene are discussed.

Material characteristics

Several studies are found that give the sheet resistance of graphene (Arvidsson et al., 2016; Kymakis et al., 2011; Sandana et al., 2013; Zhu et al., 2011). However, to compare it to the other strategies the electrical resistivity needs to be calculated. The electrical resistivity (ρ) can be calculated using sheet resistance (R_s) and thickness (t) using the following formula:

$$\rho = Rs * t$$

The calculation indicates that the graphene films mentioned by Kymakis et al. (2011) have a resistivity of 4,0 x 10^{-3} Ωcm. While Sandana et al. (2013) and Arvidsson et al. (2016) provides the sheet resistance of several graphene layers, unfortunately, it does not specify the thickness, preventing the calculation of electrical resistivity. According to Zhu et al. (2011), the calculated resistivity of undoped graphene is 0,02 Ωcm but may reach 3,5 x 10^{-3} Ωcm when it is four-layered undoped graphene. Moreover, the resistivity could be further reduced when doped, for instance, with gold(III)chloride. For this study, it is assumed that the resistivity of graphene is 3,5 x 10^{-3} Ωcm.

According to Arvidsson et al. (2016) and Pang et al. (2011), the optical transmission of a graphene monolayer is 97%, which exceeds that of ITO. It is important to note that the optical transmission can be influenced by the number of graphene layers, the substrate, and the fabrication method. For example a four-layer graphene sheet can have an optical transmission of about 90% (Arvidsson et al., 2016). For this study, the optical transmission of graphene is 90% as a four-layer graphene sheet is required for the resistivity.

Also, for graphene there is no information found in literature on the lifespan. However, it is assumed that it is not limiting the lifespan of the LCD monitor (A.R. Balkenende, personal communication, January 16, 2024).

Toxicity

Conflicting data on the toxicity of graphene is found. ECHA mentions that graphene is potentially harmful to aquatic life with long lasting effects (ECHA, 2023i). Graphene is not mentioned in the ZZS or pZZS lists of the RIVM, or ECHA's SVHC list (ECHA, 2023b; RIVM, 2023a, 2023b). Xu and Liu (2016) mentions that graphene is produced without the use of toxic chemicals and Pang et al. (2011) states that graphene is non-toxic, although they do not provide additional supporting arguments. Furthermore, no other publications are found that substantiated this. Consequently, the toxicity status of graphene remains unclear.

Inventory data

Several LCA studies have been found on graphene. Li et al. (2022) conducted an LCA study on solar cells with a graphene TCO. However, they did not specify the inventory data they used for their study. Furthermore, Arvidsson et al. (2016) performed an assessment of the energy and resource use of graphene as a substitute for ITO. In this study as well, no inventory data is provided. Ecoinvent does not contain processes related to the product system of graphene, it only includes processes on graphite.

5.2.5 Silver nanowire networks

Another alternative for ITO which has received attention is silver nanowire networks (AgNWs) (Park et al., 2015). Below, the material characteristics, possible toxicity and possible inventory data of silver nanowire networks are discussed.

Material characteristics

Several values of light transmittance of AgNWs are found in literature. The light transmittance of AgNWs can achieve 97%, as reported by Tan et al. (2020). According to Van De Groep et al. (2012), the average light transmittance of AgNWs can reach up to 91%. Sohn et al. (2019) indicates that the light transmittance of AgNWs is 82%. For this study, it is assumed that the light transmittance of AgNWs is 97%.

In literature, the sheet resistance of AgNW is mentioned, thus the electrical resistivity is calculated using the provided thickness. Lee et al. (2015) provides the sheet resistance of AgNW but does not specify the thickness. According to Song et al.

(2015), the resistivity of AgNW is approximately 1,6 x 10^{-4} Ωcm. However, according to Hu et al. (2010), the resistivity of AgNW can vary from 8,8 x 10^{-4} Ωcm to 9,6 x 10^{-5} Ωcm. For this study, it is assumed that the resistivity of AgNW is 1,0 x 10^{-4} Ωcm.

Several studies have been found on the lifespan of an AgNW. According to Zhang and Engholm (2018), AgNWs exhibit lower thermal and chemical stability, leading to a shortened lifespan. They propose a solution involving epoxy resin protection, which could extend the lifetime of a AgNW to 40 days at 85°C and 85% relative humidity. K. Wang et al. (2021) further notes that AgNWs also suffer from poor electrical stability, with the lifetime of an AgNW film lasting only 18 days under an electrical current of 17 mA/cm². Consequently, the deficient electrical stability of AgNW could significantly reduce the lifespan of electronic devices. Khaligh (2016) adds that continuous current conduction in AgNW could lead to electrode failure in as little as 5 days. While these studies highlight the drawbacks AgNWs, the average lifespan remains unclear, though it is presumed to be lower than other transparent electrodes.

Toxicity

Conflicting information regarding the toxicity of AgNWs has been found. Cheng et al. (2016) asserts that AgNWs are non-toxic. In contrast, Lehmann et al. (2019) argues that AgNW, as a novel fibre type, can be toxic for rats and mouses. Fibrous particles, upon interaction with cells and organisms, may induce cellular dysfunction, cell death, inflammation, and disease. Ratte (1999) notes that toxicity is contingent on the concentration of active free Ag^+ ions, primarily in the aqueous phase. The toxicity of silver remains very low, even at high total concentrations, in soil, sewage, sludge, and sediments. However, Ratte (1999) notes that silver nitrate is one of the most toxic silver compounds and silver nitrate is used to make the AgNWs (Emmott et al., 2012). Thus, there could be a significant risk in the production phase of AgNWs. Neither silver nor silver nanowires appear on the SVHC list of ECHA or the ZZS list of RIVM (ECHA, 2023b; RIVM, 2023b). However, silver is listed on the pZZS list of RIVM (RIVM, 2023a). Due to the conflicting data, it remains unclear whether AgNWs are toxic or not.

Inventory data

There is one LCA study found on AgNWs. Espinosa et al. (2011) did an LCA study on several possible replacements of ITO including AgNWs. The inventory data of the production of AgNWs is given. Unfortunately, no other inventory data is found on the product system of AgNWs. In ecoinvent processes are found on silver, but not on AgNWs.

5.2.6 Conducting polymers

Another material explored as an alternative to ITO is conductive polymers, with a particular focus on poly(3,4-ethylenedioxythiophene):poly-(styrenesulfonate) (PEDOT:PSS) (Chou et al., 2015). This section discusses the material characteristics, possible toxicity, and potential inventory data of PEDOT:PSS.

Material characteristics

Several studies provide the sheet resistance of PEDOT:PSS. Both Dauzon et al. (2020) and Vosgueritchian et al. (2012) offer the sheet resistance of PEDOT:PSS, but the thickness is not provided, preventing the calculation of the electrical resistivity. According to Sun et al. (2015), the resistivity of PEDOT:PSS is 3,35 Ωcm.

On the other hand, Mochizuki et al. (2018) reports that the resistivity of PEDOT:PSS is less than 1 x 10^{-2} Ωcm. For the purposes of this study, it is assumed that the resistivity of PEDOT:PSS is 1,0 x 10^{-2} Ωcm. This value implies that the layer needs to be relatively thick for application in a monitor(A.R. Balkenende, personal communication, January 16, 2024).

Several studies mentioned the optical transmittance of PEDOT:PSS. Chou et al. (2015) report that the transmittance of PEDOT:PSS is 96% for a single layer, 93% for double layers, and 89% for triple layers. It is unclear what the thickness is of a single layer. T. Wang et al. (2021) state that the optical transmittance of conductive polymers is 80%. According to Boussoualem et al. (2010), is the optical transmission of PEDOT:PSS above 92%. For this study, it is assumed that the optical transmittance of PEDOT:PSS is 89%, as the layer of PEDOT:PSS is probably relatively thick.

No specific lifespan is mentioned for PEDOT:PSS in the literature. Huseynova et al. (2020) does indicate that PEDOT:PSS could potentially determine the lifetime of an OLED device. However, the extent of this reduction and the actual lifetime of an OLED device are unclear. Most likely the lifetime of an OLED device is more than 7 years (A.R. Balkenende, personal communication, January 16, 2024). Additionally, Savva et al. (2015) mentions that PEDOT:PSS could have a negative impact on the lifetime of an organic photovoltaic (OPV). Again, in this case, the exact reduction and the average lifetime of an OPV remain unclear.

Toxicity

According to T. Wang et al. (2021), PEDOT:PSS is non-toxic and shows no carcinogenic potential. Gupta et al. (2022) also affirm that PEDOT:PSS is not toxic. However, ECHA mentions that PEDOT:PSS can cause severe skin burns and serious eye damage (ECHA, 2023f). PEDOT:PSS is not listed in the SVHC list of ECHA or the ZZS list or pZZS list of RIVM (ECHA, 2023b; RIVM, 2023a, 2023b). The conflicting data creates uncertainty regarding the toxicity of PEDOT:PSS.

Inventory data

Several LCA studies on PEDOT:PSS are found in literature. As previously mentioned, Espinosa et al. (2011) conducted an LCA study on various possible ITO replacements, including PEDOT:PSS. The inventory data for the slot-die coating of PEDOT:PSS is provided. Mohan (2018) and Hengevoss et al. (2016) both conducted LCA studies on solar panels. Mohan (2018) only mentions inventory data for the spin coating of PEDOT:PSS. Hengevoss et al. (2016) also provide inventory data on the production of PEDOT:PSS. Lastly, Soleimani et al. (2021) conducted an LCA study on thermoelectric materials, with inventory data for PEDOT:PSS limited to production. Thus, only inventory data is found on the production of PEDOT:PSS. ecoinvent does not include processes for the product system of PEDOT:PSS.

5.3 Reduction Strategies

Despite employing various keywords and combinations, no reduction strategies for ITO have been identified. As previously discussed, Minami mentions several compounds that could serve as TCOs containing indium, which could be considered as a reduction strategy because it reduces the amount of indium used. However, it is decided to classify these TCOs as avoidance strategies and, as discussed earlier, they are not further explored. Additionally, this study will not delve into reduction strategies any further due to their absence in the literature.

5.4 Control Strategies

A significant number of studies is found that focuses on the recovery and recycling of indium from electronic waste. Several of these studies specifically address the recovery of ITO from LCD waste, which cannot be reused directly. Many of these studies, however, are highly technical and thus beyond the methodological scope of this study. As a result, the decision is made to focus on pilot studies rather than laboratory-based research. The laboratory-based research that is found will be mentioned briefly.

Wang et al. (2018) mention flotation as a method to separate ITO from the glass in LCD waste, achieving a maximum indium recovery of 93%. Hasegawa et al. (2013) propose a recovery technique for indium using aminopolycarboxylate chelants (APCs) combined with a mechanochemical treatment process. They claim that APCs are effective in recovering indium from ITO-glass, although the quantity is unspecified. Amato et al. (2016) developed an indium recovery process involving acidic leaching followed by zinc cementation, achieving an indium recovery rate exceeding 90%. Building on this, Amato et al. (2019) enhanced the technique by incorporating preliminary grinding, also achieving an indium recovery rate exceeding 90%. Moreover, Choi et al. (2014) conducted a study in which ITO from LCD waste was not crushed but recovered using an electrochemical method and acid treatments, resulting in a 75% ITO recovery. However, this recovered ITO could not be reused directly as its material characteristics were altered. Yoshida et al. (2015) conducted a study on indium recovery using sub-critical water at different temperatures, achieving a 95% recovery of indium at 220°C. Yang et al. (2013) investigated a potential recycling method involving leaching and solvent extraction, demonstrating a recovery rate of over 99% for indium. Furthermore, Souada et al. (2018) explored the extraction of ITO layers from end-of-life (EOL) LCDs by leaching sulfuric acid and applying ultrasonication simultaneously to the ITO side of glass/ITO panels.

Fontana et al. (2021) provide a review of studies focused on processing waste from flat panel displays (FPDs) with the goal of indium recovery. Numerous studies have explored the leaching of indium from waste FPDs, as well as processes for separating indium from the leachate. Additionally, research has been conducted on indium recovery technologies involving thermal treatments and recovery of the ITO film itself. Fontana et al. (2021) highlight that despite the considerable number of studies on FPD waste processing, most of them remain at the laboratory scale. Consequently, a mature recycling or recovery technology is still lacking.

Two studies were found that conducted a study on pilot scale. Kang et al. (2011) reported that over 97% of ITO can be extracted from etching waste through solvent extraction and electrolytic refining. Swain et al. (2015) investigated the recovery of metals from ITO etching wastewater using liquid-liquid extraction. This technique allows indium to be fully recovered with 99.9% purity from the wastewater. However, it is worth noting that both studies focused on etching waste originating from the LCD display fabrication process. Thus, these recovery techniques are not designed for indium recovery from LCD displays or e-waste.

Interestingly, no studies have been found that mention a recovery strategy for indium or ITO that is employed in practice. This implies that currently, indium or ITO is not being recovered from LCD displays or e-waste. Consequently, ITO glass is shredded, separated, and dumped, posing potential harm to human health and the environment. For instance, when the shredded ITO glass is used for pavement, there is a risk of indium leaching into the soil (A.R. Balkenende, personal communication, December 20, 2023). Thus, the mention studies above show that indium could possibly be recovered from the e-waste of LCD monitor. However, these do not represent control strategies that could be applied to control ITO.

5.5 Selection of strategy

In the last sections, all identified strategies for ITO are discussed. As mentioned, reduction strategies are not further considered. Similarly, control strategies are not pursued due to the absence of pilot studies. This leaves the focus on strategies aimed at avoiding the use of ITO. **Error! Reference source not found.** gives an overview of the avoid strategies and ITO with their possible toxicity, material characteristics, and available inventory data.

Table 7. Overview of avoid strategies and ITO with their characteristics.

Strategy	**Toxicity**	**Light transmittance**	**Resistivity**	**Lifespan**	**Inventory data**
ITO	Toxic	90%	$1{,}0 \times 10^{-4}$ Ωcm	Not limiting	Yes, until the end-of-life
ZnO:Al	Unclear	95%	$1{,}0 \times 10^{-3}$ Ωcm	Not limiting	Yes, until the end-of-life
ZnO:Ga	Unclear	95%	$2{,}2 \times 10^{-4}$ Ωcm	Not limiting	No
SnO_2:F	Not toxic	90%	$0{,}5 \times 10^{-3}$ Ωcm	Not limiting	Partly
Graphene	Unclear	90%	$3{,}5 \times 10^{-3}$ Ωcm	Not limiting	No
AgNWs	Unclear	97%.	$1{,}0 \times 10^{-4}$ Ωcm	Lower than other TCOs	Partly, only the production
PEDOT:PSS	Unclear	89%	$1{,}0 \times 10^{-2}$ Ωcm	Lower than ITO	Partly, only the production

As illustrated in **Error! Reference source not found.**, there is considerable ambiguity surrounding these strategies. Consequently, a robust comparison between different alternatives cannot be established. However, according to A.R. Balkenende, the strategies are comparable when considering the material characteristics (personal communication, November 29, 2023). The potential toxicity of these alternatives on the other hand remains unclear, a crucial factor as the aim of SSbD is to avoid chemicals that may be harmful to human health or the environment and to prevent any unintended trade-offs with non-chemical impact categories.

Given that this study is testing and implementing the SCD method, the decision is made to select a strategy based on available data, not on the possible non-toxicity of a strategy. This selection criteria differs from the SCD method. ZnO:Al emerges as the only strategy with comprehensive inventory data extending until the end-of-life. Consequently, it becomes feasible to conduct an LCA study and compare it with ITO. Hence, the decision is made to proceed with the exploration of ZnO:Al as the chosen strategy.

6. Ex-ante LCA ITO and ZnO:Al film

In this chapter, a comparative ex-ante LCA study is conducted on ITO and ZnO:Al film in an LCD monitor, which is step 4c of the SCD method. This study follows the prescribed LCA phases defined in ISO 14044. First, the goal and scope are defined, after which the inventory analysis is presented. Hereafter, the impact assessment is discussed, ending with the interpretation and conclusion. The ex-ante LCA study will answer the last two sub-research questions of this study: *What are the life cycle environmental impacts of an LCD monitor including the selected SoC and the strategy for the selected SoC?* and *Does the chosen strategy offer a replacement or controls the selected SoC in an LCD monitor without unwanted trade-offs in other impact categories?*

6.1 Goal and scope definition

In this section the goal and scope are described in more detail for the comparative ex-ante LCA study that will be conducted in this research. Furthermore, the function, functional unit and reference flows of this study are discussed.

6.1.1 Goal definition

The goal of this study consists of several parts. Firstly, the study aims to compare the current technology, ITO, to emerging technology, ZnO:Al, to investigate whether the strategy will reduce environmental impacts. The study will be an ex-ante LCA because ZnO:Al is an emerging technology that is not yet applied on industrial level (A.R. Balkenende, personal communication, November 29, 2023). Secondly, it aims to explore to what extend trade-offs might occur with ZnO:Al as replacement of ITO. Lastly, it is checked whether the toxicity of the substances is reflected in the results of the analysis. The intended target audience of this study is the researchers and other parties involved in the NWA project. Furthermore, the scientific community interested in dealing with SoCs in consumer products.

6.1.2 Scope definition

This is a cradle-to-grave ex-ante LCA study, encompassing all processes from the extraction of materials to the end-of-life of the compared technologies. The LCA will adhere to the ISO 14044 standards, and the handbook of LCA by Guinée (2002) will be utilized. OpenLCA will be the tool used to calculate the impacts of ITO and ZnO:Al.

The geographical coverage focuses on the sale and use of LCD monitors as sold and used in Europe. Europe was chosen due to the RoHS Directive and the NWA project. The production of the LCD monitor is outside of Europe. Sun et al. (2016) mention that, typically, production for the entire world is adjusted due to the RoHS Directive, as it is more expensive to maintain two separate production lines.

The background processes of this study will be sourced from the ecoinvent v3.9.1 database. The foreground processes will be partly based on Kawajiri et al. (2022) and partly copied from the ecoinvent v3.9.1 database. Preference is given to more recent data when available, as the intention is to model monitors based on their present usage. The aim is to utilize the most fitting data for this purpose. The data for this study is collected between September 2023 and December 2023.

For the life cycle impact assessment, the chosen impact family is Product Environmental Footprint (PEF) version 3.1 (Damiani et al.). PEF is proposed by the European Commission and is a consensus of best practice based on existing and published methods (Damiani et al.).

6.1.3 Function, functional unit, and reference flows

The function, functional unit, alternatives and reference flows of this study are:

Function: Visually display information and graphics from a connected computer.
Functional unit: a 17” LCD monitor used over a period corresponding with its lifetime of 10 years.
Alternative 1: ITO film of 250 nm
Alternative 2: ZnO:Al film of 288 nm
Reference flow 1: a 17” LCD monitor with an ITO film of 250 nm used over a period corresponding with its lifetime of 10 years.
Reference flow 2: a 17” LCD monitor with a ZnO:Al film of 288 nm used over a period corresponding with its lifetime of 10 years.

