Sustainability assessment of sensor materials in applications

Ange Wang

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LUND UNIVERSITY

Supervisor: Christina Windmark, Senior Lecturer.

Examiner: Filip Lenrick, Associate Professor.

Author: Ange Wang
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Avdelningen för Industriell Produktion
Lunds Tekniska Högskola
Lunds universitet
Box 118
221 00 Lund
Sverige

Division of Production and Materials Engineering
LTH, Faculty of Engineering
Lund University
Box 118
SE-221 00 Lund
Sweden

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Lund University

Foreword

In the spring of 2026, I completed this master's thesis in the Division of Production and Materials Engineering, LTH, Faculty of Engineering, Lund University. This thesis represents the final part of my master's studies in production and materials engineering, and it is also an opportunity for me to think more deeply about an issue that has not been fully considered at the beginning of the project.

The work gradually developed around a broader reflection on the role of sensor technologies in manufacturing. In this process, indium-based materials, especially indium oxide and indium tin oxide, became the main focus of this thesis because of their important role in the field of sensors. These materials are of great value in terms of their technical properties and relevance in thin-film sensor applications. At the same time, they are also related to a number of practical and environmental issues, including material supply, processing routes, product integration and the handling of the end-of-life phase. The relationship between material properties and sustainability is not always straightforward, and this tension has become one of the core motivations of this study.

I would like to express my sincere thanks to my supervisor Christina Windmark for her guidance, patience and inspiring feedback throughout the thesis process. Our discussion helped me further clarify the direction of the research and gave me a clearer understanding of how to link the performance of technical materials with broader sustainability considerations. I would also like to thank Professor Ivan Maximov and Shohreh Ebrahim for their participation in a wider range of projects and valuable comments in our meeting discussions. Their perspectives helped me better understand the technical background of sensor materials and the broader research context in which this work is situated.

Finally, I would like to thank the Department of Production and Materials Engineering for providing a good academic environment for the development of this thesis. I also thank my classmates and friends for their encouragement, communication and support along the way. Most importantly, I would like to thank my family for their support, understanding and patience throughout my study and the process of writing my thesis.

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Ange Wang

Abstract

Sensing technologies offer several advantages for industrial tooling. In mechanical processing and manufacturing environments, sensors can be used to monitor process conditions, support predictive maintenance, reduce unnecessary material losses, and improve overall production efficiency. Therefore, as manufacturing systems become more advanced and data-driven, the integration of sensors has become more and more common.

At the same time, the benefits of sensor integration should not be evaluated only from the perspective of performance at the stage of use. Sensors cannot function independently; they usually rely on additional functional materials to achieve their sensing capabilities. If this material dimension is ignored, some important sustainability issues may be overlooked. This is especially relevant for indium-based materials. Indium is mainly obtained as a by-product of zinc production, which means that its availability is closely related to the broader metal production system, not just direct mining. In addition, indium also involves problems such as supply chain concentration, relatively complex processing routes, and uncertainty in post-use recycling.

Against this background, this thesis examines indium-based thin-film sensing materials from the perspective of sustainability. The research focuses on indium oxide (In_2O_3) and indium tin oxide (ITO), paying special attention to their role in the sensor-integrated manufacturing applications. This study did not carry out a complete quantitative life cycle assessment (LCA), but adopted a life cycle-oriented exploratory method. This enables research to discuss major sustainability issues at different stages of the material life cycle, rather than reducing the analysis to numerical indicators alone.

This analysis also considers the upstream and downstream links of the material system. The research content includes raw material acquisition, supply chain risks, processing challenges, relevance of the use stage, material stewardship, concerns related to toxicity, and the possibility of recycling at the end of life. The manufacturing stage is also included in the discussion, but mainly as a technical background. The role of this part in this thesis is to help explain why these materials are related to sensor applications and why they need to be carefully considered in sustainability assessment.

The results indicate that the sustainability significance of In_2O_3- and ITO-based sensor materials cannot be evaluated solely on the basis of their small mass contribution to the final product. A broader material-system perspective is required, since these materials are embedded in supply and processing structures that may generate sustainability concerns beyond the sensor layer itself. The main hotspots identified in this study include the by-product dependence of indium supply, geographic concentration of refining capacity, limited transparency in processing routes, reliance on manufacturing scrap rather than mature end-of-life recycling systems, and the technical difficulty of recovering thin and spatially dispersed sensor layers from engineering products. At the same time, the use of indium-based sensor materials may be justifiable in applications where sensor integration can produce measurable reductions in scrap, rework, downtime, premature tool failure, or unnecessary energy consumption.

The thesis concludes that indium-based sensor materials should not be classified as inherently sustainable or unsustainable. Their sustainability performance depends on the balance between upstream and downstream burdens and the functional benefits achieved during the use phase. The study provides an initial analytical framework for assessing emerging sensor materials in sensor-integrated manufacturing systems and identifies key knowledge gaps that should be addressed in future application-specific life cycle assessment studies.