6.2 Inventory analysis

In this section, the system of ITO and ZnO:Al film is defined. The system boundaries, flowchart and data collection are discussed. The OpenLCA file is available as Appendix E.

6.2.1 System boundaries

As discussed in section 6.1.2, this ex-ante LCA study is a cradle-to-grave analysis. The primary focus revolves around the environmental impact and possible toxicity of the films ITO and ZnO:Al. Consequently, the infrastructure and machinery involved in production are intentionally excluded from the study's scope.

Economy-environment system boundary

LCA is a system analysis in which two systems are distinguished: the economic system and environmental system. LCAs distinguish flows in environmental or economic flows. Environmental (elementary) flows are categorized as such when they enter or exit the economic system without human intervention. Emissions directly released into the air and water are thus classified as elementary flows. Determining whether certain flows, like agricultural soil or water, belong to the economic system or the environment system can be challenging for some cases. This is also the case in this study. In the deposition of ITO and ZnO:Al, oxygen is needed. While oxygen is normally an environmental flow, in this product system, it is considered and modelled as an economic flow.

Cut-off

While the aim of LCA is to incorporate every element of a product system into its model, there is a practical limit to achieving this. Consequently, there will always be certain inputs or processes that cannot be included in the LCA and are treated as cut-offs. The first cut-off occurs in the production of tin oxide, specifically regarding the flow of ammonium hydroxide. This flow is excluded due to its unavailability in the ecoinvent database. Efforts were made to identify similar substances or explore the possibility of modelling the production of this substance, but neither option is available in ecoinvent.

Furthermore, the mouse, keyboard, and desktop of the LCD computer are cut-offs in both product systems. These flows are excluded from the study as they fall outside the study's scope and are exactly the same for both alternatives. The study exclusively focuses on the LCD monitor, without considering the entire computer.

6.2.2 Flow Charts

The flow charts shown in Figure 7 and Figure 8 show the product systems of ITO and ZnO:Al that are modelled in OpenLCA (Appendix E). The flow charts are based on Kawajiri et al. (2022) and the database ecoinvent v3.9.1.

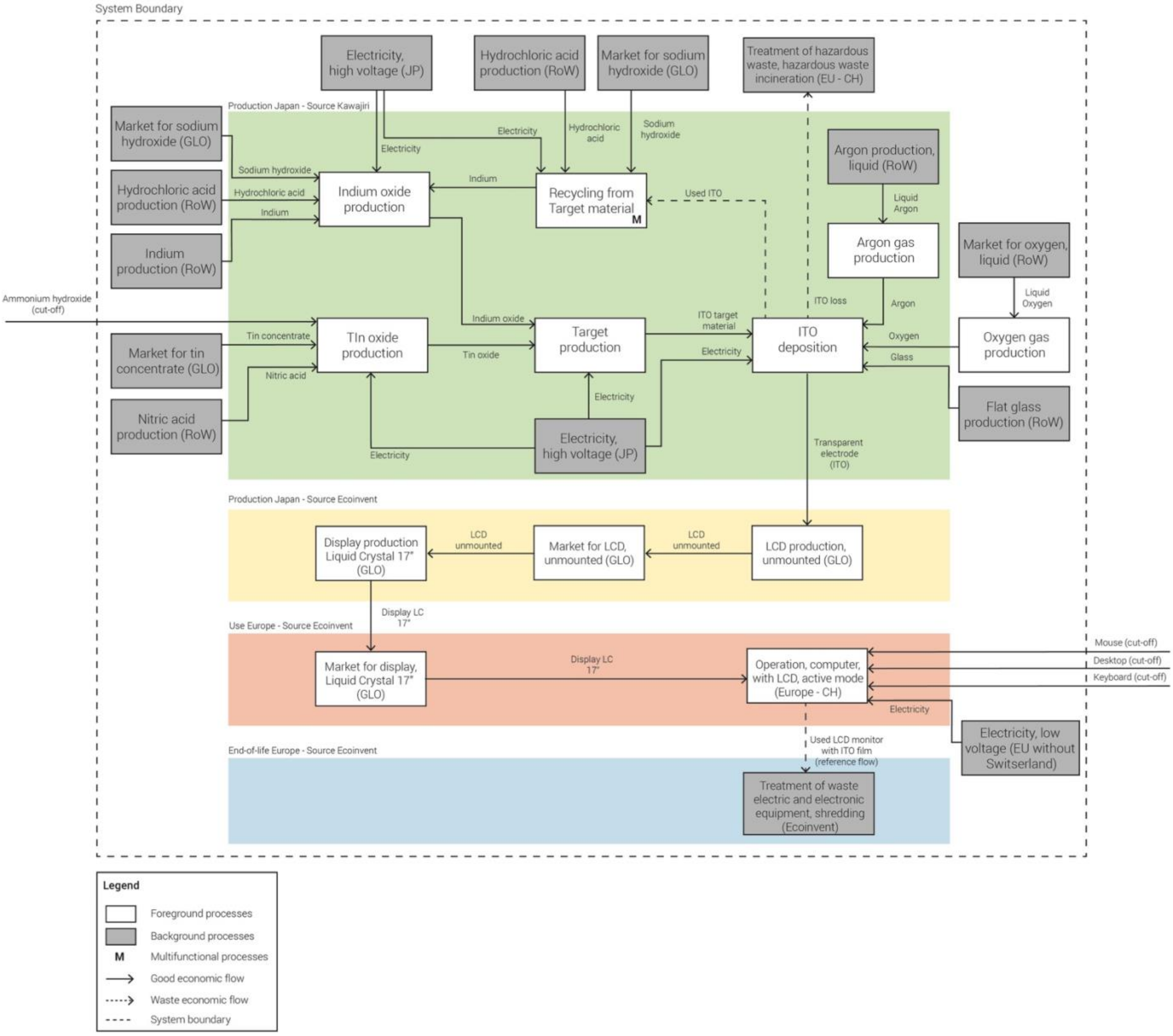


Figure 7. Flow chart of ITO system

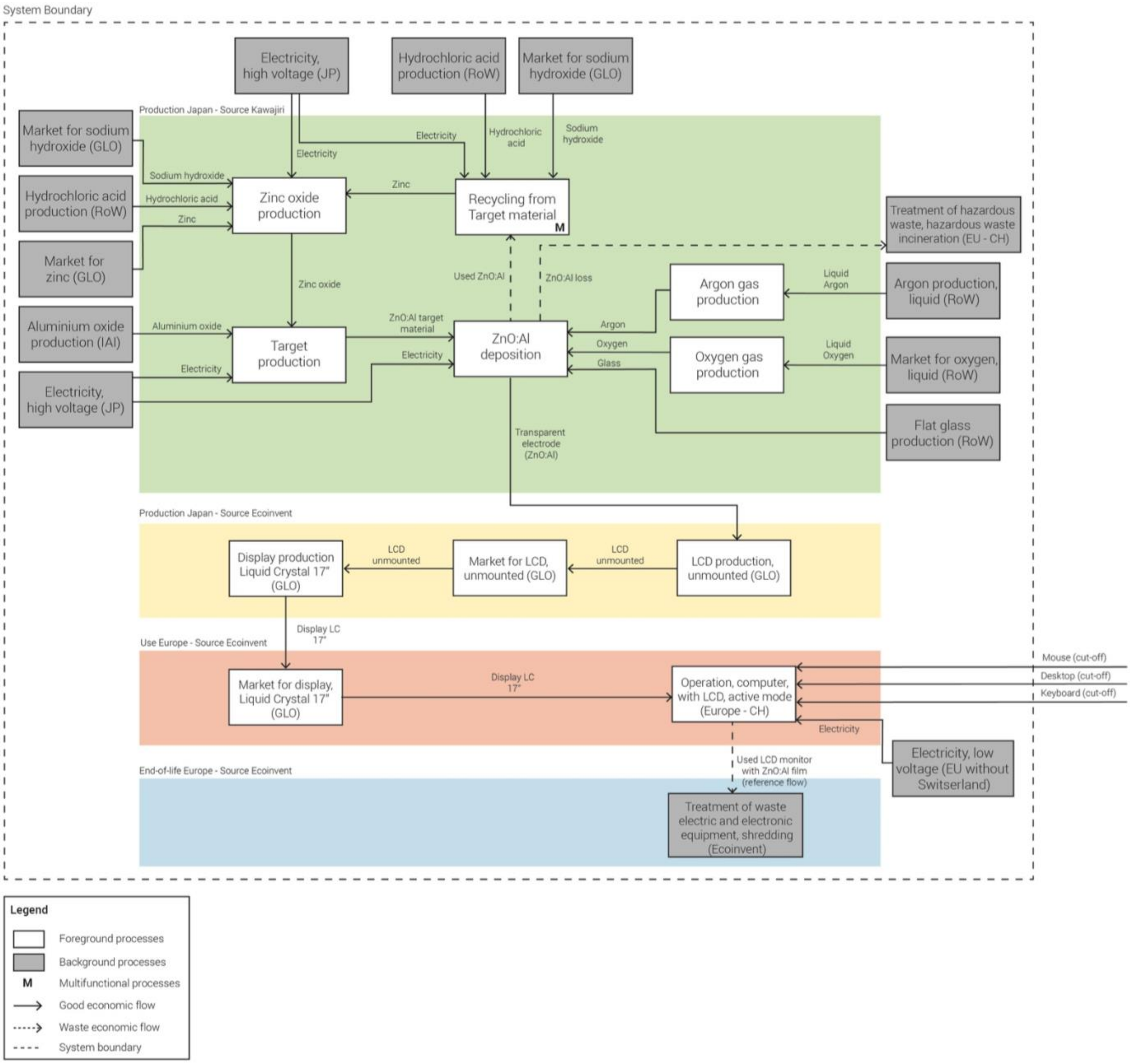


Figure 8. Flow chart of ZnO:Al system

6.2.3 Data collection

For this study, data from Kawajiri et al. (2022) and the database ecoinvent v3.9.1 (cut-off) is utilised to model the product systems of ITO and ZnO:Al film. The inventory data from Kawajiri et al. (2022) is shown in Appendix A. Main calculations and assumptions are presented and explained in this chapter. More detailed explanations of assumptions and calculations can be found in Appendix B. All unit process data with calculations can be found in Appendix D.

Calculations

The inventory data from Kawajiri et al. (2022) relates to an LCD TV of 32". However, the ecoinvent processes involve the production of an LCD monitor of 17". To ensure a more comprehensive comparison, the decision is made to convert the inventory data from Kawajiri et al. (2022) to the ecoinvent processes for both systems. The assumption made is that a conversion is feasible due to the data sourced from Kawajiri et al. (2022) focusing solely on the ITO film. Whereby, it is assumed that the amount of ITO film scales proportionally with the area of the screen. Hence, should the most accurate conversion be calculated by considering the surface area of both screen sizes. Which results in the following conversion factor (f):

$$f = \frac{17" \ = 40\,cm\ *\ 29\,cm}{32" \ =\ 81\,cm\ *\ 43\,cm} = 0{,}33$$

Furthermore, for both films the target is sputtered on glass substrate in an LCD monitor (Mereu et al., 2014). However, this substrate is not mentioned in the inventory data of Kawajiri et al. (2022). Thus, the amount of glass substrate is calculated and added by the researcher. This full calculation is shown in Appendix B.

Assumptions both systems

Several assumptions are made for the modelling of both product systems, of which the main assumptions are discussed in this section. The rest of the assumptions are listed in Appendix B.

The inventory data of Kawajiri et al. (2022) is only on the TCO films. It is assumed that TCO films are the same in a TV as in a monitor.

Given the more recent nature of the inventory data in Kawajiri et al. (2022), it is decided to employ their data for the production of the LCD panel in both product systems. However, for the production of the LCD monitor onwards, ecoinvent processes will be adopted until the end-of-life stage. Notably, an ecoinvent process is copied for the use-phase, where the electricity inventory data of Kawajiri et al. (2022) is applied.

It is worth noting that Kawajiri et al. (2022) do not specify the geographical scope of their LCA study. Since the paper is published in Japan, it is assumed that their inventory data pertains to Japan. Consequently, the production of ITO and ZnO:Al is attributed to Japan, while the copied ecoinvent processes for the remaining LCD monitor production stages keep their locations (Global or Europe without Switzerland). There are no ecoinvent processes for the remaining of the LCD monitor production with the location of Japan.

Ecoinvent lacks modelled processes for the end-of-life of an LCD monitor. Furthermore, there is no inventory data found in literature on the end-of-life of an LCD monitor. The widespread method of waste treatment for electronic devices is shredding (Her & Chang, 2017), a process readily available in ecoinvent. Therefore, this process will be employed to model the end-of-life phase of both product systems.

No additional transport is modelled for either system because it will be the same for both systems. Moreover, transport is already included in the duplicated ecoinvent processes from the production of the LCD monitor. Finally, it is assumed that transport will not significantly contribute to the environmental impact of the films.

Several assumptions are done on the inventory data of Kawajiri et al. (2022). Regrettably, despite numerous attempts, no contact could be established with the authors of the paper. The inventory data for both product systems does not clearly indicate whether recycled target material serves as an additional input in raw material production. However, according to the flow chart created by Kawajiri et al. (2022), as shown in Figure 9, the recycled product should be an input in raw material production. Therefore, it is presumed that recycled indium constitutes an additional input in the production of indium oxide.

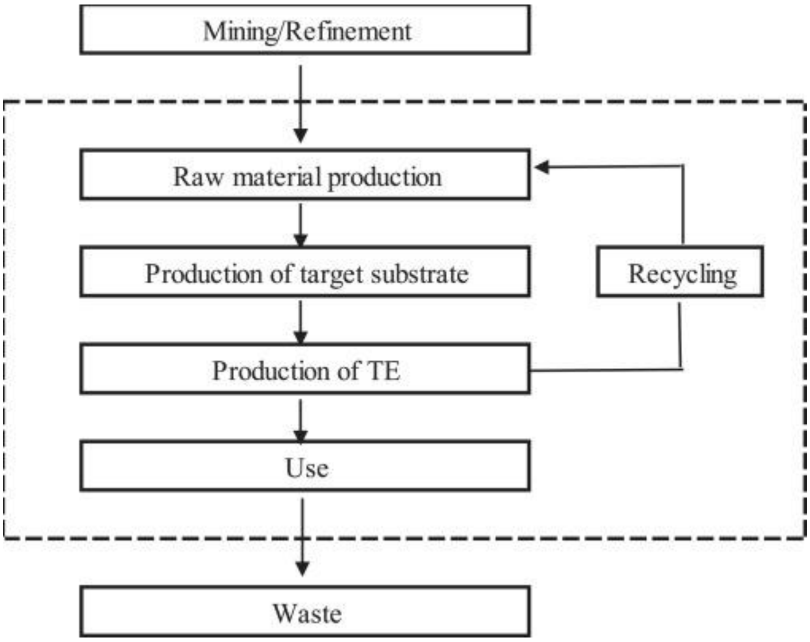


Figure 9. Flow chart of study Kawajiri et al. 2022 (TE = Transparent Electrode)

In both systems, there is a loss during the deposition process. Kawajiri et al. (2022) do not provide information or data regarding the treatment of this ITO and ZnO:Al loss. For the purposes of this analysis, it is assumed for both systems that the losses will be treated as hazardous waste.

6.2.4. Multifunctionality and allocation

As illustrated in Figure 7 and Figure 8, both systems demonstrate a multifunctional process. This arises from the input of waste in the process and the production of a good as output. However, since this multifunctional process occurs entirely within the system's boundaries, the choice of allocation becomes insignificant. Therefore, this study will not delve further into the allocation methods for these processes.

6.3 Impact assessment

In this section, the impact assessment of the alternatives is discussed. The OpenLCA file is available as Appendix E. This ex-ante LCA study is mainly focussed on the characterization results. In this study, the main focus is on the characterization results.

6.3.1 Impact categories, characterization models and factors, category indicators

As previously discussed, this study will utilise the PEF family version 3.1 (Damiani et al., 2022). PEF encompasses several distinct impact categories, each representing environmental concerns to which inventory results are assigned (e.g., Climate change). The impact categories included in PEF are: climate change (total), ozone depletion, human toxicity (cancer and non-cancer), particulate matter, ionizing radiation, photochemical oxidant formation, acidification, eutrophication (terrestrial, freshwater and marine), ecotoxicity freshwater, land use, water use, resource use (minerals and metals, fossils) (Damiani et al., 2022). In version 3.1, the toxic impact categories are further divided into inorganics and organics, offering enhanced insights into the product's toxicity.

6.3.2 Characterization results and discussion

In Figure 10, the characterization results are shown of this study. As can be seen, ITO scores about 4% higher on every impact category. This is most likely a result from the inventory data from Kawajiri et al. (2022), which assigns 4% less electricity use to ITO than ZnO:Al.

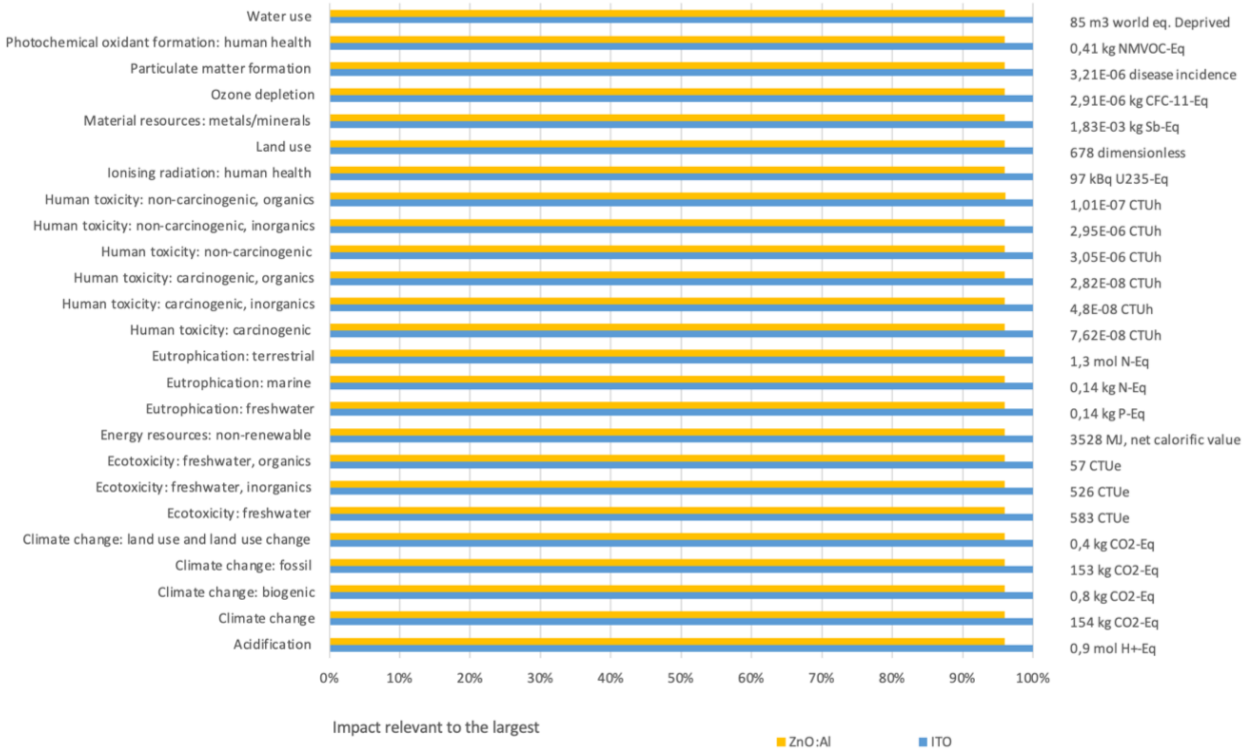


Figure 10. Characterization results for ITO and ZnO:Al film

6.4 Interpretation

First, the model undergoes an initial review to guarantee its consistency and completeness, ensuring that the results can be accurately interpreted. Once consistency and completeness are confirmed, the results undergo contribution analysis. Additionally, the robustness of modelling choices and assumptions is tested through sensitivity analysis. Conclusions are subsequently formulated based on these results.