Keywords: Sustainability assessment; sensor materials; indium oxide; indium tin oxide; life-cycle-oriented assessment; sensor-integrated manufacturing.

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1. Introduction

1.1. Research background

The integration of sensing technologies into industrial manufacturing systems has become increasingly important in the development of advanced and data-driven production environments. By embedding sensors into tools, components, or manufacturing equipment, it becomes possible to monitor process-related conditions such as temperature, vibration, strain, wear, and other operational variables more directly during use. Such sensing functions can support improved process monitoring, more responsive process control, predictive maintenance, and more efficient use of tools and materials. For this reason, sensor-integrated manufacturing systems are increasingly considered relevant for improving productivity and resource efficiency in industrial applications [1], [2].

The realization of these sensing functions, however, depends on the introduction of additional functional materials into engineering products. In thin-film sensing systems, indium-based materials such as indium oxide (In_2O_3) and indium tin oxide (ITO) are of particular interest because of their electrical functionality, compatibility with thin-film fabrication processes, and potential stability under demanding operating conditions. These materials have been widely studied in thin-film devices and sensor-related applications, including high-temperature sensing systems and thermocouple-type structures [3], [4]. Their relevance therefore extends beyond their technical sensing function, since they also represent a distinct material system introduced into products that may otherwise be dominated by conventional bulk engineering materials.

From a sustainability perspective, this material-system dimension is significant. Although In_2O_3 and ITO are typically used in very small quantities as thin functional layers, their relevance cannot be assessed only on the basis of mass contribution in the final product. Indium is mainly recovered as a by-product of zinc-related production, and its availability is shaped by host-metal production, refining capacity, recovery efficiency, supply-chain concentration, and end-of-life recovery limitations [5], [6], [18]. Consequently, indium-based sensor materials provide a useful case for examining how functional materials used in emerging sensing applications are connected to broader upstream and downstream sustainability concerns.

1.2. Research problem

Despite the increasing attention given to sensor-integrated manufacturing systems, the sustainability implications of the sensor materials themselves remain insufficiently examined. Existing studies on sensing technologies often focus on technical performance, including sensitivity, signal stability, thermal response, durability, and suitability for process monitoring. By contrast, less attention has been paid to the material-related implications associated with the upstream sourcing, processing, integration, use, and end-of-life treatment of the functional materials that enable these sensing functions. As a result, sensor integration may be evaluated mainly through its operational advantages, while the broader life-cycle relevance of the sensor materials remains only partially understood.

This problem is particularly relevant for indium-based sensor materials such as indium oxide (In_2O_3) and indium tin oxide (ITO). Although these materials are generally applied as very thin functional layers, their sustainability relevance cannot be judged only by reference to the small quantity present in the final sensor-integrated product. Indium is mainly obtained as a by-product of zinc mining and refining, which means that its availability is influenced not only by demand for indium-containing technologies, but also by the production dynamics, recovery efficiency, residue treatment, and processing infrastructure of the host-metal system [5], [6], [18]. Consequently, even limited use of indium in thin-film sensor applications may be connected to broader concerns related to material provenance, supply dependence, processing complexity, and restricted end-of-life recoverability.

The sustainability relevance of indium-based sensor materials is therefore not limited to the final sensor layer or to the small amount of material used in the finished product. Instead, it needs to be considered in relation to the broader material system through which the material is sourced, processed, refined, integrated into products, used, and eventually treated at end of life. This is especially important for functional materials based on critical, scarce, or by-product metals, because environmental and social concerns may arise before the material reaches its final application.

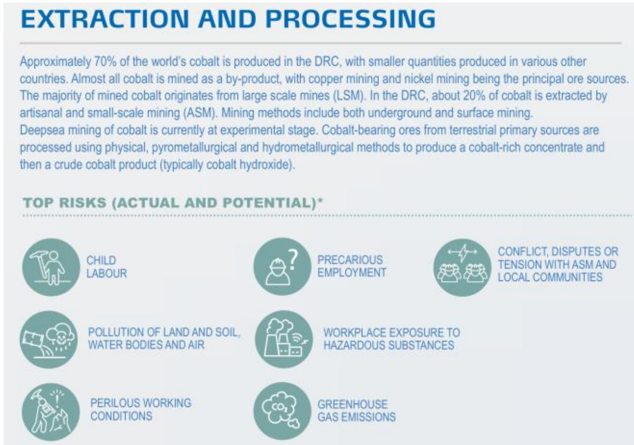

Figure 1. *Extraction and processing stage and selected sustainability risks in a critical metal value chain, adapted from the Cobalt Institute [27].*

Although Figure 1 refers to cobalt, it is used here only as a conceptual illustration of upstream risk categories in critical-metal value chains. This perspective is relevant because indium is also embedded in zinc-related metallurgical systems as a by-product metal.