6.4.1 Consistency check

In this section, the consistency of the model with the goal and scope of the study is assessed. The checklist below is used to verify the alignment of the assumptions, model and data with the goal and scope of the study, ensuring that choices and data maintain consistency across the two alternatives.

- Difference in data sources: Both alternatives use the same data sources.
- Differences in data accuracy: Both alternatives share the same data sources, so no inconsistencies in data accuracy are anticipated. However, ZnO:Al is not yet utilized on an industrial level in LCDs, unlike ITO (A.R. Balkenende, personal communication, November 29, 2023). Consequently, the data accuracy of ZnO:Al is likely to be lower, besides Kawajiri et al. (2022) does not provide information regarding the data accuracy of either alternative.
- Temporal differences and differences in data age: since all data sources are the same for both alternatives, there are no differences in data age or temporal issues.
- Differences in geographical representativeness: Both films are produced in Japan and the rest of the production of the LCD monitor is global. Furthermore, is the use and end-of-life phase both in Europe. All locations are consistent in both alternatives.
- Differences in the function performed: Both alternatives serve the same function, acting as a TCO (with a specific electrical resistivity and transmission) in a 17” LCD monitor.

6.4.2 Completeness check

As mentioned earlier, this ex-ante LCA study is partially conducted to examine the toxicity of both alternatives. It should be noted that the ecoinvent database and Kawajiri et al. (2022) lacks emission flows for toxic substances that could occur in the lifecycle of ITO. Consequently, the toxicity of ITO is not shown in the characterization results.

Similarly, for the alternative ZnO:Al, the toxicity is also not presented in the characterization results. Although there is an emission flow for zinc oxide, the impact family PEF lacks a characterization factor for this emission. Therefore, the potential toxicity of zinc oxide is not reflected in the characterization results.

6.4.3 Contribution analysis

In this section, the contribution analysis of both alternatives is discussed, and the results are presented in Appendix G. The contribution analysis focuses on the economic flow level, where economic flows for both alternatives are grouped to gain a better understanding of the hotspots for each impact category.

Figure 11 displays the results of the contribution analysis for ITO film. It reveals that the most significant contributor for all impact categories for ITO is the electricity used in the use phase. The impacts of all other economic flows are grouped under 'other.' The contribution analysis demonstrated that this accounts for not more than 0,8%, making it a minor contribution.

Figure 12 shows the results of the contribution analysis for ZnO:Al film. In this alternative as well, the electricity used in the use phase emerges as the primary contributor. Additionally, the contribution from other economic flows does not exceed 0,8%.

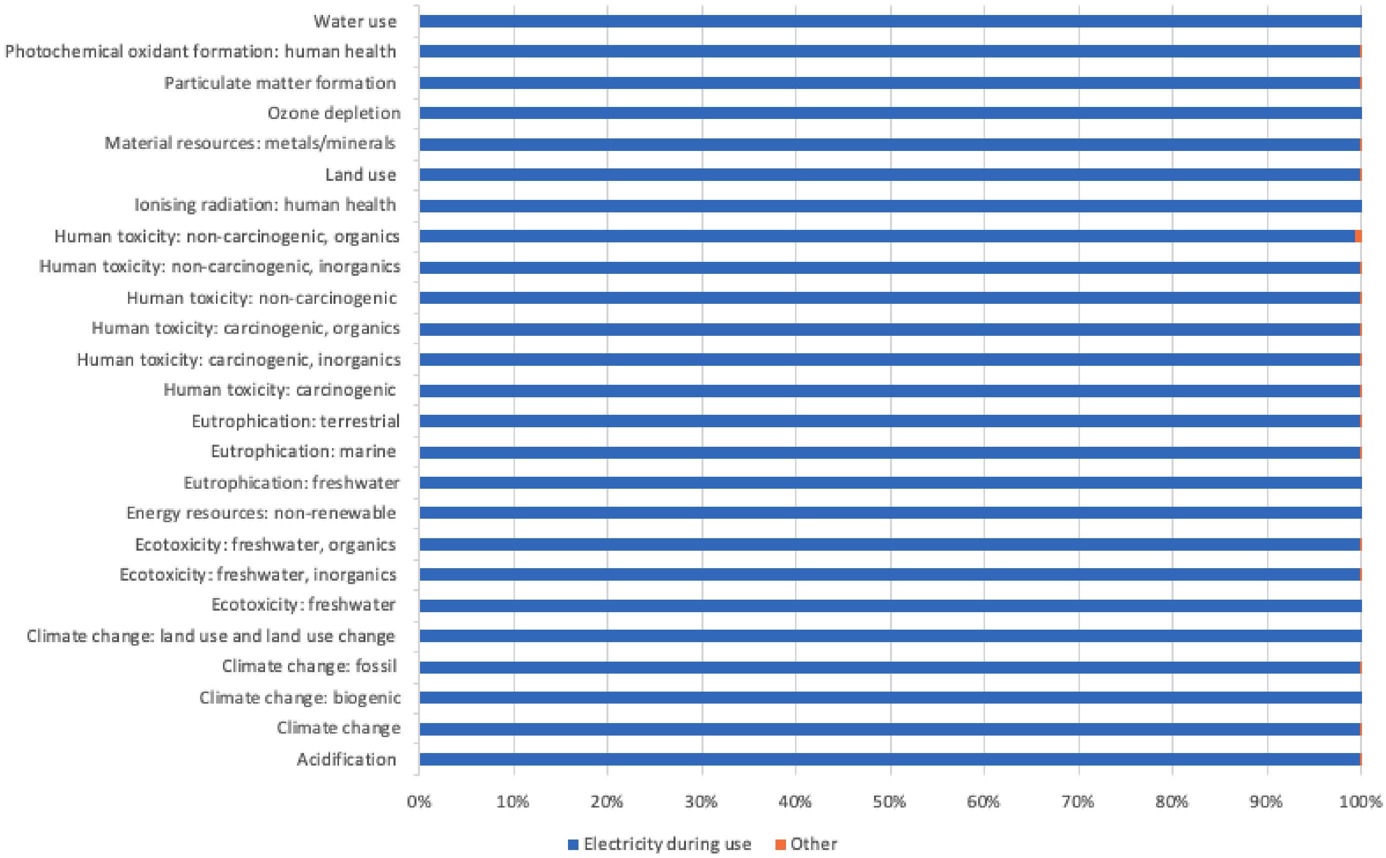


Figure 11. Contribution analysis of ITO film

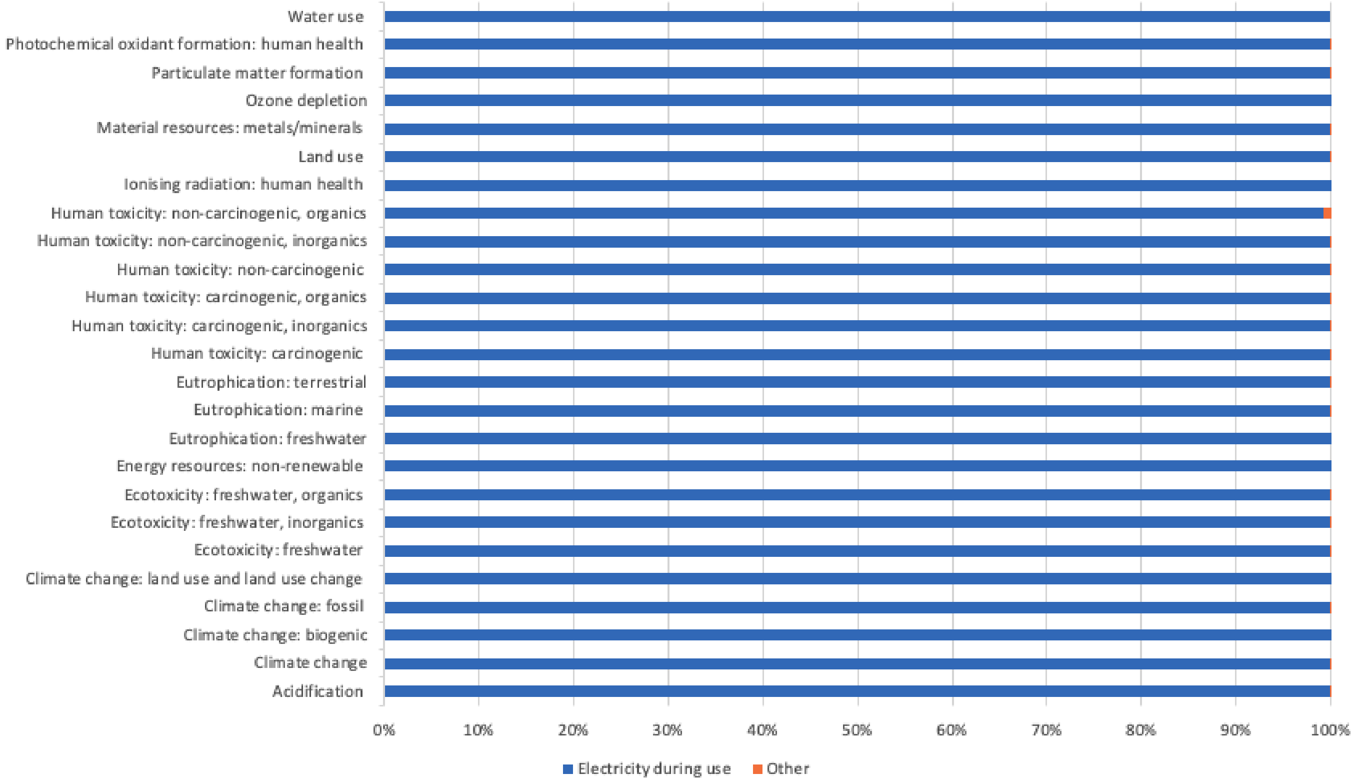


Figure 12. Contribution analysis of ZnO:Al film

6.4.4 Sensitivity analysis

In this study, various sensitivity analyses have been conducted. Given certain assumptions and unexpected outcomes, like the dominance of the electricity in the use phase, in this research, specific aspects are subjected to sensitivity analyses to validate the findings. Each sensitivity analysis is discussed, and the results are shown in Appendix F.

Cradle to gate

As indicated in the results of the contribution analysis, the calculated impacts of both alternatives are dominated by the energy use of the LCD monitor. These results do not offer insights into the impact of both films and their toxicity. Therefore, a sensitivity analysis is conducted by performing an LCA study up to the gate without considering the electricity used during operation.

Figure 13 illustrates the characterization results of both films when the LCA study is recalculated from cradle to gate focusing on the ITO alternatives only. ZnO:Al demonstrates the highest impact in almost every impact category, while ITO film has the highest impact in the material resources, ecotoxicity of freshwater, and ecotoxicity of freshwater inorganics categories. Due to the absence of emission flows and characterization factors of SoCs for both films, the results do not offer any insights into the differences in potential toxicity of either film.

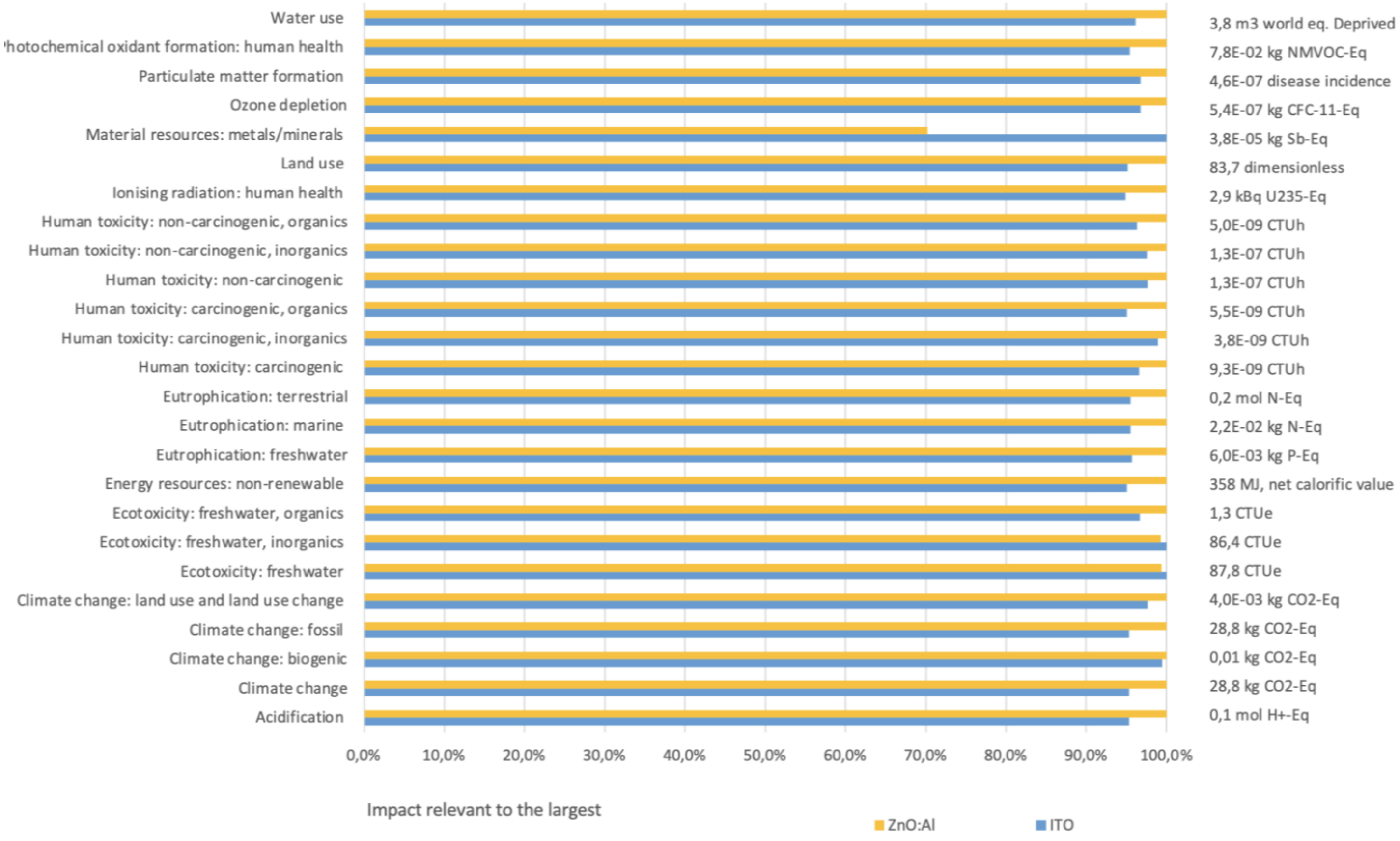


Figure 13. Characterization results of ITO and ZnO:Al film cradle-to-gate

Different thickness ZnO:Al
Kawajiri et al. (2022) mentions that their inventory data is for ZnO:Al with a thickness of 288 nm and ITO has a thickness of 250 nm. However, according to A.R. Balkenende, ZnO:Al has a typical thickness of 700-1000 nm, with ITO film averaging 150 nm (personal communication, November 29, 2023). A sensitivity analysis on the thickness of the ZnO:Al film was conducted, where the inventory data of Kawajiri et al. (2022) was multiplied by a factor 3, resulting in a thickness of about 700-1000 nm. The thickness of ITO remained unchanged.

Figure 14 displays the characterization results of both ITO and ZnO:Al films (cradle to gate) with an increased thickness for ZnO:Al. The findings indicate that ZnO:Al has a higher impact in all the impact categories, if the thickness of ITO is considered excessive in the inventory data from Kawajiri et al. (2022).

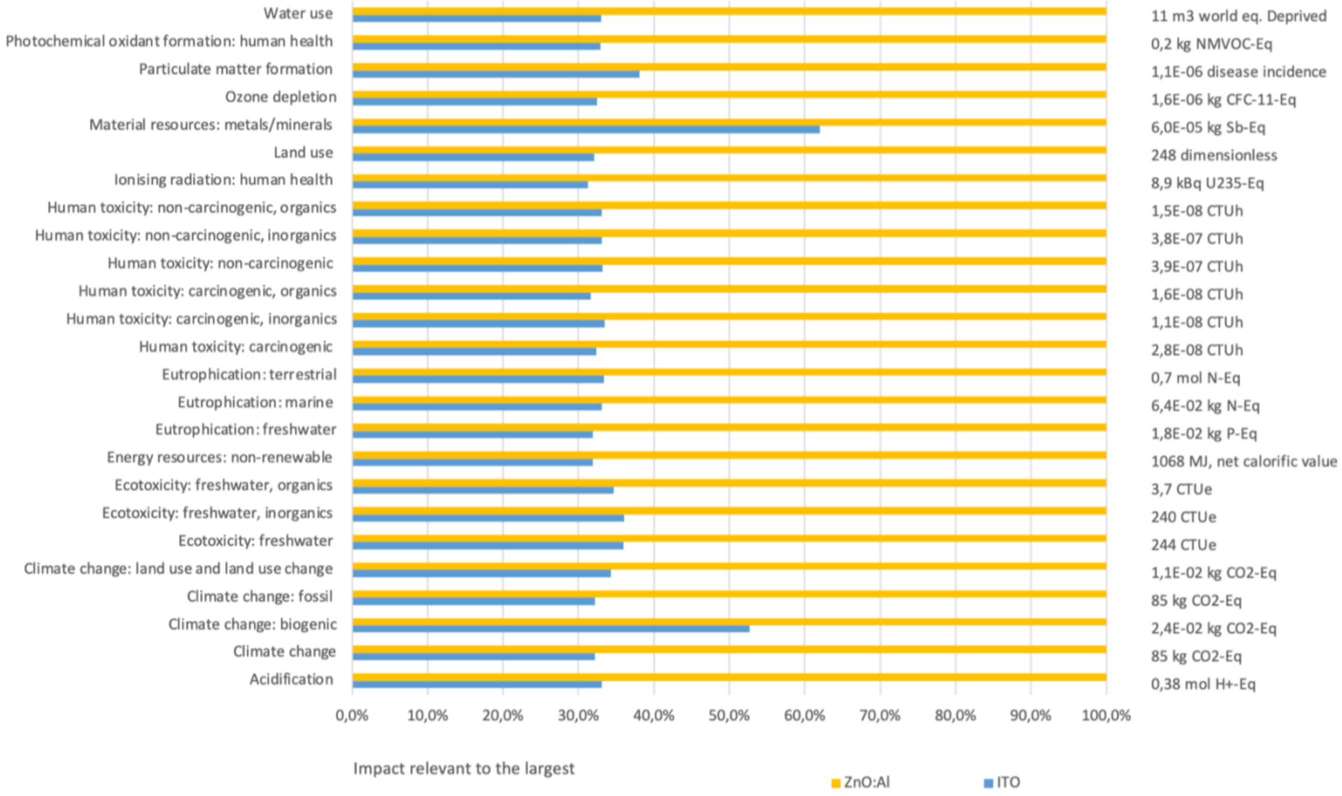


Figure 14. Characterization results of ITO and ZnO:Al film with another thickness for ZnO:Al

Characterization factor zinc oxide
As discussed in section 6.3.2, there is no characterization factor for the emission of zinc oxide in the impact family PEF. A search was conducted to find a similar impact family that does have a characterization factor for zinc oxide emissions. Unfortunately, no such family was found. Consequently, it is not possible to conduct a sensitivity analysis on this aspect to gain a better understanding of the toxicity of ZnO:Al.

ITO system ecoinvent
Moreover, a sensitivity analysis was performed on the data from Kawajiri et al. (2022) by comparing it to the ITO system of ecoinvent from cradle to gate. The

characterization results are shown in Figure 15. The results show that the inventory data of Kawajiri et al. (2022) is higher in most impact categories, while the system of ecoinvent also includes the infrastructure (i.e. building of the production site).

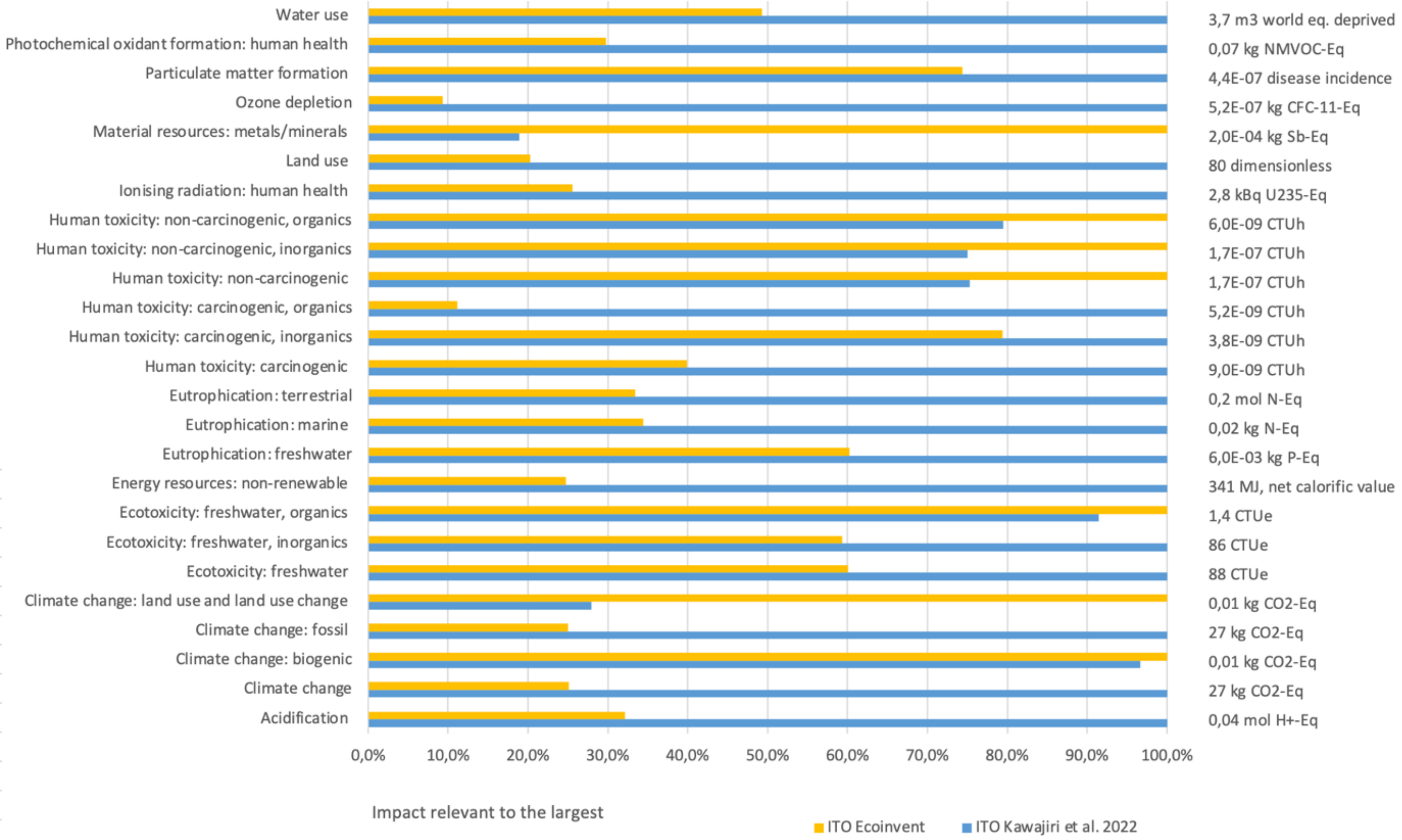


Figure 15. Characterization results ITO (Kawajiri et al. 2022) vs ITO Ecoinvent

Electricity

The contribution analysis results in
Figure 11 and Figure 12 indicate that the environmental impact of both systems is notably influenced by the amount of electricity used during the use phase. According to A.R. Balkenende, the average thickness of ZnO:Al is likely to be significantly greater than that of ITO, leading to reduced light transmittance (personal communication, November 29, 2023). This reduced light transmittance would result in higher electricity consumption during the LCD's use phase. The characterization results for ZnO:Al are approximately 4% lower than ITO (Figure 10), attributed to the inventory data from Kawajiri et al. (2022), which assigns 4% less electricity use to ITO than ZnO:Al. However, A.R. Balkenende argues that the reverse should be true, indicating higher electricity use for ZnO:Al compared to ITO. According to A.R. Balkenende, when the thickness of ZnO:Al is approximately 700 nm, it reduces light transmittance by about 2% compared to ITO, leading to a 2% increase in electricity consumption during the use phase (personal communication, November 29, 2023). The contribution analysis suggests that electricity used in the use phase is the primary contributor to the characterization results of both films. Therefore, if the electricity consumption of ZnO:Al were 2% higher, its characterization results would be approximately 2% higher than ITO for every impact category.

Moreover, characterization results of adjusting the energy source to solar energy generated from PV panels is shown in Appendix E. Even with this change, electricity remained the predominant contributor (>99%) to the environmental impacts.

6.5 Conclusion

As mentioned in the beginning of this chapter, the conducted ex-ante LCA study answered two sub-research questions. In this section, the conclusion is discussed for both these sub-research question.

First the sub-research question '*What are the life cycle environmental impacts of an LCD monitor including the selected SoC and the strategy for the selected SoC?'* is discussed. As can be seen in the results of this ex-ante LCA study, electricity consumption during the use phase of the LCD monitor is the most significant contributor to the environmental impacts of both films. Consequently, reducing this electricity used in the use phase has the potential to decrease the overall environmental impact of the LCD monitor. According to A.R. Balkenende, it is more likely that the electricity used in the use phase of an LCD monitor with a ZnO:Al film is higher than that of an ITO film (personal communication, November 29, 2023), which means that the environmental impact of ZnO:Al is higher than that of an ITO film.

Furthermore, when the ex-ante LCA study is only conducted for the cradle-to-gate, the ZnO:Al film has higher environmental impacts than ITO for almost every impact category, especially when the thickness of ZnO:Al is recalculated to a more realistic thickness. It can be assumed that the environmental impact of ZnO:Al is higher than that of ITO, though only marginally and surrounded by assumptions and uncertainties.

Lastly the sub-research question *'Could the chosen strategy be applied to replace or control SoC in an LCD monitor without unwanted trade-offs in other impact categories?'* is answered. As mentioned earlier, the environmental impact of ZnO:Al is higher (cradle-to-gate), however, because of the many assumptions and uncertainties it cannot yet persuasively be concluded if ZnO:Al generates unwanted trade-offs. Given the absence of data on emission flows and characterization factors for key chemicals, such as indium, potential toxic trade-offs were not identified. However, it is most likely that the electrical use of ZnO:Al will be higher, which would imply several unwanted trade-offs. Consequently, based on the findings of this ex-ante LCA study, is it assumed that ZnO:Al cannot be utilised without incurring unwanted trade-offs in other impact categories.

7. Discussion

In this chapter, the results of the entire study are discussed and reviewed. The main research question of this study is repeated: *Which insights can be obtained by applying the SCD method through a case of an LCD monitor on the European market, exploring a range of a possible strategies to replace, reduce or control a SoC that aim to reduce the risks to the environment and human health as well as its life cycle environmental impacts?*

The sub-research questions of this study are systemically addressed at each step of the study. Figure 16 provides an overview of the steps conducted and their corresponding chapters in this study. First, the possible SoCs within an LCD monitor were identified, and a specific SoC, ITO, was chosen based on available data. Subsequently, possible strategies for ITO were identified or developed, leading to the selection of one strategy: ZnO:Al film. Finally, an ex-ante LCA study was conducted on ITO film and ZnO:Al film.

The initial part of this chapter involves reflecting on the current study, including the SCD method developed by Bolaños Arriola et al. (2023) and the implementation of an ex-ante LCA study. The discussion includes overall insights and challenges encountered in the study, along with specific challenges associated with the SCD method. Proposed alterations to enhance the SCD method are presented. Additionally, this chapter explores insights and challenges from both LCA expert and designer perspectives. Lastly, the overarching challenges in S(S)bD studies are discussed.

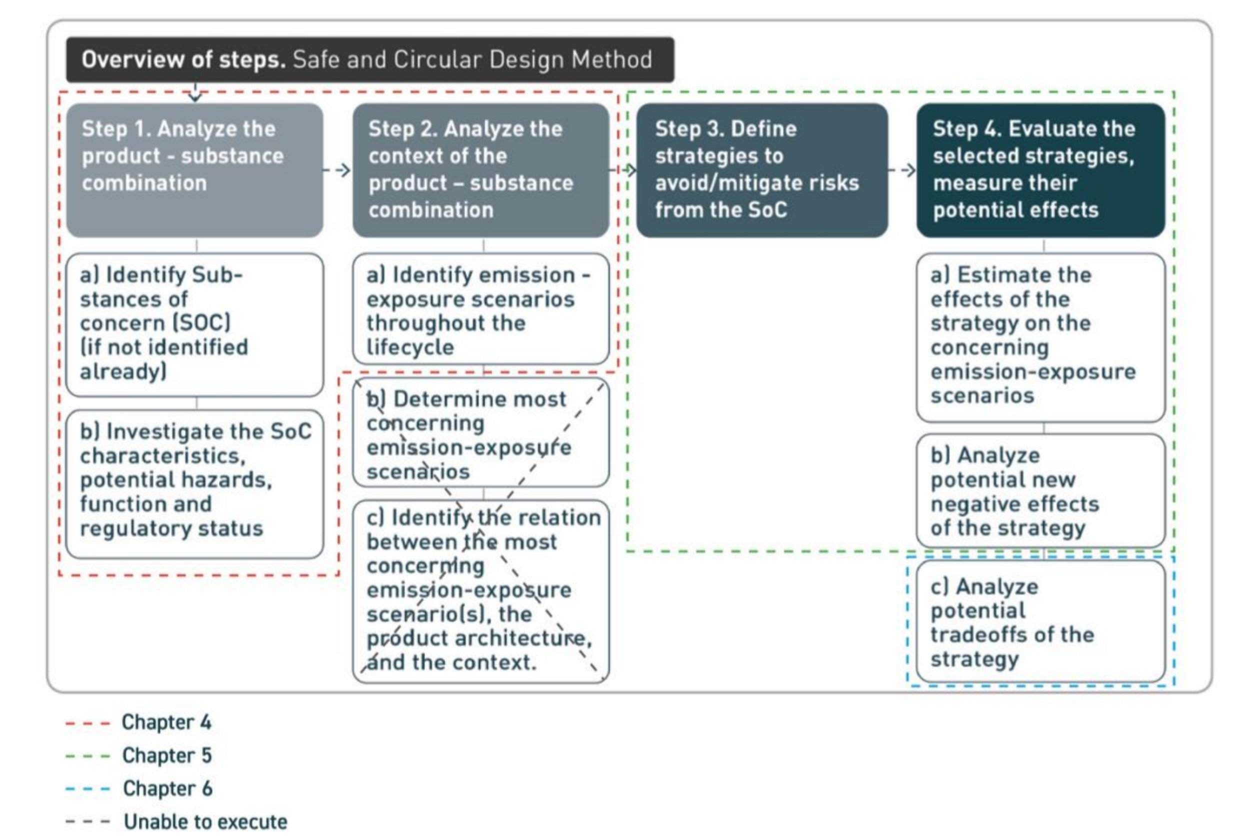


Figure 16. Overview of the steps and their corresponding chapters in this study

7.1 Lessons learned from applying the SCD method to the case of an LCD monitor

The aim of this study is to provide insights from an attempt to replace, reduce or control a SoC in an LCD monitor to fit the principles of an CE by applying and testing the SCD method. Thus, in this chapter these insights are discussed within the context of its corresponding steps. Some of these insights are on this study and some on the SCD method itself.

7.1.1 Step 1: Analyse the product – substance combination

The first step consists of the identification of the SoC and comprehensively describing the SoC. This step was carried out in Chapter 4 of this study through a literature review. Several insights and challenges were encountered during the execution of this step, which are discussed below.

Guidance for gathering information on SoC

The method functions as a valuable guiding tool to gather all the essential information regarding the SoC. It not only outlines the necessary steps to collect relevant data but also offers guidance on where to locate this information.

Definitions

Early in the literature review, it became apparent that various terms were used interchangeably for SoCs in an LCD monitor. Some of these terms include SoC, SVHC, hazardous substance, toxic compounds, and chemical hazards. Unfortunately, these terms were not consistently defined in the literature, leading to ambiguity regarding their intended meanings. This highlighted the significance of establishing a definition of SoC, which was carried out at the beginning of this study. This inconsistency in terms also occurs in the S(S)bD approach. For instance, as discussed in Chapter 2.2, different definitions are adapted for SVHC by ECHA and RIVM. The same issue occurs for the terms product, chemical, and life cycle in S(S)bD as discussed by Guinée et al. (2022). Thus, this is a point of attention for the SCD method, and these terms should be clearly defined at the beginning of a project that applies the SCD method in order to avoid ambiguities. Additionally, a precise definition for SoC needs to be established, possibly by the EU.

Lack of data and information on SoCs in LCD monitor

Another challenge in this step involved collecting data and information on the SoCs present in an LCD monitor. Unfortunately, no data or information was found on SoCs that could be generated during the life cycle of the LCD monitor. Furthermore, no study providing a comprehensive overview of all SoCs present in an LCD monitor was found. Instead, only a few articles were discovered on the SoCs in an LCD monitor, and these articles exhibited differences in identifying which SoCs are present in an LCD monitor. Table 3 and Table 4 illustrate that certain substances are mentioned in multiple studies, while others are mentioned only once or twice. This difference could be a result of differences between the assessed monitor models. However, the studies were unclear about which LCD monitor models were assessed, making it uncertain whether the mentioned SoCs are universally present or exclusive to the assessed models.

Furthermore, information was lacking on the location of the SoCs in the LCD monitor. Only for indium and tin in the substance ITO a clear location was provided. Without a specific location of a SoC, it would not be possible to conduct the rest of the study. Consequently, developing strategies for the SoC would be impossible, and conducting the LCA study would also be challenging. Thus, it is of importance that the location of the (chosen) SoC is known. Interestingly, the importance of the location of the SoC in the product is not mentioned in the SCD method. This is likely due to the method being tailored for designers who are (re-)designing a product they are already familiar with. Therefore, this study diverges from the typical starting point for the SCD method.

Hence, a significant amount of information and data were absent concerning the SoCs in or generated by an LCD monitor during its lifecycle. This led to the selection of a SoC based on data availability. It's worth noting that this selection criteria differs from those used in the SCD method, which prioritizes SoCs based on their highest potential toxicity. Without more comprehensive information on SoCs in an LCD monitor, choosing a SoC based on, its potential toxicity remains unfeasible. This challenge is likely a result of this study not being conducted within a design team or with a product client, where more information on the SoCs in the product would probably be available.

Material characteristics ITO

In this step, the material characteristics of ITO were also discussed. Studies on the material characteristics of ITO proved to be challenging to understand without specific expertise in the field of physics. Moreover, literature did not provide clear information on the lifespan of ITO. Without the expertise from A.R. Balkenende, understanding the material characteristics of ITO and obtaining precise values would have been nearly unfeasible. This challenge also arises from the fact that this study was not conducted within a design team or with a product client, who would possess this information.

Overlap of steps

Moreover, in accordance with the SCD method, Step 1 involves discussing the potential hazards of ITO. Specifically, the exposure of humans and/or organisms to the substance and if the substance is currently regulated. However, there is a slight ambiguity in the SCD method, as Step 2 also calls for a description of toxicity, specifically focusing on emission and exposure scenarios throughout ITO's lifecycle. However, in practice during this study, steps 1 and 2 of the SCD method were combined into a single step. The challenges encountered in collecting data of the emission and exposure scenarios and the potential hazards of ITO are discussed in the following section.