A further challenge is that application-specific environmental impact data for In_2O_3- and ITO-based thin-film sensor materials remain limited. Detailed information on fabrication processes, material losses, deposition efficiency, use-phase performance improvements, and realistic end-of-life recovery routes is often incomplete or uncertain. This makes it difficult to conduct a robust full quantitative life cycle assessment for these materials in sensor-integrated manufacturing applications at the present stage. The lack of such data should not be treated only as a practical limitation, but also as part of the sustainability assessment problem itself, since emerging sensor materials may be introduced into advanced manufacturing systems before their broader material-system implications are fully understood.

The central research problem of this thesis is therefore how to assess the sustainability relevance of indium-based thin-film sensor materials from a life-cycle-oriented perspective, with particular attention to their upstream and downstream implications. The thesis focuses on identifying key sustainability hotspots related to raw material sourcing, by-product supply, refining concentration, processing complexity, use-phase relevance, stewardship, toxicity-related issues, and end-of-life recovery. Based on these findings, the thesis further discusses how the identified material-system burdens may be interpreted in relation to the potential functional benefits of sensor integration, such as improved process monitoring, reduced scrap, lower rework, longer tool life, and more efficient use of tools and materials.

1.3. Aim and research questions

This thesis studies indium-based thin-film sensor materials used in sensor-integrated manufacturing applications. The discussion mainly focuses on two materials: indium oxide (In_2O_3) and indium tin oxide (ITO). These materials are valuable in thin-film sensor systems because of their functional properties.. However, their technical practicality is only one aspect of the problem. Because these materials are closely related to the supply of indium, processing routes, product integration, and treatment at the end of life, they also raise broader sustainability issues.

Therefore, the aim of this thesis is to examine these materials from a life-cycle-oriented perspective. The study does not only focus on their performance at the stage of use, but also examines how sustainability concerns arise at different stages of the material life cycle. In the upstream, the thesis focuses on the raw material sourcing and data limitations, by-product supply, refining concentration, processing complexity and available data. Downstream, the discussion turns to the relevance of the use stage, material stewardship, toxicity-related concerns, and the possibilities and challenges of end-of-life recovery.

This thesis does not carry out a complete quantitative life cycle assessment. The reason is that detailed and application-specific environmental data for sensor systems based on In_2O_3 and ITO are still limited. Therefore, this thesis adopts an exploratory method to identify major sustainability hotspots, uncertainties and knowledge gaps. At the same time, the thesis also discusses how to understand the possible benefits of sensor integration in combination with these hotspots.

The thesis addresses the following research questions:

RQ1: How are indium-based sensor materials positioned within the upstream value chain, and what sustainability concerns arise from the by-product nature, supply concentration, and processing complexity of indium?

RQ2: What downstream sustainability considerations are relevant when In_2O_3- and ITO-based thin-film sensor materials are integrated into engineering products, particularly in relation to use-phase relevance, stewardship, toxicity-related aspects, and end-of-life recovery?

RQ3: Given the limited availability of application-specific environmental impact data, how can the identified upstream and downstream sustainability hotspots be interpreted in relation to the potential functional benefits of sensor integration?

These research questions guide the structure of the thesis. They do not intend to produce a complete quantified environmental profile of indium-based sensor materials. Instead, they help build a clearer understanding of the main upstream and downstream issues that future sustainability assessments should consider.

1.4. Scope and limitations

The scope of this thesis is limited to indium-based thin-film sensor materials, with particular attention given to In_2O_3 and ITO in sensor-integrated manufacturing and tooling-related applications. Although the study adopts a life-cycle-oriented perspective, it does not attempt to examine every life-cycle stage with the same level of detail. Instead, the discussion is directed toward the stages that are most relevant for understanding the sustainability implications of these materials. These include raw material sourcing, upstream processing, the context of thin-film fabrication, product integration, use-phase relevance, and end-of-life treatment.

This thesis also does not aim to calculate the complete environmental footprint of a specific sensor-integrated product. Nor does it perform a full quantitative Life Cycle Assessment in accordance with ISO 14040 and ISO 14044. One reason for this limitation is the lack of sufficiently detailed inventory data, particularly for sensor fabrication processes, measured benefits during the use phase, and realistic recovery routes at end of life. In the case of indium-based materials, the outcome of an assessment may also change depending on how system boundaries are drawn, how allocation is handled, the quality of the available data, and what assumptions are made about recovery and recycling [7].

The fabrication stage is included mainly to provide technical background. Deposition routes, material properties, and processing conditions are discussed because they affect the function and sustainability relevance of In_2O_3 and ITO thin films. However, the thesis does not develop a complete process inventory for deposition, post-treatment, transport, or industrial-scale sensor manufacturing.

The use phase is also discussed at a conceptual level. Sensor integration may improve process control, reduce defective production, extend tool life, lower downtime, and support more efficient use of resources. These possible benefits are not measured in a specific industrial case. For this reason, the use-phase discussion should be understood as an exploratory interpretation rather than verified quantitative performance data.

End-of-life treatment represents another important boundary of the present study. Although indium can be recovered from certain manufacturing scrap and some ITO-related waste streams, its recovery from very thin and dispersed sensor layers in engineering products is still far less certain. In these applications, the material is often present in small quantities and may be closely integrated with other product components. This makes it difficult to separate and recycle in practice. Existing evidence also shows that the recycling path of indium-containing film applications may be technically demanding and economically challenging, especially when the amount of recycling is limited and difficult to separate from the surrounding product system [8], [18].

Therefore, this thesis should be understood as a preliminary analytical framework, not a complete quantitative sustainability evaluation. The limited access to application-specific environmental data is not only a methodological limitation, but also an important discovery of this study itself. It shows that future research requires more detailed fabrication inventories, actual measurement data on the benefits of the use stage, and more realistic end-of-life scenarios for integrated sensor manufacturing tools.

1.5. Methodological approach

This thesis adopts a life-cycle-oriented exploratory assessment method. Since the available data are not sufficient to support a complete quantitative Life Cycle Assessment, this method is applicable to this study. The purpose of the research is not to calculate the final environmental impact, but to identify and explain the main sustainability hotspots, uncertainties and knowledge gaps related to indium-based thin-film sensor materials.

This assessment is first based on the materials and application background of In_2O_3 and ITO. This provides a basis for understanding why these materials are relevant in thin-film sensor applications and why their technical functions need to be considered in sustainability discussions. They play a very important role in sensing performance, but they are also closely related to the material source, processing requirements and subsequent management problems in the product.

Subsequently, the thesis examines the upstream characteristics of indium-based sensing materials. This part discusses the supply of by-products, material sources, refining concentration, processing complexity, residue processing, secondary supply and available data limitations. By analyzing these aspects, this study shows how these materials are associated with a wider range of supply and processing systems before being integrated into sensor applications.

The analysis also further shifted to downstream issues, and its focus shifted from material production to product use and follow-up processing. In this part, the discussion includes sensor integration, the relevance of the use stage, material stewardship, concerns related to toxicity, and recycling at the end of life. These aspects are very important, because once the indium-based film enters the engineering product, it is no longer an isolated material. They will become part of a larger technology system, which may make it more difficult to assess their benefits and recycling.

Finally, the upstream and downstream findings are brought together in the discussion. The identified hotspots are interpreted as the possible benefits of sensor integration, such as improved monitoring, reduced waste, and more efficient manufacturing. In this way, the thesis develops a structured qualitative assessment that can serve as a starting point for future application-specific LCA studies.

1.6. Thesis structure

This thesis is organised into six chapters. Chapter 1 sets out the overall foundation of the study. It introduces the research background and the problem addressed in the thesis, followed by the aim, research questions, scope and limitations, and methodological approach.

Chapter 2 provides the material and application background for indium-based thin-film sensor materials, with particular attention to In_2O_3 and ITO. The chapter explains their main functional properties, the fabrication context in which they are used, and why these materials are relevant when sustainability is considered alongside technical performance.

The upstream sustainability aspects of indium-based sensor materials are examined in Chapter 3. This includes issues such as by-product supply, material origin, refining concentration, geopolitical vulnerability, processing complexity, residue handling, and limitations in available data. The chapter mainly contributes to answering RQ1.

Chapter 4 then focuses on downstream sustainability issues related to the integration of sensors into engineering products. This chapter discusses the relevance of the use stage, material stewardship, concerns related to toxicity, the treatment of the end-of-life stage, and the impact of recycling. Therefore, this chapter mainly supports RQ2.

Chapter 5 combines upstream and downstream research findings. This chapter does not make a full quantitative comparison between environmental burden and functional benefits, but discusses the main sustainability hotspots, uncertainties and trade-offs identified in this study. This chapter also examines how these problems should be understood in combination with the potential benefits of sensor integration, and mainly responds to RQ3.

Finally, Chapter 6 presents the main conclusion of this thesis. This chapter answers three research questions, summarizes the contributions of this study, and reflects on the main limitations. At the same time, this chapter also puts forward the future research direction, especially those aspects that require more detailed data or specific application evaluation.

2. Material Background

2.1. Indium-based sensor materials

Indium-based oxide materials are relevant in thin-film technologies because they combine electrical functionality, chemical stability, and compatibility with established deposition processes. Among them, indium oxide (In_2O_3) and indium tin oxide (ITO) are particularly important for this study. In_2O_3 is an n-type semiconducting oxide, while ITO is a tin-doped form of indium oxide and one of the most established transparent conducting oxides. Owing to its conductivity, optical transparency, and chemical stability, ITO has been widely used in transparent electrodes, displays, photovoltaics, and sensor-related thin-film systems [3]. In_2O_3 has also been investigated in sensing applications because of its electronic properties and suitability for oxide-based sensor design [4], [10].