7.1.2 Step 2: Analyse the context of the product-substance combination

In step 2 of the SCD method, the context of the product-substance combination is examined. This involves identifying emission-exposure scenarios throughout the lifecycle of the product and SoC and determining the most concerning scenarios. Additionally, this identification highlights the potential hazards associated with ITO. This step was undertaken in Chapter 4, and the challenges and insights encountered are discussed below.

Lack of data on emission-exposure scenarios ITO
In chapter 4.2.2., multiple studies were found regarding the emission and exposure scenarios of ITO, particularly in its production phase. However, through the available exposure and emission information on the production of ITO it was unclear as to whether it applies universally to all different production techniques of ITO. Additionally, the studies lacked clarity on whether this toxicity arises from inadequate regulations or is an inherent challenge in the production of ITO. Thus, the information is to unclear to conclude.

Furthermore, the exposure to potentially toxic substances and emissions of ITO during the rest of its life cycle, other than the production phase, was examined. No data was found on emission and exposure scenarios during the use of ITO. According to A.R. Balkenende, ITO is safely trapped into the LCD during use (personal communication, November 29, 2023). However, it is unclear what kind of exposure or risk could occur, for example, if an LCD monitor (accidentally) breaks during use. This could potentially result in various end-of-life scenarios, but this remains unclear.

Lastly, the possible exposure and emissions during the end-of-life of ITO in an LCD monitor was investigated, revealing significant data gaps. A few studies were found on the end-of-life of ITO mentioning elevated indium levels in soil and air at e-waste recycling facilities. In this case as well, it is unclear whether this occurs due to inadequate regulations or is an inherent challenge of the end-of-life of ITO.

For the researcher of this study, it was unclear if the SCD method also looks into the emission and exposure scenarios of possible substances that could potentially occur during the lifecycle of the SoC. For instance, as discussed in chapter 4.2.2., $InCl_3$, $In(NO_3)_3$ and $In(OH)_3$ can occur after the end-of-life of ITO (when it is dumped on a landfill) (Pabo & Plamthottam, 2012). It is assumed of the broad definition for SoC defined by Bolaños Arriola et al. (2023) that these emission and exposure scenarios are included. Particularly, as it is crucial to investigate these emission and exposure scenarios because the released substances could potentially be toxic to humans, animals, or the environment. Furthermore, it gives a more comprehensive understanding of the potential toxicity of ITO during its life cycle. Consequently, this study also delved into the emission and exposure scenarios of potential substances that might occur during the lifecycle of ITO. However, no studies were found stating the kind of exposure and emissions that could occur when an LCD monitor with ITO is e.g., shredded and, for instance, deposited under pavement.

Unable to execute all sub steps
As shown in Figure 3, there are three sub steps in Step 2. However, the determination of the most concerning scenarios cannot be carried out in this study due to a lack and ambiguity of data (step 2b). Additionally, the following sub step (step 2c), which involves identifying the relationship between the most concerning emissions-exposure scenarios, the product architecture, and the context, cannot be implemented.

7.1.3 Step 3: Define strategies to avoid/mitigate risks from the SoC

The third step of the SCD method involves the definition or selection of strategies that could avoid, reduce, or control ITO. This step was conducted in Chapter 5 of this study. The insights and challenges that occurred are discussed below.

SCD method provides helpful guide

In this step, the SCD method served as an excellent guide for defining strategies to avoid or mitigate the risks associated with ITO. This was particularly valuable as the method provided an extensive list of optional strategies that could be considered, especially given that no other stakeholders, such as additional designers or a product client, were involved in this study.

Need for chemical expertise

A significant challenge encountered was the need for chemical knowledge to comprehend and compare the different strategies, especially dealing with control strategies demanded a high level of chemical expertise. The complexity of the control strategies that recover indium made it unfeasible to fully understand them without the assistance of external experts within the timeframe of this study. Especially since most of the recovery strategies were only on the laboratory level.

Lack of reduce and control strategies

As discussed in chapter 5.3, no reduction strategies for ITO were identified in literature. Furthermore, as discussed in chapter 5.4, there is a scarcity of control strategies at the pilot level for ITO in existing literature. While recovery methods were found at the laboratory scale, these are beyond the methodological scope of this study due to the absence of chemical expertise. This is a challenge for this study due to time constraints and the absence of involvement from other stakeholders such as the product client.

Unable to design new strategies

As this study was not conducted within a design team or in collaboration with a product client, it was not feasible to develop (new) strategies. A multidisciplinary team can lead to the development of new strategies that may not have been explored previously. Thus, ideally there would be a broad set of experts involved. For instance, for this study, experts on display technology, electronic engineers, TCOs, end-of-life of a TCO/ITO, etc.

7.1.4 Step 4: Evaluate the selected strategies, measure their potential effects

In the fourth step, the generated strategies undergo evaluation which was done in Chapter 5 and 6. The strategies were evaluated on several topics like possible emission-exposure scenarios and potential drawbacks. Furthermore, one strategy was selected and assessed in an ex-ante LCA study. During this step several insights and challenges occurred, which are discussed below.

Material characteristics avoidance strategies

The challenge encountered in step 1, which involves understanding the material characteristics of ITO, is also present in this step, particularly concerning the material characteristics of avoidance strategies. The studies on the material characteristics of avoidance strategies also proved challenging to comprehend. Additionally, there is a lack of data regarding the lifespan of different avoidance strategies. Without expert input, it will be impossible to compare the strategies based on identified material characteristics.

Scarcity of toxicity data on avoidance strategies

Additionally, a challenge in this step was the scarcity of data on the possible toxicity and possible emission and exposure scenarios for the various strategies. When toxicity data was available, it was in some cases inconsistent, as discussed in chapter 5.2. For instance, a study might claim that a substance is not toxic, while ECHA would state that it is toxic. Moreover, certain papers labelled substances as either toxic or non-toxic without providing sufficient argumentation for such classifications. Additionally, in some cases there was only a small amount of data available that stated that a substance is non-toxic without argumentations, which means that a substance still could be toxic. Furthermore, when emission and exposure data are found for a certain avoidance strategy, it is often still unclear in which specific life cycle phase a strategy might exhibit risk or if the risk is for humans and/or animals. Furthermore, selecting a strategy for the ex-ante LCA study based on its potential non-toxicity was unfeasible in this study. It's worth noting that in the SCD method, a strategy would be chosen based on its non-toxicity rather than its data availability, as was the case in this study.

In this step, an examination is conducted into the emission and exposure scenarios of potential substances that might occur during the life cycle of the strategy. Additionally, there was some uncertainty, as in in step 2, regarding whether this aspect is also included in the SCD method. However, due to the broad definition provided for SoC, it is assumed that this is indeed a part of the SCD method. There is a lack of data regarding the substances that could potentially emerge during the lifecycle of a strategy. Consequently, the potential toxicity of these substances is unknown.

Lack of inventory data for LCA study

In Chapter 5, the possible inventory data of a strategy was also discussed as an additional selection criterion of the strategy. Inventory data was only found for a few strategies. For most strategies, the available inventory data was limited to the production phase, lacking comprehensive data for the entire life cycle.

Uncertainties in used inventory data

As discussed before, ZnO:Al is chosen as the alternative for ITO in the LCA study because of the availability of data. Whilst conducting the ex-ante LCA study, several uncertainties in the inventory data of Kawajiri et al. (2022) were identified. Despite several attempts, contact could not be established with the authors of the paper to address the uncertainties. For instance, Kawajiri et al. (2022) determined the thickness of their films to be 250 nm for ITO and 288 nm for ZnO:Al. However, on average, the thickness of ITO is 150 nm, and ZnO:Al should be 7 times thicker (A.R. Balkenende, personal communication, November 29, 2023). It is unclear on what data Kawajiri et al. (2022) relied upon for establishing the thicknesses of the films. Additionally, it is noteworthy that the weight of ZnO:Al (thickness of 288 nm) is nearly three times lower than that of ITO (thickness of 250 nm) in their inventory data. It is unclear where this data originates from. They mention that the differences in inventory data are based on differences in material properties, but what this difference is and how it altered the inventory data is not mentioned. Thus, there is also a lack of data on the differences between the two films.

Lack of inventory data on end-of-life

Inventory data is needed to be able to conduct an ex-ante LCA study. In the context of this ex-ante LCA study, only inventory data until the use phase was available for both alternatives. Consequently, assumptions were made regarding the end-of-life phase for both alternatives. As discussed in chapter 4.2.2. and 5.2.1, there is a significant potential for hazards during the end-of-life phase for both alternatives. However, due to the lack of inventory data for this phase for both alternatives, these possible hazards are not considered in the ex-ante LCA study. Furthermore, the environmental impact of this phase for both alternatives remains unclear because it is based on assumptions.

Lack of emission flows and characterization factors

The ex-ante LCA study aimed, among other things, to assess the possible toxicity of both alternatives. However, the toxicity of both substances is not reflected in the results due to the absence of emission flows and characterization factors of possible toxic substances. In the case of ITO film, there are no emission flows for substances that could potentially arise during the production of ITO or after the end of its life, for instance indium. Furthermore, there is a lack of characterization factors, meaning that the toxicity of possible toxic substances is not considered in the LCA results.

A similar situation exists for ZnO:Al film. Although there is an emission flow for zinc oxide, no impact assessment method including a characterization factor for this emission was identified. Consequently, the potential toxic impact of these substances is not incorporated into the LCA results. For the other possible substances that could occur in the lifecycle of ZnO:Al, such as $Zn(OH)_2$, there are no emission flows and characterization factors. Without these emission flows and characterization factors, it is impossible to map potential toxic trade-offs of the assessed alternatives. However, the ex-ante LCA study can provide insights in the possible non-toxic trade-offs.

Limitations ex-ante LCA

In this study, not all steps of an elaborate ex-ante LCA are conducted. Typically, an ex-ante LCA delves into various scenarios for potential future outcomes, which was deemed beyond the scope of this study. This decision was influenced by several factors. Firstly, the study was primarily exploratory in nature. Additionally, while ZnO:Al is an emerging technology, it already exists and is simply not yet applied to an LCD monitor.

7.1.5 Summary

In summary, the application of the SCD method to the LCD monitor case revealed various insights and challenges. Some of these challenges are not inherent to the framework of the method, but rather arise in its implementation. Like issues related to terminology, a general lack of information and (toxicity) data, and the absence of emission flows and characterization factors for the LCA study.

However, there have also been insightful aspects of the SCD method that proved beneficial during this study. For instance, the guidance provided in step 1 on gathering information about a SoC and the direction offered in step 3 for developing strategies for ITO.

Specific challenges within the study were also attributed to the SCD method. Notably, there was an overlap between steps 1 and 2, and the method lacked specificity regarding the significance of knowing the location of the SoC. Additionally, the SCD method did not specify clearly whether the possible generated substances during the lifecycle of an SoC are also examined, for both step 2 and step 4.

Furthermore, several challenges and limitations were associated with this study. For example, the absence of a design team or communication with the product client posed challenges in accessing the material characteristics of ITO and in generating or developing (new) strategies. Additionally, different choices were made compared to the guidance provided by the SCD method, such as the selection of the SoC and the strategy based on data availability.

7.2 Improvements SCD method

This study was the first to implement the SCD method by Bolaños Arriola et al. (2023) in practice. The researcher of this study implemented an ex-ante LCA study in the SCD method. In the sections above, several insights and challenges were identified in the application of the SCD method. To prevent the recurrence of some of these identified challenges in subsequent studies, various improvements are suggested for the SCD method.

Figure 17 displays the enhanced SCD method with alterations to further refine and enhance the SCD method. Figure 3 exhibits the SCD method by Bolaños Arriola et al. (2023) to facilitate the comparison of differences. The modifications are highlighted in **bold** text, and each alteration is briefly discussed.

An improvement is proposed for the first step of the SCD method. As became apparent in this study, is it of importance to determine the location of the SoCs present in the evaluated product. Identifying the location of the SoC is crucial for designing or finding suitable strategies and for conducting an (ex-ante) LCA study. The location is likely to be established when the SCD method is implemented within a design team collaborating with the product client. Nonetheless, it would enhance the comprehensiveness of the SCD method to explicitly address this aspect.

As depicted in Figure 3, the first step involves the examination of the potential hazards of the SoC. Subsequently, in step 2, the analysis of emission and exposure scenarios takes place. However, during this study, steps 1 and 2 of the SCD method were combined. This is because, when investigating the potential hazards of an SoC, the emission and exposure scenarios are most likely also discussed. Therefore, it is proposed to adjust steps 1 and 2. Step 1 should focus solely on investigating the possible SoCs in a product and introducing the selected SoC. Step 2, on the other hand, should focus on the toxicity of the SoC.

An additional improvement proposed for step 2 of the SCD method is to clearly address that during examining the emission and exposure scenarios of potential substances are involved that are generated during the lifecycle of the SoC. The current SCD method leaves uncertainty about whether this should be analysed, consequently this aspect should be more explicitly clarified in the enhanced SCD method.

According to Bolaños Arriola et al. (2023), step 4 involves evaluating the selected strategies. It was unclear upon what criteria the strategies should be selected. It is recommended to evaluate all the defined/generated strategies when it fits in the timeframe of the study. This evaluation provides the opportunity to choose a strategy based on, for example, its low toxicity. Furthermore, in this step it should also be more explicitly clarified that the emission and exposure scenarios of substances potentially generated during the lifecycle of a strategy should be analysed. However, when the SCD method is combined with a RA or a LCA study, it is often impractical to evaluate all the defined or generated strategies due to time constraints. In such cases, it is advisable to select several strategies based on the available information gathered thus far.

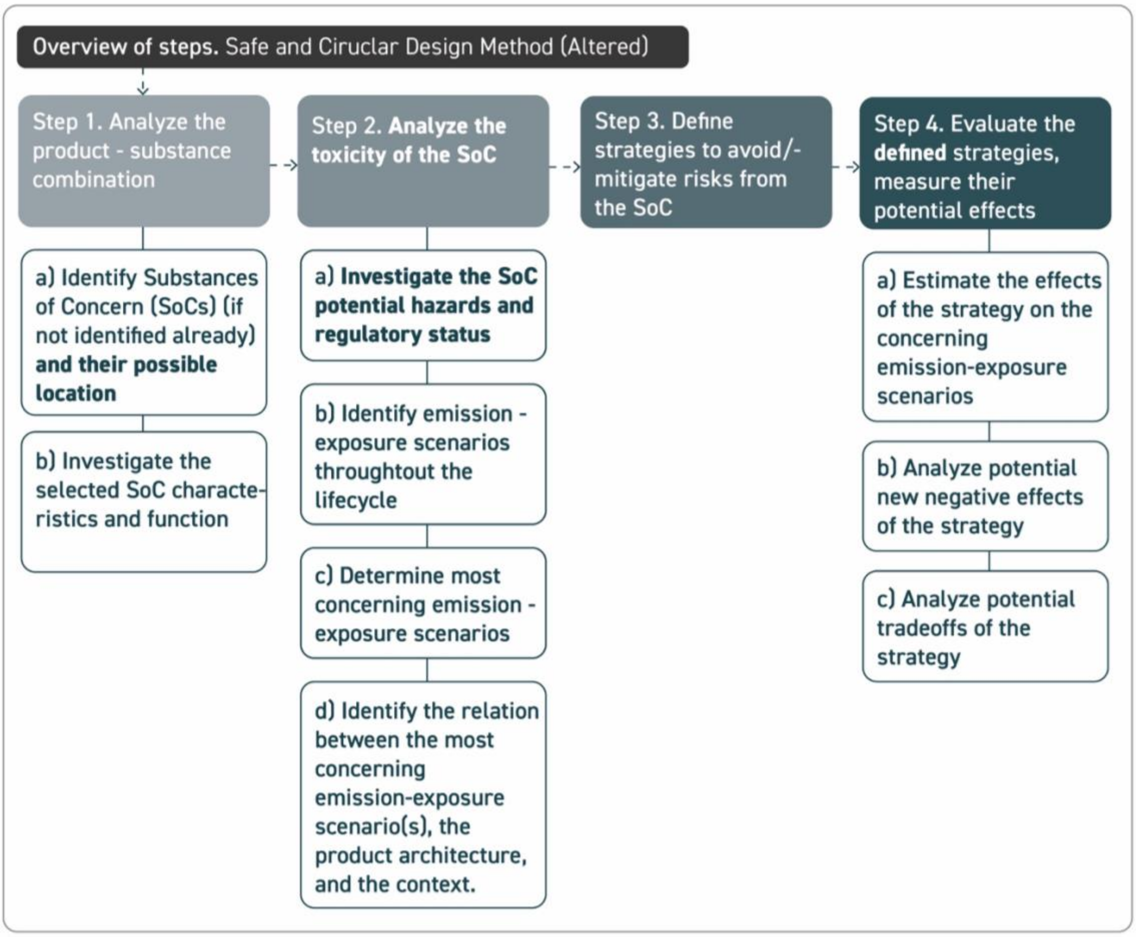


Figure 17. Steps of the SCD method including recommendations for improvements

7.3 Two perspectives on different areas of expertise

Within S(S)bD studies, the involvement of a multidisciplinary teams is imperative. This chapter introduces two distinct perspectives from varied areas of expertise. The researcher of this study possesses a background as both a product designer and an LCA expert, providing a unique opportunity to evaluate the study process from both perspectives.

7.3.1 LCA expert

As discussed in the preceding sections, the study encountered various challenges. For an LCA expert, dealing with the necessary chemical and physics knowledge proved to be a significant challenge. Understanding the data and drawing conclusions on, for instance, the material characteristics would have been impossible without the expert input of A.R. Balkenende.

Moreover, navigating the numerous uncertainties in the data throughout the study presented a challenge. In particular, comprehending the uncertainty of toxicity data related to ITO and the different strategies was difficult. Additionally, the inconsistency in toxicity data, for instance, that ECHA states a substance is toxic while literature says the opposite, made it almost impossible to interpret the data. Specifically, with the toxicity data of the strategies, it was impossible to determine whether a strategy could potentially result in toxicity for humans, animals, or the environment.

From the researcher's expertise, it is common in LCA studies to have incomplete inventory data and the need to construct a model based partly on assumptions. However, the inability to draw conclusions about the toxicity of the alternatives due to the lack of emission flows and characterization factors presented a distinct challenge when interpreting LCA results. Addressing this issue requires adjustments to impact assessment methods, an aspect that goes beyond the expertise of this LCA expert. Despite conducting an elaborate LCA study, it remains challenging to determine if (toxic) trade-offs could occur.

7.3.2 Product designer

The SCD method by Bolaños Arriola et al. (2023) was employed. This method is intended to assist designers in addressing SoCs in products. The method proved to be a valuable guide throughout the study, ensuring a holistic view and comprehensive consideration of every aspect. This guidance was particularly beneficial during the development and exploration of strategies for ITO, providing useful directions for potential strategies. Thus, it can be concluded that the SCD method is especially focusing on the D of Design in the S(S)bD approach.