In this thesis, In_2O_3 and ITO are considered as functional thin-film sensor materials rather than only as transparent conducting or semiconducting oxides. Their thin-film form makes them suitable for integration onto different substrates and compact sensor architectures, including high-temperature sensing systems and thin-film thermocouple-type devices [4], [10]. Once integrated into engineering products, these materials become part of a broader material system with its own sourcing, fabrication, integration, and end-of-life implications, especially because the functional layer contains a by-product metal such as indium.

2.2. Functional properties of In_2O_3 and ITO

In sensor applications, In_2O_3 and ITO thin films are of interest because they can provide both electrical functionality and sensing-related performance. In_2O_3 acts as a semiconducting oxide, while ITO becomes more electrically conductive through the addition of tin. These characteristics allow the films to generate relatively stable signals and to respond to changes in operating conditions within sensor systems [3].

Their behaviour, however, cannot be explained by material composition alone. How the film is produced is just as important. Factors such as the deposition method, film thickness, dopant concentration, annealing conditions, oxygen content, crystallinity, and substrate material can all influence the final film structure. As a result, properties such as resistivity, carrier concentration, grain structure, adhesion, and long-term stability may vary considerably between films that are nominally based on the same material system [3], [4], [10].

This processing–performance relationship is particularly important in thin-film thermocouples and high-temperature sensor applications. In these devices, the measured response is produced by the layered structure as a whole rather than by a single material layer in isolation. The thin film, counter electrode, substrate, and thermal stability of the system all contribute to the final output. Studies on In_2O_3/ITO and oxide/metal thin-film thermocouples show that output voltage and thermoelectric coefficient may change depending on the material pairing, microstructure, and thermal treatment conditions [4], [10].

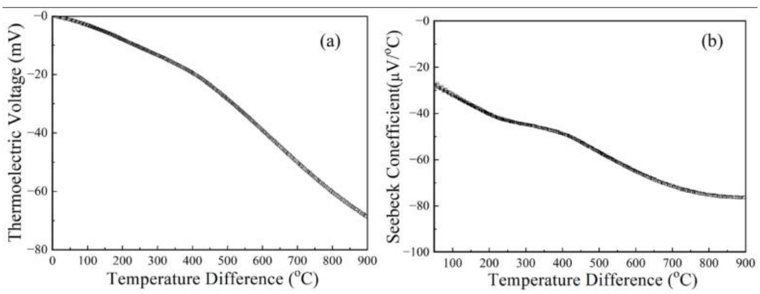

Figure 2. *Thermoelectric voltage and Seebeck coefficient as functions of temperature difference for an indium-based thin-film thermocouple system, adapted from Liu et al. [4].*

As illustrated in Figure 2, the thermoelectric response of an indium-based thin-film thermocouple system changes with temperature difference. The figure shows that the sensor function is not determined only by the nominal chemical composition of In_2O_3 or ITO, but also by the operating conditions and the configuration of the thin-film system. This supports the view that sensor-material performance must be understood together with fabrication and operating conditions, which later affects sustainability assessment.

2.3. Fabrication context of thin-film sensor materials

In_2O_3 and ITO films can be produced through a variety of fabrication routes, such as magnetron sputtering, evaporation, sol-gel and spray pyrolysis. In these methods, sputtering is often used in the preparation of functional oxide films, mainly because it can deposit a relatively uniform film layer under controlled process conditions [3], [9].

The preparation route is not only an actual processing choice, but also directly affects the performance of the final film. Parameters such as deposition atmosphere, oxygen partial pressure, substrate temperature, target composition, film thickness, annealing conditions and doping concentration will affect the film growth and structure during growth and post-treatment. These factors may affect the stoichiometric ratio, crystallinity, grain size, defect concentration, adhesion, density, conductivity and thermal response. In this sense, the sensing behavior of In_2O_3 and ITO films is not only affected by the material system itself, but also by the specific conditions of film preparation [4].

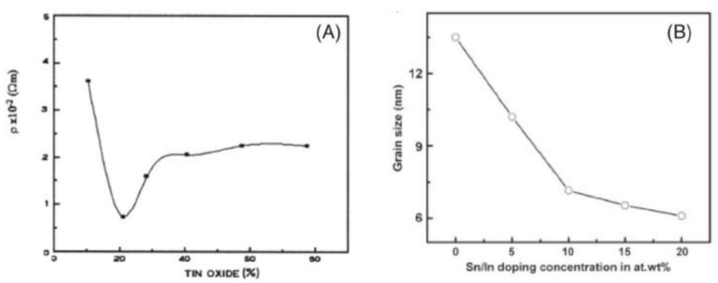

Figure 3. *Relationship of (a) resistivity with tin oxide content and (b) grain size with Sn/In doping concentration in ITO-based films, adapted from Rajendran and Kumar [3].*

Figure 3 presents an example of this processing-performance relationship. The figure indicates that the content of tin oxide and the doping concentration of Sn/In will affect the resistivity and grain size of the ITO-based film. These changes are of great significance for sensor applications, as the electrical response, thermal stability, and long-term reliability are all closely related to the composition and microstructure of the film.

After fabrication, the thin film has to work as part of a product. In sensor-integrated engineering products, the film may be deposited on ceramic, metallic, or other engineering substrates. Its performance depends on adhesion, thermal expansion compatibility, chemical stability, and resistance to damage during service. This is especially important in high-temperature or machining-related applications, where the sensor layer must still work under mechanical, thermal, and chemical stresses.

For this reason, indium-based sensor films should not be treated as free-standing materials. They should be considered as part of a multilayer product system. This product-level view is also relevant to sustainability. Thin-film deposition may require high-purity inputs, controlled processing conditions, energy-consuming equipment, and post-treatment steps. Deposition efficiency and process scrap may also affect material efficiency and secondary indium recovery.

2.4. Relevance to sustainability assessment

The material and fabrication background outlined above is directly relevant to the sustainability assessment developed in this thesis. In_2O_3 and ITO are technically relevant because their electrical, thermoelectric, and stability-related properties make them suitable for thin-film sensor applications. However, their function depends on controlled fabrication, material quality, integration conditions, and service environment. Therefore, their sustainability relevance cannot be reduced to chemical composition or small mass contribution alone.

At the same time, the use of indium-based materials introduces upstream and downstream sustainability questions. Upstream, indium is mainly recovered as a by-product of zinc-related production, which links In_2O_3 and ITO to host-metal dependence, refining capacity, and processing complexity [5], [6]. Downstream, thin sensor layers may become difficult to identify, separate, or recover once integrated into engineering products. On this basis, Chapter 3 examines the upstream sustainability profile of indium-based sensor materials, while Chapter 4 discusses downstream integration, use-phase relevance, and end-of-life implications.

3. Upstream Sustainability Analysis of Sensor Materials

3.1. Upstream supply-side characteristics of indium-based sensor materials

The upstream sustainability assessment of indium-based sensor materials starts with one basic question: where does the indium come from, and how does it become available for use in functional thin films? This section answers this question from three angles. It first explains the by-product nature of indium supply. It then discusses mine-linked origin and reserve concentration. It finally examines refinery concentration and the geopolitical risks linked to refined indium supply.

3.1.1. By-product supply structure of indium

Indium is usually not obtained through special mining routes. Its main commercial source is sphalerite, a zinc sulfide ore mineral. In fact, this means that indium is mainly recycled as a by-product in zinc-related mining, smelting, refining and recycling systems [12], [18]. Therefore, its supply mode is different from those bulk metals that are mainly mined according to their own market demand.

This by-product attribute has an important impact on supply flexibility. Even if the demand for indium-based technology increases, the production of indium cannot be simply expanded in a direct way like primary metals. It still depends on the production of zinc, the economy of host metals, the available recycling technology, and decision-making at the refinery level. Another practical problem is that the refinery must have suitable intermediate streams or residual streams so that indium can really be recovered from it. Therefore, the supply of indium is shaped by a wider range of associated metal systems, rather than relying on the demand for indium itself [6], [13].

This situation is reflected in the critical assessment of the European Union in 2023. In the evaluation, indium was examined in the processing phase rather than the mining stage, and the report described it as a by-product mainly related to zinc and copper [14]. This distinction is important. The upstream challenge is not only whether indium exists in ore deposits, but whether it can be captured, refined, and supplied through technically and economically suitable processing routes.

For In_2O_3- and ITO-based thin-film sensor materials, this upstream structure should not be overlooked. A sensor layer may contain only a very small amount of indium, but the material is still connected to a much longer production chain. Before it reaches the thin-film fabrication stage, indium has already passed through ore extraction, concentration, metallurgical recovery, refining, and conversion into functional materials suitable for deposition. Energy use, chemical inputs, material losses, and supply constraints may therefore arise well before the sensor itself is manufactured.