For a product designer, interpreting the found toxicity data in this study, when available, proved to be a significant challenge. This is based on the fact that as an LCA expert, it was challenging to interpret the data, and it is assumed that designers would encounter similar challenges. Furthermore, the same difficulties were encountered by product designers as discussed above for LCA experts. Moreover, the lack of toxicity data, inconsistencies in the data, and the absence of experts made it impossible to formulate or design strategies based on the available toxicity data. Overall, implementing design to generate and develop strategies is unfeasible if there is no design team or product client involved in the project. This is partly due to challenges in interpreting toxicity data and the absence of collaborative expertise. However, most likely is the SCD method only implemented when there is a design team and a product client involved.

The holistic perspective maintained by a designer is invaluable in studies of this nature, as an LCA expert and possibly other expert are more inclined to become immersed in specific details. Furthermore, a designer, by contemplating how the product is used and envisioning the potential impact of a chosen strategy on the product's usage, acquires valuable insights.

7.3.3 Need for multidisciplinary team

As evident from the preceding sections, it is impossible for a product designer or an LCA expert to deal with a SoC individually. Even the researcher of this study, possessing a background in both product design and LCA, cannot deal with a SoC on her own. Therefore, a multidisciplinary team is required.

It is presumed that the following experts are essential for S(S)bD projects. A designer is required to provide a holistic perspective and to develop and generate potential strategies. Additionally, an expert is necessary on the product under evaluation, possessing a deep understanding of the product and its production processes. Furthermore, an expert is needed to address the potential toxicity of the SoC and its emission and exposure scenarios. Moreover, the involvement of a LCA expert is crucial to evaluate the chosen strategy or strategies and identify any potential trade-offs. A risk assessment expert is also required to conduct a comprehensive risk assessment. In cases like the one presented in this study, physics and chemical experts are indispensable to comprehend the complexities of the technology and explore potential strategies. The collaborative effort of these experts is presumed to be necessary for the successful execution of S(S)bD projects.

7.4 Overarching problems in S(S)bD studies

The challenges encountered in this study are compared to the challenges identified in the case studies investigated by Bolaños Arriola et al. (2022). The overall scarcity of data and information is not unique to this case. Bolaños Arriola et al. (2022) faced similar issues during their case studies. However, they could find more data on the potential toxicity of their SoCs, possibly because their focus was primarily on organic substances. It is presumed that there is more (publicly) available data and information on organic substances than inorganic substances like the SoC of this study. Addressing these challenges associated with data scarcity requires increased availability of (public) data and information, as well as the involvement of experts or a multidisciplinary team. The complexity of dealing with SoCs in products is heightened by the absence of (public) data and information.

Bolaños Arriola et al. (2022) also encountered inconsistencies and vagueness in toxicity data in their case studies, which led to difficulties in conducting a screening RA and LCA study in their study. Furthermore, their investigated cases faced an overall shortage of toxicity data. Additionally, Bolaños Arriola et al. (2022) also mentioned that there is a lack of emission flows and characterization factors.

Thus, overarching challenges for S(S)bD studies include the shortage of data and information on SoCs and possible strategies. Furthermore, there is a scarcity of data on the potential toxicity, as well as the emissions and exposure scenarios, of SoCs and possible strategies, resulting in uncertainty about whether strategies yield unwanted trade-offs. Additionally, the absence of emission flows and characterization factors for SoCs and possible strategies poses challenges.

8. Conclusion and recommendations

8.1 Conclusion

An answer will be given to the following main research question: *Which insights can be obtained by evaluating the SCD method through a case of an LCD monitor on the European market, to develop a possible strategy to replace, reduce or control a SoC that possibly reduces the risks to the environment and human health as well as its life cycle environmental impacts?*

To answer this research question, five sub-research questions were formulated. The first two sub-research questions were on the possible SoCs in an LCD and the selection of the SoC that will be used as an example for this study. This resulted in the selection of ITO as the SoC for this study, since it was the only SoC with a known location and enough data for the rest of the study.

The following sub-research question centred on developing possible strategies that could replace, reduce or control ITO in an LCD monitor and determining which strategy would be selected for this study. While literature provided several replace strategies, no reduce strategies were identified, and only a few control strategies were found, primarily at the pilot scale. Ultimately, ZnO:Al was chosen as the strategy for this study due to its availability of data.

The final two sub-research questions focused on the ex-ante LCA study comparing ITO film to ZnO:Al film. The first question sought to determine the life cycle environmental impacts of an LCD monitor incorporating both ITO and ZnO:Al films. The second sub-question explored whether ZnO:Al resulted in undesired trade-offs in other impact categories. The findings of this ex-ante LCA study suggest that ZnO:Al cannot be utilized without resulting in unwanted trade-offs in other impact categories.

Every step of this study, including each sub-research question, aligned with the SCD method. Chapter 7 provides a comprehensive discussion of every insight and challenge encountered during the implementation and evaluation of the SCD method. A prominent insight is the consistent lack of information and data throughout this study, which proves to be a recurring challenge. For example, the deficiency of data and information on the SoCs in an LCD monitor and the absence of data on the potential toxicity of SoCs and strategies. Additionally, the found data is sometimes also inconsistent. This challenge, rooted in the scarcity and inconsistency of data and information, cannot be addressed by modifying the SCD method, as it represents a broader issue in S(S)bD. This goes beyond the scope of LCA experts and designers to tackle this problem.

Another prominent insight is the need for a multidisciplinary team to be able to deal with SoCs in products. This study demonstrates that neither an LCA expert nor a designer can handle SoCs in products alone. Other disciplines, such as a toxicity expert, are necessary. Furthermore, this study showed that an ex-ante LCA can offer insights into possible non-toxic trade-offs. However, in this study, an ex-ante LCA was unable to provide insights in possible toxic trade-offs due to the lack of emission flows and characterization factors for possible toxic substances. This is likely to occur in other (ex-ante) LCA studies because many SoCs lack available emission flows and characterization factors.

8.2 Recommendations

The study introduces some alterations to further refine and enhance the SCD method. It is advisable to assess the effectiveness of this method in other case studies, preferably across a wide range of cases. This includes evaluating organic and inorganic SoCs as well as diverse product types. This broader application is recommended to ensure that the improved SCD method remains applicable and effective across a varied scope of studies.

To improve S(S)bD studies, organisations, companies, and governments should implement changes and regulations. There needs to be enhanced overall availability of data and information on products and their components. For instance, information and data on substances that are currently used in products (or materials) should be publicly available. Therefore, it is recommended that companies make data and information on their products available to the public or at least to businesses they work with. If companies do not voluntarily provide this information, governments should enact regulations to enforce disclosure. Moreover, besides assisting in addressing issues similar to those explored in this study, the data and information can also empower customers to make better decisions.

The same principle applies to toxicity data. Governments and organizations, such as RIVM and ECHA, should invest in and conduct more research on the potential toxicity of substances if the toxicity data is not yet available. Furthermore, companies should be transparent about the (possible) toxicity of their products. Moreover, it should be more common to only use substances when it is proven that the substance is non-toxic in the context it is used or could be safely controlled after its lifespan. Rather than employing a substance due to the lack of proof regarding its toxicity or harm to humans, animals, and/or the environment.

Moreover, there are notable gaps in emission flows and characterization factors for SoCs in LCA studies. Additionally, for some substances, there might already be an emission flow without an associated characterization factor, or vice versa. Research efforts should concentrate on filling these gaps by developing characterization factors for existing emission flows and vice versa. Without these, it is impossible to determine if unwanted toxic trade-offs occur when a strategy is applied.

In summary, evaluating the SCD method through an LCD monitor case has highlighted significant challenges stemming from data scarcity and quality issues. Enhancing data availability and interdisciplinary collaboration are crucial for ensuring safer and more sustainable product development.

9. References

Abbas, S., Haoua, A. B., Haoua, B. B., & Rahal, A. (2014). Optical and Structural Characterization of Fluorine-Doped SnO2 Thin Films Prepared by Spray Ultrasonic. *Journal of New Technology and Materials*, *4*, 106-111.

AKB. (2022). *How To Prolong the Life of LCD Display?* Retrieved December 4 from https://www.campuscomponent.com/blogs/post/how-to-prolong-the-life-of-lcd-display#:~:text=Monitors%20with%20Liquid%20Crystal%20Displays,two%20sheets%20of%20polarizing%20material.

Akcil, A., Agcasulu, I., & Swain, B. (2019). Valorization of waste LCD and recovery of critical raw material for circular economy: A review. *Resources, Conservation and Recycling*, *149*, 622-637.

Al-Ofi, H., Abd El-Raheem, M., Al-Baradi, A. M., & Atta, A. (2012). Structural and optical properties of Al2ZnO4 thin films deposited by DC sputtering technique. *Journal of Non-Oxide Glasses Vol*, *3*(3), 39-54.

Amato, A., Becci, A., Mariani, P., Carducci, F., Ruello, M. L., Monosi, S., Giosuè, C., & Beolchini, F. (2019). End-of-life liquid crystal display recovery: toward a zero-waste approach. *Applied Sciences*, *9*(15), 2985.

Amato, A., Rocchetti, L., & Beolchini, F. (2017). EVALUATION OF DIFFERENT STRATEGIES FOR END-OF-LIFE LIQUID CRYSTAL DISPLAYS (LCD) MANAGEMENT. *Environmental Engineering & Management Journal (EEMJ)*, *16*(8).

Amato, A., Rocchetti, L., Fonti, V., Ruello, M. L., & Beolchini, F. (2016). Secondary indium production from end-of-life liquid crystal displays. *physica status solidi (c)*, *13*(10-12), 979-983.

Andooz, A., Eqbalpour, M., Kowsari, E., Ramakrishna, S., & Cheshmeh, Z. A. (2022). A comprehensive review on pyrolysis of E-waste and its sustainability. *Journal of Cleaner Production*, *333*, 130191.

Arvidsson, R., Kushnir, D., Molander, S., & Sandén, B. A. (2016). Energy and resource use assessment of graphene as a substitute for indium tin oxide in transparent electrodes. *Journal of Cleaner Production*, *132*, 289-297.

Awan, U. (2022). Industrial ecology in support of sustainable development goals. In *Responsible consumption and production* (pp. 370-380). Springer.

Ayinde, S., Fasakin, O., Olofinjana, B., Adedeji, A., Oyedare, P., Eleruja, M., & Ajayi, E. (2019). Optical, structural and electrical properties of aluminum doped zinc oxide thin films by MOCVD technique. *Journal of Electronic Materials*, *48*, 3655-3661.

Banyamin, Z. Y., Kelly, P. J., West, G., & Boardman, J. (2014). Electrical and optical properties of fluorine doped tin oxide thin films prepared by magnetron sputtering. *Coatings*, *4*(4), 732-746.

Bhakar, V., Agur, A., Digalwar, A., & Sangwan, K. S. (2015). Life cycle assessment of CRT, LCD and LED monitors. *Procedia CIRP*, *29*, 432-437.

Bolaños Arriola, J., Subramanian, V., Bakker, C., & Balkenende, R. (2023). *Safe and Circular Design - A design method for dealing with substances of concern in products.* .

Bolaños Arriola, J., Subramanian, V., Bakker, C., Balkenende, R., & Cucurachi, S. (2022). *Safe by Design – A design approach for dealing with hazardous substances in products*.

Bomhard, E. M. (2016). The toxicology of indium tin oxide. *Environmental Toxicology and Pharmacology*, *45*, 282-294.

Bomhard, E. M. (2018). The toxicology of indium oxide. *Environmental Toxicology and Pharmacology*, *58*, 250-258.

Bomhard, E. M. (2020). The toxicology of gallium oxide in comparison with gallium arsenide and indium oxide. *Environmental Toxicology and Pharmacology*, *80*, 103437.

Boussoualem, M., King, R. C. Y., Brun, J.-F., Duponchel, B., Ismaili, M., & Roussel, F. (2010). Electro-optic and dielectric properties of optical switching devices based on liquid crystal dispersions and driven by conducting polymer [poly (3, 4-ethylene dioxythiophene): polystyrene sulfonate (PEDOT: PSS)]-coated electrodes. *Journal of Applied Physics*, *108*(11).

Boutet, S., Gamard, A., Jousseaume, B., Toupance, T., Campet, G., & Cachet, H. (2002). Fluorinated organotins as precursors of F-doped tin dioxide. *Main group metal chemistry*, *25*(1-2), 59-66.

Brigden, K., I. Labunska, D. Santillo, & Allsopp, M. (2005). *Recycling of electronic wastes in China and India: workplace and environmental contamination*.

Brigden, K., Labunska, I., Santillo, D., & Johnston, P. (2008). *Chemical contamination at e-waste recycling and disposal sites in Accra and Korforidua, Ghana*.

Caldeira, C., Farcal, L. R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). Safe and sustainable by design chemicals and materials. Framework for the definition of criteria and evaluation procedure for chemicals and materials. *EUR*.

Centers for Disease Control and Prevention. (2022). *Per- and Polyfluorinated Substanes (PFAS)*. Retrieved April 12 from https://www.cdc.gov/biomonitoring/PFAS_FactSheet.html#:~:text=The%20per%2Dand%20polyfluoroalkyl%20substances,in%20a%20variety%20of%20products.

Chen, H.-W., Lee, J.-H., Lin, B.-Y., Chen, S., & Wu, S.-T. (2018). Liquid crystal display and organic light-emitting diode display: present status and future perspectives. *Light: Science & Applications*, *7*(3), 17168-17168.

Cheng, Z., Han, M., Yuan, P., Xu, S., Cola, B. A., & Wang, X. (2016). Strongly anisotropic thermal and electrical conductivities of a self-assembled silver nanowire network. *RSC advances*, *6*(93), 90674-90681.

Choi, D., Kim, Y. S., & Son, Y. (2014). Recovery of indium tin oxide (ITO) and glass plate from discarded TFT-LCD panels using an electrochemical method and acid treatment. *RSC advances*, *4*(92), 50975-50980.

Chonan, T., Taguchi, O., & Omae, K. (2007). Interstitial pulmonary disorders in indium-processing workers. *European Respiratory Journal*, *29*(2), 317-324.

Chou, T.-R., Chen, S.-H., Chiang, Y.-T., Lin, Y.-T., & Chao, C.-Y. (2015). Highly conductive PEDOT: PSS films by post-treatment with dimethyl sulfoxide for ITO-free liquid crystal display. *Journal of Materials Chemistry C*, *3*(15), 3760-3766.

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of emerging technologies. *Procedia CIRP*, *69*, 463-468.

Cummings, K. J., Donat, W. E., Ettensohn, D. B., Roggli, V. L., Ingram, P., & Kreiss, K. (2010). Pulmonary alveolar proteinosis in workers at an indium processing facility. *American journal of respiratory and critical care medicine*, *181*(5), 458-464.

Cummings, K. J., Nakano, M., Omae, K., Takeuchi, K., Chonan, T., Xiao, Y.-l., Harley, R. A., Roggli, V. L., Hebisawa, A., & Tallaksen, R. J. (2012). Indium lung disease. *Chest*, *141*(6), 1512-1521.

Cummings, K. J., Suarthana, E., Day, G. A., Stanton, M. L., Saito, R., & Kreiss, K. (2012). *An Evaluation of Preventive Measures at an Indium-Tin Oxide Production Facility*. US Department of Health and Human Services, Centers for Disease Control and ….

Damiani, M., Ferrara, N., & Ardente, F. (2022). Understanding Product Environmental Footprint and Organisation Environmental Footprint methods.

Dauzon, E., Lin, Y., Faber, H., Yengel, E., Sallenave, X., Plesse, C., Goubard, F., Amassian, A., & Anthopoulos, T. D. (2020). Stretchable and transparent conductive PEDOT: PSS-based electrodes for organic photovoltaics and strain sensors applications. *Advanced Functional Materials*, *30*(28), 2001251.

Diamond, M. L., de Wit, C. A., Molander, S., Scheringer, M., Backhaus, T., Lohmann, R., Arvidsson, R., Bergman, Å., Hauschild, M., & Holoubek, I. (2015). Exploring the planetary boundary for chemical pollution. *Environment international*, *78*, 8-15.

Dodbiba, G., Nagai, H., Wang, L. P., Okaya, K., & Fujita, T. (2012). Leaching of indium from obsolete liquid crystal displays: Comparing grinding with electrical disintegration in context of LCA. *Waste management*, *32*(10), 1937-1944.

Dondapati, H., Santiago, K., & Pradhan, A. (2013). Influence of growth temperature on electrical, optical, and plasmonic properties of aluminum: zinc oxide films grown by radio frequency magnetron sputtering. *Journal of Applied Physics*, *114*(14).

Dong, L., Zhu, G., Xu, H., Jiang, X., Zhang, X., Zhao, Y., Yan, D., Yuan, L., & Yu, A. (2019). Preparation of indium tin oxide (ITO) thin film with (400) preferred orientation by sol–gel spin coating method. *Journal of Materials Science: Materials in Electronics*, *30*, 8047-8054.

Duan, H., Eugster, M., Hischier, R., Streicher-Porte, M., & Li, J. (2009). Life cycle assessment study of a Chinese desktop personal computer. *Science of the total environment*, *407*(5), 1755-1764.