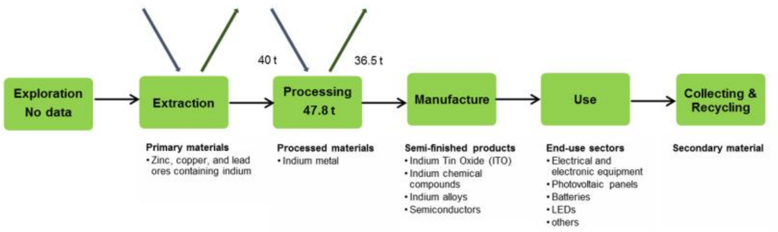

Figure 4. *Simplified value chain for indium, illustrating the upstream sourcing and processing structure of indium as a by-product metal, adapted from SCRREEN2 [18].*

Figure 4 shows how indium reaches downstream applications through a host-metal production system. It shows that indium is not an isolated material flow. It is connected to zinc extraction and processing, and its recovery depends on metallurgical conditions and refinery decisions. For sensor-integrated manufacturing systems, this means that the material used in a thin-film sensor layer may carry upstream sustainability issues that are not visible from the final product mass alone.

3.1.2. Mine-linked origin and reserve concentration

The by-product structure of indium also makes its mine source information not as straightforward as it originally seemed. Since indium is mainly related to zinc mining and processing, official national-level mine production data is usually not reported like native metals. On the contrary, the existing data often refers to the estimated value of indium contained in zinc ore, rather than a direct measurement of the yield of indium mines [13].

This distinction is very important. The indium contained in zinc ore is not automatically converted into refined indium. Some of it may not be recycled, some may be lost in the process of beneficiation or smelting, and some may enter the residue that has not been treated by the indium recovery route. Therefore, the data related to the mine should be interpreted carefully. They help to show which zinc-related mining streams in indium is embedded, but should not be regarded as direct production data.

Table 1. *Estimated indium content of mined zinc ores in selected countries, 2009 and 2013, adapted from Lokanc et al. [13].*

Country	2009(t)	2013(t)
Australia	29	31
Bolivia	13	12
Canada	39	30
China	231	373
India	21	24
Ireland	12	10
Kazakhstan	14	11
Mexico	12	18
Peru	45	39
United States	22	23
Other	44	58
Total	481	629

Note: Values represent estimated indium content in mined zinc ores rather than actual reported indium mine output. The estimates indicate the amount of indium embedded in zinc-related mining flows and should therefore be interpreted as estimate-based provenance information rather than direct production data.

As shown in Table 1, the estimated distribution of indium content in zinc ore mined in 2013 is not uniform, of which China accounts for the largest share. However, this does not mean that an equal amount of indium is recovered and converted into refined metals. The table shows more in which zinc-related mining systems in which indium may exist. It also points out a broader data problem: the upstream source of indium usually needs to be inferred based on zinc production data and the assumed indium concentration in the ore.

The estimate of reserves adds another meaning to this situation. They do not represent indium that can be used immediately in industrial production. On the contrary, they indicate the broader geological foundations associated with zinc deposits and the potential basis for future indium recovery.

Table 2. *Estimated global distribution of indium reserves, 2007 and 2013, adapted from Lokanc et al. [13].*

Country	**2007(t)**	**2013(t)**	**Share 2007**	**Share 2013**
Canada	150	180	1%	1%
China	8,000	10,400	75%	69%
Peru	360	480	3%	3%
Russia	80	80	1%	1%
United States	280	200	3%	1%
Other	1,800	3,700	17%	25%
Total	11,000	15,000	100%	100%

Note: Reserve values are estimate-based and should be interpreted as indicative rather than directly reported indium reserves. The 2013 figures were derived using a *pro rata* increase in global zinc reserves between 2007 and 2013, following the method described by Lokanc et al. [13].

Table 2 suggests that estimated indium reserves were also highly concentrated. China accounted for about 69% of the estimated global total in 2013. Taken together, the two tables highlight different but related aspects of the upstream supply picture. Table 1 reflects estimated mine-linked zinc flows, while Table 2 gives an indication of the longer-term reserve base. Both point in the same direction: indium-based sensor materials are connected to a supply system shaped by geographical concentration, by-product dependence, and limited data transparency.

3.1.3. Refinery concentration and geopolitical vulnerability

Mine-related estimates and reserve data help to understand where indium may come from, but they do not indicate the actual amount of refined indium available. The refining supply depends on the process after mining: the indium contained in zinc-related ores and intermediate streams must be recovered, separated, refined, and then converted into a form suitable for industrial applications. In this sense, the upstream problem is not only a matter of geological availability, but also about whether the processing system is capable and willing to convert scattered indium into usable materials.

One of the most important concerns about this part of the supply chain is the concentration of refining capacity. According to the U.S. Geological Survey, the global refining production of indium in 2025 is about 1,100 metric tons, of which China accounts for about 70% of the total [12]. Therefore, the supply of refined indium is not only limited by the scale of production, but also highly dependent on a dominant producer. For users of In_2O_3 and ITO-based film materials, this concentration may increase the risk of supply interruption, especially in the event of changes in terms of trade, industrial policies or export controls.