ECHA. (2016). *Substances of very high concern (SVHC)*. Retrieved October 25 from https://echa.europa.eu/-/chemicals-in-our-life-chemicals-of-concern-svhc

ECHA. (2023a). Retrieved December 23 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.039.944

ECHA. (2023b). *Candidate List of substances of very high concern for Authorisation*. Retrieved November 3 from https://echa.europa.eu/candidate-list-table?p_p_id=disslists_WAR_disslistsportlet&p_p_lifecycle=1&p_p_state=normal&p_p_mode=view&_disslists_WAR_disslistsportlet_javax.portlet.action=searchDissLists

ECHA. (2023c). *Search for chemicals - zinc oxide*. Retrieved November 24 from https://echa.europa.eu/nl/search-for-chemicals?p_p_id=disssimplesearch_WAR_disssearchportlet&p_p_lifecycle=0&_disssimplesearch_WAR_disssearchportlet_searchOccurred=true&_disssimplesearch_WAR_disssearchportlet_sessionCriteriaId=dissSimpleSearchSessionParam101401700844916640

ECHA. (2023d). *Substance infocard - Zinc hydroxide*. Retrieved Decembere 23 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.039.816

ECHA. (2023e). *Substance Infocard Aluminium oxide*. Retrieved November 3 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.014.265

ECHA. (2023f). *Substance infocard Benzenesulfonic acid, ethenyl-, homopolymer, compd. with 2,3-dihydrothieno[3,4-b]-1,4-dioxin homopolymer*. Retrieved November 14 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.157.402

ECHA. (2023g). *Substance Infocard Dialuminium zinc tetraoxide*. Retrieved November 6 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.031.898#OTHER_IDENTIFIERScontainer

ECHA. (2023h). *Substance Infocard Digallium trioxide*. Retrieved November 6 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.031.525

ECHA. (2023i). *Substance infocard Graphene*. Retrieved November 7 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.227.924

ECHA. (2023j). *Substance infocard Indium hydroxide*. Retrieved December 7 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.054.156

ECHA. (2023k). *Substance Infocard Indium oxide*. Retrieved November 1 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.032.501

ECHA. (2023l). *Substance infocard Indium Tin Oxide*. Retrieved October 6 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.106.463

ECHA. (2023m). *Substance Infocard Indium trichloride*. Retrieved December 7 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.030.027

ECHA. (2023n). *Substance Infocard Tin*. Retrieved November 1 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.168.135

ECHA. (2023o). *Substance Infocard tin dioxide*. Retrieved November 1 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.038.311

ECHA. (2023p). *Substance infocard Zinc oxide*. Retrieved November 3 from https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.013.839

ECHA. (2023q). *Zinc oxide*. Retrieved November 6 from https://echa.europa.eu/nl/brief-profile/-/briefprofile/100.013.839#collapseSeven

Editorial Team. (2020). *How Long Monitor (LCDs, LEDs, CRTs, OLEDs) Lifespan Is?* Retrieved December 4 from https://digitalworld839.com/how-long-does-a-monitor-last/#1_lifespan_of_LCD_Monitorv

Ellen Macarthur Foundation. (2013). *Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition*.

Ellen Macarthur Foundation. (2015). *Towards a Circular Economy: Business rationale for an accelerated transition*. Retrieved October 10 from https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition

Emmott, C. J., Urbina, A., & Nelson, J. (2012). Environmental and economic assessment of ITO-free electrodes for organic solar cells. *Solar Energy Materials and Solar Cells*, *97*, 14-21.

Eshaghi, A., & Hajkarimi, M. (2014). Optical and electrical properties of aluminum zinc oxide (AZO) nanostructured thin film deposited on polycarbonate substrate. *Optik*, *125*(19), 5746-5749.

Espinosa, N., Garcia-Valverde, R., Urbina, A., & Krebs, F. C. (2011). A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions. *Solar Energy Materials and Solar Cells*, *95*(5), 1293-1302.

Espinosa, N., Serrano-Luján, L., Urbina, A., & Krebs, F. C. (2015). Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective. *Solar Energy Materials and Solar Cells*, *137*, 303-310.

European Commission. (2020a). *Chemicals Strategy for Sustainability - Towards a Toxic-Free Environment*.

European Commission. (2020b). A new circular economy action plan for a cleaner and more competitive Europe. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*.

European Commission. (2022). *Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS)*. Retrieved 31 October from https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en

European Environment Agency. (2018). *Consumption of hazardous chemicals*. Retrieved April 12 from

DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, (2023). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02011L0065-20230301

Fang, G., Li, D., & Yao, B.-L. (2002). Fabrication and vacuum annealing of transparent conductive AZO thin films prepared by DC magnetron sputtering. *Vacuum*, *68*(4), 363-372.

Farhan, M. S., Zalnezhad, E., Bushroa, A. R., & Sarhan, A. A. D. (2013). Electrical and optical properties of indium-tin oxide (ITO) films by ion-assisted deposition (IAD) at room temperature. *International Journal of Precision Engineering and Manufacturing*, *14*, 1465-1469.

Fischer, R., Gregori, A., Sahakalkan, S., Hartmann, D., Büchele, P., Tedde, S. F., & Schmidt, O. (2018). Stable and highly conductive carbon nanotube enhanced PEDOT: PSS as transparent electrode for flexible electronics. *Organic Electronics*, *62*, 351-356.

Fontana, D., Forte, F., Pietrantonio, M., & Pucciarmati, S. (2021). Recent developments on recycling end-of-life flat panel displays: A comprehensive review focused on indium. *Critical reviews in environmental science and technology*, *51*(5), 429-456.

Fortunato, E., Assuncao, V., Goncalves, A., Marques, A., Aguas, H., Pereira, L., Ferreira, I., Vilarinho, P., & Martins, R. (2004). High quality conductive gallium-doped zinc oxide films deposited at room temperature. *Thin solid films*, *451*, 443-447.

Fujimori, T., Takigami, H., Agusa, T., Eguchi, A., Bekki, K., Yoshida, A., Terazono, A., & Ballesteros Jr, F. C. (2012). Impact of metals in surface matrices from formal and informal electronic-waste recycling around Metro Manila, the Philippines, and intra-Asian comparison. *Journal of Hazardous Materials*, *221*, 139-146.

Gao, X.-Y., Chen, C., & Zhang, S. (2014). Optical properties of aluminum-doped zinc oxide films deposited by direct-current pulse magnetron reactive sputtering. *Chinese Physics B*, *23*(3), 030701.

Gautam, P., Behera, C. K., Sinha, I., Gicheva, G., & Singh, K. K. (2022). High added-value materials recovery using electronic scrap-transforming waste to valuable products. *Journal of Cleaner Production*, *330*, 129836.

Groß, R., Bunke, D., Gensch, C.-O., Zangl, S., & Manhart, A. (2008). Study on hazardous substances in electrical and electronic equipment, not regulated by the RoHS Directive. *Study made at the Öko-Institut eV (Head Office Freiburg)*.

Guinée, J. (2023). *Life Cycle Assessment (LCA) : "You'll only see it when you understand it"*. https://scholarlypublications.universiteitleiden.nl/handle/1887/3643758

Guinée, J. B. (2002). *Handbook on life cycle assessment: operational guide to the ISO standards* (Vol. 7). Springer Science & Business Media.

Guinée, J. B., Heijungs, R., Vijver, M. G., Peijnenburg, W. J., & Mendez, G. V. (2022). The meaning of life… cycles: lessons from and for safe by design studies. *Green Chemistry*, *24*(20), 7787-7800.

Gupta, S., Datt, R., Mishra, A., Tsoi, W. C., Patra, A., & Bober, P. (2022). Poly (3, 4-ethylenedioxythiophene): Poly (styrene sulfonate) in antibacterial, tissue engineering and biosensors applications: Progress, challenges and perspectives. *Journal of Applied Polymer Science*, *139*(30), e52663.

Ha, N. N., Agusa, T., Ramu, K., Tu, N. P. C., Murata, S., Bulbule, K. A., Parthasaraty, P., Takahashi, S., Subramanian, A., & Tanabe, S. (2009). Contamination by trace elements at e-waste recycling sites in Bangalore, India. *Chemosphere*, *76*(1), 9-15.

Hamaguchi, T., Omae, K., Takebayashi, T., Kikuchi, Y., Yoshioka, N., Nishiwaki, Y., Tanaka, A., Hirata, M., Taguchi, O., & Chonan, T. (2008). Exposure to hardly soluble indium compounds in ITO production and recycling plants is a new risk for interstitial lung damage. *Occupational and Environmental Medicine*, *65*(1), 51-55.

Hasegawa, H., Rahman, I. M., Egawa, Y., Sawai, H., Begum, Z. A., Maki, T., & Mizutani, S. (2013). Recovery of indium from end-of-life liquid-crystal display panels using aminopolycarboxylate chelants with the aid of mechanochemical treatment. *Microchemical Journal*, *106*, 289-294.

He, Z., Zhang, X., Wei, X., Luo, D., Ning, H., Ye, Q., Wu, R., Guo, Y., Yao, R., & Peng, J. (2022). Solution-Processed Silicon Doped Tin Oxide Thin Films and Thin-Film Transistors Based on Tetraethyl Orthosilicate. *Membranes*, *12*(6), 590.

Heijungs, R. (2012). CMLCA: Scientific software for LCA, IOA, EIOA, and more. *Retrieved April*, *21*, 2017.

Hengevoss, D., Baumgartner, C., Nisato, G., & Hugi, C. (2016). Life Cycle Assessment and eco-efficiency of prospective, flexible, tandem organic photovoltaic module. *Solar Energy*, *137*, 317-327.

Her, S.-C., & Chang, C.-F. (2017). Fabrication and characterization of indium tin oxide films. *Journal of Applied Biomaterials & Functional Materials*, *15*(2), 170-175.

Hischier, R., & Baudin, I. (2010). LCA study of a plasma television device. *The international journal of life cycle assessment*, *15*, 428-438.

Hoet, P., De Graef, E., Swennen, B., Seminck, T., Yakoub, Y., Deumer, G., Haufroid, V., & Lison, D. (2012). Occupational exposure to indium: what does biomonitoring tell us? *Toxicology letters*, *213*(1), 122-128.

Homma, T., Ueno, T., Sekizawa, K., Tanaka, A., & Hirata, M. (2003). Interstitial pneumonia developed in a worker dealing with particles containing indium-tin oxide. *Journal of occupational health*, *45*(3), 137-139.

Hu, L., Kim, H. S., Lee, J.-Y., Peumans, P., & Cui, Y. (2010). Scalable coating and properties of transparent, flexible, silver nanowire electrodes. *ACS nano*, *4*(5), 2955-2963.

Huseynova, G., Hyun Kim, Y., Lee, J.-H., & Lee, J. (2020). Rising advancements in the application of PEDOT: PSS as a prosperous transparent and flexible electrode material for solution-processed organic electronics. *Journal of Information Display*, *21*(2), 71-91.

ISIE, I. S. f. I. E.-. (n.d.). *What is industrial ecology?* Retrieved October 25 from https://is4ie.org/about/what-is-industrial-ecology

ISO, I. O. f. S. (2006). *Environmental management: life cycle assessment; requirements and guidelines* (Vol. 14044). ISO Geneva, Switzerland.

Kang, H. N., Lee, J.-Y., & Kim, J.-Y. (2011). Recovery of indium from etching waste by solvent extraction and electrolytic refining. *Hydrometallurgy*, *110*(1-4), 120-127.

Kawajiri, K., Tahara, K., & Uemiya, S. (2022). Lifecycle assessment of critical material substitution: Indium tin oxide and aluminum zinc oxide in transparent electrodes. *Resources, Environment and Sustainability*, *7*, 100047.

Kawamoto, H. (2012). The history of liquid-crystal display and its industry. 2012 Third IEEE HISTory of ELectro-Technology CONference (HISTELCON),

Khaligh, H. H. (2016). *Silver nanowire transparent electrodes for device applications* University of Waterloo].

Kim, K.-H., & Song, J.-K. (2009). Technical evolution of liquid crystal displays. *NPG Asia materials*, *1*(1), 29-36.

Kolias, K., Hahladakis, J. N., & Gidarakos, E. (2014). Assessment of toxic metals in waste personal computers. *Waste management*, *34*(8), 1480-1487.

Kudina, O., & Verbeek, P.-P. (2019). Ethics from within: Google Glass, the Collingridge dilemma, and the mediated value of privacy. *Science, Technology, & Human Values*, *44*(2), 291-314.

Kymakis, E., Stratakis, E., Stylianakis, M., Koudoumas, E., & Fotakis, C. (2011). Spin coated graphene films as the transparent electrode in organic photovoltaic devices. *Thin solid films*, *520*(4), 1238-1241.

Lee, S. H., Lim, S., & Kim, H. (2015). Smooth-surface silver nanowire electrode with high conductivity and transparency on functional layer coated flexible film. *Thin solid films*, *589*, 403-407.

Lehmann, S. G., Toybou, D., Pradas del Real, A.-E., Arndt, D., Tagmount, A., Viau, M., Safi, M., Pacureanu, A., Cloetens, P., & Bohic, S. (2019). Crumpling of silver nanowires by endolysosomes strongly reduces toxicity. *Proceedings of the National Academy of Sciences*, *116*(30), 14893-14898.

Li, Q., Monticelli, C., & Zanelli, A. (2022). Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. *Renewable Energy*, *195*, 906-917.

Lim, S.-R., & Schoenung, J. M. (2010). Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays. *Journal of Hazardous Materials*, *177*(1-3), 251-259.

Lippens, P., Muehlfeld, U., Chen, J., Cranton, W., & Fihn, M. (2012). Indium Tin Oxide (ITO): Sputter Deposition Processes. In.

Lison, D., Laloy, J., Corazzari, I., Muller, J., Rabolli, V., Panin, N., Huaux, F., Fenoglio, I., & Fubini, B. (2009). Sintered indium-tin-oxide (ITO) particles: a new pneumotoxic entity. *Toxicological Sciences*, *108*(2), 472-481.

Mereu, R., Marchionna, S., Donne, A. L., Ciontea, L., Binetti, S., & Acciarri, M. (2014). Optical and electrical studies of transparent conductive AZO and ITO sputtered thin films for CIGS photovoltaics. *physica status solidi (c)*, *11*(9-10), 1464-1467.

Minami, T. (2008). Substitution of transparent conducting oxide thin films for indium tin oxide transparent electrode applications. *Thin solid films*, *516*(7), 1314-1321.

Mochizuki, T., Takigami, Y., Kondo, T., & Okuzaki, H. (2018). Fabrication of flexible transparent electrodes using PEDOT: PSS and application to resistive touch screen panels. *Journal of Applied Polymer Science*, *135*(10), 45972.

Mohan, M. (2018). Perovskite Photovoltaics: Life Cycle Assessment. In *Perovskite Photovoltaics* (pp. 447-480). Elsevier.

MTI. (n.d.). *ITO Coated Glass Substrate 1" x 1" x 1.1 mm, R:8-10 ohm/sq, Nominal ITO film thickness: 180 nm*. Retrieved November 30 from https://www.mtixtl.com/ITO-252507-15C-1.aspx

Nagano, K., Nishizawa, T., Umeda, Y., Kasai, T., Noguchi, T., Gotoh, K., Ikawa, N., Eitaki, Y., Kawasumi, Y., & Yamauchi, T. (2011). Inhalation carcinogenicity and chronic toxicity of indium-tin oxide in rats and mice. *Journal of occupational health*, *53*(3), 175-187.

Nakano, M., Omae, K., Tanaka, A., Hirata, M., Michikawa, T., Kikuchi, Y., Yoshioka, N., Nishiwaki, Y., & Chonan, T. (2009). Causal relationship between indium compound inhalation and effects on the lungs. *Journal of occupational health*, *51*(6), 513-521.

Noon, M. S., Lee, S.-J., & Cooper, J. S. (2011). A life cycle assessment of end-of-life computer monitor management in the Seattle metropolitan region. *Resources, Conservation and Recycling*, *57*, 22-29.

Omae, K., Nakano, M., Tanaka, A., Hirata, M., Hamaguchi, T., & Chonan, T. (2011). Indium lung—case reports and epidemiology. *International archives of occupational and environmental health*, *84*, 471-477.

Omura, M., Tanaka, A., Hirata, M., Inoue, N., Ueno, T., Homma, T., & Sekizawa, K. (2002). Testicular toxicity evaluation of indium-tin oxide. *Journal of occupational health*, *44*(2), 105-107.

Organisation for Economic Co-operation and Development. (2020). *Moving Towards a Safe(r) Innovation Approach (SIA) for More Sustainable Nanomaterials and Nano-enabled Products, Series on the Safety of Manufactured Nanomaterials No. 96*.

Ossila. (n.d.). *ITO glass substrate (unpatterned)*. Retrieved November 30 from https://www.ossila.com/en-eu/products/ito-glass-substrates-unpatterned

Pabo, N., & Plamthottam, S. (2012). Identifying substances of concern during informal recycling of electronics.

Pakrashi, S., Dalai, S., Humayun, A., Chakravarty, S., Chandrasekaran, N., & Mukherjee, A. (2013). Ceriodaphnia dubia as a potential bio-indicator for assessing acute aluminum oxide nanoparticle toxicity in fresh water environment. *PloS one*, *8*(9), e74003.

Pang, S., Hernandez, Y., Feng, X., & Müllen, K. (2011). Graphene as transparent electrode material for organic electronics. *Advanced Materials*, *23*(25), 2779-2795.

Park, E. J., Lee, G. H., Yoon, C., Jeong, U., Kim, Y., Cho, M. H., & Kim, D. W. (2016). Biodistribution and toxicity of spherical aluminum oxide nanoparticles. *Journal of applied toxicology*, *36*(3), 424-433.

Park, H.-G., Heo, G.-S., Park, S.-G., Jeong, H.-C., Lee, J. H., & Seo, D.-S. (2015). Silver nanowire networks as transparent conducting films for liquid crystal displays. *ECS Solid State Letters*, *4*(10), R50.

Ramírez-Amador, R., Flores-Carrasco, G., Alcántara-Iniesta, S., Rodríguez González, J., García-Teniza, O., Mercado-Agular, E., & Vásquez-Ortiz, A. B. (2019). Structural, morphological, optical, and electrical characterization of fluorine doped tin oxide (FTO) thin films synthesized by PSP. *Solid State Phenomena*, *286*, 64-71.

Rao, H. K. R., Gemechu, E., Thakur, U., Shankar, K., & Kumar, A. (2021). Life cycle assessment of high-performance monocrystalline titanium dioxide nanorod-based perovskite solar cells. *Solar Energy Materials and Solar Cells*, *230*, 111288.

Ratte, H. T. (1999). Bioaccumulation and toxicity of silver compounds: a review. *Environmental toxicology and chemistry: an international journal*, *18*(1), 89-108.

Rebels, N. (n.d.). *How Do You Find Out The Dimensions Of Your Laptop?* Retrieved November 30 from https://www.new-rebels.com/en/service/dimensions-laptop-laptopbag/

RIVM. (2023a). *Lijst van Potentieel Zeer Zorgwekkende Stoffen*. Retrieved November 1 from https://rvszoeksysteem.rivm.nl/ZZSlijst/PotentieleZZSlijst

RIVM. (2023b). *Totale lijst van Zeer Zorgwekkende Stoffen*. Retrieved November 3 from https://rvszoeksysteem.rivm.nl/ZZSlijst/TotaleLijst

RIVM. (n.d.-a). *Indentificatie Zeer Zorgwekkende Stoffen*. Retrieved October 25 from https://rvs.rivm.nl/onderwerpen/Zeer-Zorgwekkende-Stoffen/Identificatie-Zeer-Zorgwekkende-Stoffen

RIVM. (n.d.-b). *Potentiële ZZS*. Retrieved October 25 from https://rvs.rivm.nl/onderwerpen/Zeer-Zorgwekkende-Stoffen/Potentiele-ZZS

Rizki, A. M., Yunita, F. E., Lalasari, L. H., Irawan, J., Arini, T., Firdiyono, F., Andriyah, L., Natasha, N. C., & Yuwono, A. H. (2022). MORPHOLOGY AND RESISTIVITY VALUE OF FLOURINE-DOPED TIN OXIDE (FTO) USING INDONESIAN LOCAL DIMETHYLTIN DICHLORIIDE (DTMC) PRECURSORS. *Metalurgi*, *37*(3).

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., & Schellnhuber, H. J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society*, *14*(2).

Sadiq, I. M., Pakrashi, S., Chandrasekaran, N., & Mukherjee, A. (2011). Studies on toxicity of aluminum oxide (Al 2 O 3) nanoparticles to microalgae species: Scenedesmus sp. and Chlorella sp. *Journal of nanoparticle research*, *13*, 3287-3299.

Safe-by-Design. (n.d.). *Circular Economy*. Retrieved May 16 from https://www.safe-by-design-nl.nl/home+english/circular+economy/default.aspx

Salieri, B., Barruetabeña, L., Rodríguez-Llopis, I., Jacobsen, N. R., Manier, N., Trouiller, B., Chapon, V., Hadrup, N., Jiménez, A. S., & Micheletti, C. (2021). Integrative approach in a safe by design context combining risk, life cycle and socio-economic assessment for safer and sustainable nanomaterials. *NanoImpact*, *23*, 100335.

Sandana, V., Rogers, D., Teherani, F. H., Bove, P., & Razeghi, M. (2013). Graphene versus oxides for transparent electrode applications. Oxide-based Materials and Devices IV,

Sarialtin, H., Geyer, R., & Zafer, C. (2020). Life cycle assessment of hole transport free planar–mesoscopic perovskite solar cells. *Journal of Renewable and Sustainable Energy*, *12*(2).

Savva, A., Georgiou, E., Papazoglou, G., Chrusou, A. Z., Kapnisis, K., & Choulis, S. A. (2015). Photovoltaic analysis of the effects of PEDOT: PSS-additives hole selective contacts on the efficiency and lifetime performance of inverted organic solar cells. *Solar Energy Materials and Solar Cells*, *132*, 507-514.

Savvilotidou, V., Hahladakis, J. N., & Gidarakos, E. (2014). Determination of toxic metals in discarded Liquid Crystal Displays (LCDs). *Resources, Conservation and Recycling*, *92*, 108-115.

Schwarz-Schampera, U. (2014). Indium. *Critical metals handbook*, 204-229.

Shain, F. L., Mani, A. M., Li, L. M., Salleh, S., & Alias, A. (2014). Temperature dependence of Ga: ZnO film deposited by RF magnetron sputtering. 2014 IEEE International Conference on Semiconductor Electronics (ICSE2014),

Sheasby, P. G., Pinner, R., & Wernick, S. (2001). *The surface treatment and finishing of aluminium and its alloys* (Vol. 1). ASM international Materials Park, OH.

Socolof, M. L., Overly, J. G., & Geibig, J. R. (2005). Environmental life-cycle impacts of CRT and LCD desktop computer displays. *Journal of Cleaner Production*, *13*(13-14), 1281-1294.

Sohn, H., Park, C., Oh, J.-M., Kang, S. W., & Kim, M.-J. (2019). Silver nanowire networks: Mechano-electric properties and applications. *Materials*, *12*(16), 2526.

Soleimani, Z., Zoras, S., Ceranic, B., Shahzad, S., & Cui, Y. (2021). The cradle to gate life-cycle assessment of thermoelectric materials: A comparison of inorganic, organic and hybrid types. *Sustainable Energy Technologies and Assessments*, *44*, 101073.

Song, Q., Wang, Z., Li, J., & Yuan, W. (2013). Life cycle assessment of desktop PCs in Macau. *The international journal of life cycle assessment*, *18*, 553-566.

Song, T.-B., Rim, Y. S., Liu, F., Bob, B., Ye, S., Hsieh, Y.-T., & Yang, Y. (2015). Highly robust silver nanowire network for transparent electrode. *ACS applied materials & interfaces*, *7*(44), 24601-24607.

Souada, M., Louage, C., Doisy, J.-Y., Meunier, L., Benderrag, A., Ouddane, B., Bellayer, S., Nuns, N., Traisnel, M., & Maschke, U. (2018). Extraction of indium-tin oxide from end-of-life LCD panels using ultrasound assisted acid leaching. *Ultrasonics sonochemistry*, *40*, 929-936.

Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser—An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*, 100012.

Sun, B., Hu, Y., Cheng, H., & Tao, S. (2016). Kinetics of brominated flame retardant (BFR) releases from granules of waste plastics. *Environmental Science & Technology*, *50*(24), 13419-13427.

Sun, K., Li, P., Xia, Y., Chang, J., & Ouyang, J. (2015). Transparent conductive oxide-free perovskite solar cells with PEDOT: PSS as transparent electrode. *ACS applied materials & interfaces*, *7*(28), 15314-15320.

Swain, B., Mishra, C., Hong, H. S., Cho, S.-S., & kyu Lee, S. (2015). Commercial process for the recovery of metals from ITO etching industry wastewater by liquid–liquid extraction: simulation, analysis of mechanism, and mathematical model to predict optimum operational conditions. *Green Chemistry*, *17*(7), 3979-3991.

Tan, D., Jiang, C., Li, Q., Bi, S., & Song, J. (2020). Silver nanowire networks with preparations and applications: a review. *Journal of Materials Science: Materials in Electronics*, *31*, 15669-15696.

Tanaka, A., Hirata, M., Omura, M., Inoue, N., Ueno, T., Homma, T., & Sekizawa, K. (2002). Pulmonary toxicity of indium-tin oxide and indium phosphide after intratracheal instillations into the lung of hamsters. *Journal of occupational health*, *44*(2), 99-102.

Thomas, N. J., Chang, N.-B., & Qi, C. (2012). Preliminary assessment for global warming potential of leading contributory gases from a 40-in. LCD flat-screen television. *The international journal of life cycle assessment*, *17*, 96-104.

toolbox, T. e. (2003). *Gases - Densities*. Retrieved November 30 from https://www.engineeringtoolbox.com/gas-density-d_158.html

Tran, Q.-P., Fang, J.-S., & Chin, T.-S. (2015). Properties of fluorine-doped SnO2 thin films by a green sol–gel method. *Materials Science in Semiconductor Processing*, *40*, 664-669.

Txintxurreta, J., G-Berasategui, E., Ortiz, R., Hernandez, O., Mendizábal, L., & Barriga, J. (2021). Indium tin oxide thin film deposition by magnetron sputtering at room temperature for the manufacturing of efficient transparent heaters. *Coatings*, *11*(1), 92.

Tyagi, A., & Chatterjee, D. S. (2013). Liquid crystal display: environment & technology. *International Journal of Environmental Engineering Science and Technology Research*, *1*(7), 110-123.

uitrekenen, O. (n.d.). *Soortelijk gewicht glas (dichtheid)? Gewicht glas berekenen!* Retrieved November 30 from https://onlineuitrekenen.nl/soortelijk-gewicht-glas/

Van De Groep, J., Spinelli, P., & Polman, A. (2012). Transparent conducting silver nanowire networks. *Nano letters*, *12*(6), 3138-3144.

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, *259*, 120904.

van Leeuwen, C. J., & Vermeire, T. G. (2007). *Risk assessment of chemicals: an introduction* (Vol. 94). Springer.

Varanytsia, A., Weng, L., Lin, T.-C., Yang, J., & Chien, L.-C. (2016). High-performance and low-cost aluminum zinc oxide and gallium zinc oxide electrodes for liquid crystal displays. *Journal of Display Technology*, *12*(10), 1033-1039.

Vosgueritchian, M., Lipomi, D. J., & Bao, Z. (2012). Highly conductive and transparent PEDOT: PSS films with a fluorosurfactant for stretchable and flexible transparent electrodes. *Advanced Functional Materials*, *22*(2), 421-428.

Wang, K., Jin, Y., & Xiao, F. (2021). Long-term electrically stable silver nanowire composite transparent electrode under high current density. *Journal of Materials Science: Materials in Electronics*, *32*, 20919-20935.

Wang, S., He, Y., Yang, J., & Feng, Y. (2018). Enrichment of indium tin oxide from colour filter glass in waste liquid crystal display panels through flotation. *Journal of Cleaner Production*, *189*, 464-471.

Wang, T., Lu, K., Xu, Z., Lin, Z., Ning, H., Qiu, T., Yang, Z., Zheng, H., Yao, R., & Peng, J. (2021). Recent developments in flexible transparent electrode. *Crystals*, *11*(5), 511.

Way, A., Luke, J., Evans, A. D., Li, Z., Kim, J.-S., Durrant, J. R., Hin Lee, H. K., & Tsoi, W. C. (2019). Fluorine doped tin oxide as an alternative of indium tin oxide for bottom electrode of semi-transparent organic photovoltaic devices. *AIP Advances*, *9*(8).

White, S. J. O., & Hemond, H. F. (2012). The anthrobiogeochemical cycle of indium: a review of the natural and anthropogenic cycling of indium in the environment. *Critical reviews in environmental science and technology*, *42*(2), 155-186.

Wolff, R., Henderson, R., Eidson, A., Pickrell, J., Rothenberg, S., & Hahn, F. (1988). Toxicity of gallium oxide particles following a 4-week inhalation exposure. *Journal of applied toxicology*, *8*(3), 191-199.

Wu, J.-M., Lv, Y.-P., Wu, H., Zhang, H.-S., Wang, F., Zhang, J., Wang, J.-Z., & Xu, X.-H. (2022). Stable GeSe thin-film solar cells employing non-toxic SnO2 as buffer layer. *Rare Metals*, *41*(9), 2992-2997.

Xu, Y., & Liu, J. (2016). Graphene as transparent electrodes: fabrication and new emerging applications. *Small*, *12*(11), 1400-1419.

Yamada, T., Ikeda, K., Kishimoto, S., Makino, H., & Yamamoto, T. (2006). Effects of oxygen partial pressure on doping properties of Ga-doped ZnO films prepared by ion-plating with traveling substrate. *Surface and Coatings Technology*, *201*(7), 4004-4007.

Yamamoto, N., Makino, H., Osone, S., Ujihara, A., Ito, T., Hokari, H., Maruyama, T., & Yamamoto, T. (2012). Development of Ga-doped ZnO transparent electrodes for liquid crystal display panels. *Thin solid films*, *520*(12), 4131-4138.

Yamamoto, N., Makino, H., & Yamamoto, T. (2011). *Transparent ZnO Electrode for Liquid Crystal Displays*. INTECH Open Access Publisher.

Yang, J., Retegan, T., & Ekberg, C. (2013). Indium recovery from discarded LCD panel glass by solvent extraction. *Hydrometallurgy*, *137*, 68-77.

Yeom, J.-M., Jung, H.-J., Choi, S.-Y., Lee, D. S., & Lim, S.-R. (2018). Environmental effects of the technology transition from liquid–crystal display (LCD) to organic light-emitting diode (OLED) display from an E-waste management perspective. *International Journal of Environmental Research*, *12*, 479-488.

Yoshida, H., Izhar, S., Nishio, E., Utsumi, Y., Kakimori, N., & Asghari, F. S. (2015). Recovery of indium from TFT and CF glasses of LCD wastes using NaOH-enhanced sub-critical water. *The Journal of Supercritical Fluids*, *104*, 40-48.

Yousef, M., Al-Hamadani, M., & Kamel, M. (2019). Reproductive toxicity of aluminum oxide nanoparticles and zinc oxide nanoparticles in male rats. *Nanoparticle*, *1*(1), 3.

Yu, L., Moriguchi, Y., Nakatani, J., Zhang, Q., Li, F., He, W., & Li, G. (2019). Environmental impact assessment on the recycling of waste LCD panels. *ACS Sustainable Chemistry & Engineering*, *7*(6), 6360-6368.

Zaitseva, N., Zemlyanova, A. A., Stepankov, M., & Ignatova, A. (2018). Scientific forecasting of toxicity and evaluation of hazard potential of aluminum oxide nanoparticles for human health. *Ekologiya cheloveka (Human Ecology)*, *25*(5), 9-15.

Zhang, R., & Engholm, M. (2018). Recent progress on the fabrication and properties of silver nanowire-based transparent electrodes. *Nanomaterials*, *8*(8), 628.

Zhu, Y., Sun, Z., Yan, Z., Jin, Z., & Tour, J. M. (2011). Rational design of hybrid graphene films for high-performance transparent electrodes. *ACS nano*, *5*(8), 6472-6479.

Appendices

Appendix A. Inventory data Kawajiri et al. (2022)

Table 8. Inventory Data of ITO Life Cycle Assessment

		Name	Unit	32 in LCD equivalent	GHG kg-CO2eq
Raw Material	Input	Metal indium	kg	0.00291	0.10867
		Hydrochloric acid	kg	0.00643	0.02102
		Sodium hydroxide	kg	0.00707	0.00949
		Electoric power	kWh	0.00079	0.00048
	Output	Indium Oxide	kg	0.00804	
	Input	Cassiterite	kg	0.00328	0.00238
		Nitric acid	kg	0.00230	0.00378
		Ammonium hydroxide	kg	0.00099	0.00103
		Electoric power	kg	0.00220	0.00133
	Output	Stannous oxide	kg	0.00086	
Target Production	Input	Indium Oxide powder	kg	0.00804	
		Stannous oxide powder	kg	0.00086	
		Bonding material	kg	0.00000	
		Electoric power	kWh	0.05530	0.03351
	Output	ITO target material	kg	0.00864	
TE Production	Input	ITO target material	kg	0.00864	
		Oxygen	m^3	0.00060	0.00015
		Argon	m^3	0.03888	0.00948
		Electoric power	kWh	67.99680	41.20831
	Output	Tranceparent electrode	kg	0.00173	
		Used ITO	kg	0.00518	
		ITO loss	kg	0.00173	
Recycle from Target Material	Input	Used target	kg	0.00518	
		Hydrochloric acid	kg	0.00368	0.01203
		Sodium hydroxide	kg	0.00399	0.00536
		Electoric power	kWh	0.22291	0.13509
	Output	Metal indium	kg	0.00384	
Use	Output	Electoric power	kWh	1279.09091	775.17142

Table 9. Inventory Data of AZO Life Cycle Assessment

		Name	Unit	32 in LCD equivalent	GHG kg-CO2eq
Raw Material Production	Input	Metal zinc	kg	0.000617782	
		Electric power	kWh	5.33898E-05	
	Output	Zinc oxide	kg	0.002786988	0.0006
	Output	Aluminum oxide	kg	0.00031	0.00058
Target Material Production	Input	Zinc Oxide powder	kg	0.00279	
		Alumium oxide	kg	0.00031	
			kg		
		Electric power	kWh	0.06370	0.03860
	Output	AZO target material	kg	0.00310	
TE Production	Input	AZO target material	kg	0.00310	
		Oxygen	m^3	0.00065	0.00016
		Argon	m^3	0.04151	0.01012
		Electric power	kWh	72.60068	43.99842
	Output	Transparent electrode	kg	0.00062	
		Used AZO	kg	0.00186	
		AZO loss	kg	0.00062	
Recycle from Target Material	Input	Used Target	kg	0.00186	
		Hydrochloric acid	kg	0.00132	0.00431
		Sodium hydroxide	kg	0.00143	0.00192
		Electric power	kWh	0.07989	0.04842
	Output	Metal zinc	kg	0.00137	
Use	Output	Electric power	kWh	1227.92727	744.16457

Appendix B. Data assumptions and calculations

C.1. Assumptions

The main assumptions done for both systems are discussed in the main text. In this appendix the rest of the assumptions are discussed.

The selection of sputtering as the fabrication technique for ITO and ZnO:Al film in this product system is based on several factors. Firstly, it is based on the availability of inventory data, as the sole data found is sourced from Kawajiri et al. (2022), which exclusively employs sputtering. Secondly, according to Her and Chang (2017) is sputtering the most commonly used production technique of ITO film. Moreover, the processes sourced from ecoinvent also utilise sputtering.

In the modelling program OpenLCA there is no function to add a cut-off flow to a process and then to not include the flow in the calculations. For this reason, is chosen to not add the cut-off flows to the model. The cut-off flows are mentioned in the unit process in Appendix D.

Oxygen and argon gas that are used during the deposition of ITO and ZnO:Al are not available in ecoinvent as a good, only as an environmental flow. Liquid oxygen and argon do exist as a good in ecoinvent. Thus, the conversion of liquid to gas is modelled for both compounds in both product systems.

The inventory data indicates that sodium hydroxide is used in both product systems during the recycling of target material. However, the form of sodium hydroxide used (e.g., solution or solid) is not specified. It is assumed that the sodium hydroxide in ecoinvent is the same as that used in the recycling of target material in both product systems.

Cassiterite is mentioned as input for the production of tin oxide in the inventory data. However, cassiterite is not found as flow in ecoinvent. Though, tin concentrate is available in ecoinvent. Thus, tin concentrate is used as cassiterite in the model.

C.2. Calculations

Glass substrate

Both targets are sputter on glass substrate in an LCD monitor. However, the inventory data of Kawajiri et al. (2022) does not mention the substrate. Thus, the amount of glass substrate needs to be calculated and added to the model.

It is assumed that the thickness of the glass substrate is 1,1 mm (MTI, n.d.; Ossila, n.d.). The thickness of ITO is around 150nm, thus that is negligible in this calculation. Furthermore, is assumed that a 17” screen is 40 x 29 cm (Rebels, n.d.). Lastly, it is assumed that the density of glass is 2,5 kg/mm/m^2 (uitrekenen, n.d.). The amount of glass is calculated with the following calculation:

<u>Amount of glass</u> = (0,4 x 0,29) x 1,1 x 2,5 = 0,32 kg

As mentioned in section XX, there is a glass substrate present at both sides of the LCD. Thus, the above calculated amount of glass is multiplied by two:

Amount of glass in LCD = 0,32 x 2 = 0,64 kg

Oxygen and argon
Both oxygen and argon gas are used in the deposition of the film. However, in ecoinvent there is only an economic flow for liquid oxygen and argon. Thus, a process needs to be modelled to convert liquid oxygen to gas oxygen, similar for argon. The conversion from liquid to gas is calculated with the density of the substances. The density of oxygen is 1,43 kg/m^3 and of argon is 1,79 kg/m^3 (toolbox, 2003).

Amount of liquid oxygen ITO = 1,43 x 0,00032 = 0,00046 kg
Amount of liquid argon ITO = 1,79 x 0,02066 = 0,03697 kg

Amount of liquid oxygen ZnO:Al = 1,43 x 0,00035 = 0,00049 kg
Amount of liquid argon ZnO:Al = 1,79 x 0,02205 = 0,03947 kg

Appendix C. keywords and search combinations literature review

External excel file

Appendix D. Unit processes

External excel file

Appendix E. OpenLCA file

External OpenLCA file

Appendix F. Impact assessment

External excel file

Appendix G. Contribution analyses

External excel file