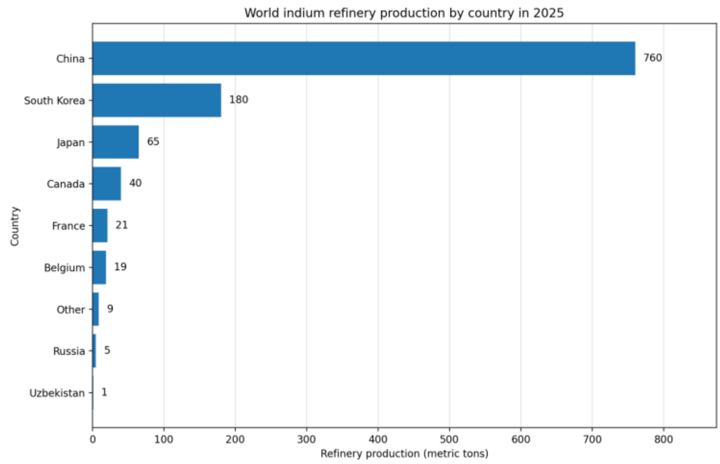

Figure 5. *World refinery production of indium by country in 2025, based on data from U.S. Geological Survey [12].*

Figure 5 illustrates the uneven distribution of indium refinery production across countries. China represents by far the largest share, while South Korea, Japan, Canada, France, Belgium, Russia, and Uzbekistan contribute smaller amounts. This pattern is important because refined indium availability is shaped by more than the presence of mineral resources. It also depends on processing capacity, refinery infrastructure, policy decisions, trade relations, export restrictions, and broader market conditions.

The EU 2023 criticality assessment gives a similar policy view. It assesses indium at the processing stage because global and EU supply data were available only for processing. The same report identifies indium as a by-product mainly linked to zinc and copper. It also reports concentrated processing-stage supply shares, with China, South Korea, Japan, Canada, France, and Belgium as key contributors [14].

Refinery concentration also has geopolitical importance. When refined indium supply depends on a small number of countries, downstream users become more exposed to policy changes, export limits, trade problems, and price changes. This risk may be large even when the final sensor layer contains only a small amount of indium, because the supply of the sensor material depends on the stability of the whole refining system.

3.2. Processing complexity and upstream environmental pressures

For indium-based sensing materials, the upstream sustainability of indium cannot be understood only by examining its deposit position in zinc ore. The more practical question is whether these indiums can really be recycled and processed into usable materials. This is especially important because indium is usually embedded in zinc-related metallurgical systems rather than extracted through specialized native mining routes.

Therefore, the processing process becomes the core part of the upstream evaluation. Before indium can be used in functional materials such as In_2O_3 and ITO, it must be separated, refined and transformed into a suitable material form. The following discussion will examine how the EU criticality framework handles this processing stage, how indium is recycled from zinc-related systems, and how the processing process is linked to environmental pressure, residue treatment, secondary supply and available data limitations.

3.2.1. Processing-stage relevance in the EU criticality framework

The crucial assessment of the European Union for 2023 provides a useful starting point for this discussion. By distinguishing between the mining stage and the processing stage, the framework helps to identify possible bottlenecks in the raw material value chain. In the case of indium, since global supply data and EU procurement data are available at the processing stage, but not at the mining stage, the assessment is only carried out at the processing stage. The same assessment also identifies indium as a by-product mainly related to zinc and copper [14].

This classification is of great significance to this thesis. It shows that the evaluation of indium should not be limited to mine origin, ore accumulation or reserve distribution. Metallurgical systems that can recover, separate, refine and supply indium are equally important. In other words, processing is not just an intermediate technical step between mining and use. It is one of the main conditions for determining whether indium can be used as a functional material in applications such as In_2O_3 and ITO films.

Table 3 summarises selected indicators for indium from the EU 2023 criticality framework.

Table 3. *Selected EU 2023 criticality assessment indicators for indium, adapted from European Commission [14].*

Indicator	**Value**
Supply Risk (SR)	0.6
Economic Importance (EI)	2.6
Stage used in SR	Processing
Stages assessed	Processing
Processing: supply used in SR	GS+EU
Processing: supply risk	0.6

Note: In the EU 2023 assessment, indium was assessed only at the processing stage. GS = global supply; EU = EU sourcing. Adapted from European Commission [14].

As shown in Table 3, indium does not exceed the EU 2023 criticality thresholds for either Supply Risk or Economic Importance. Its Supply Risk value is 0.6, while its Economic Importance value is 2.6. This means that, under the EU 2023 threshold-based methodology, indium is not formally classified as critical. However, this does not mean that indium is irrelevant from a sustainability perspective. For this thesis, the most important point is that indium is assessed at the processing stage, which highlights the importance of recovery, refining capacity, supply-chain organization, and data availability.

The EU assessment also has methodological implications. It notes that, for some materials, sourcing data may be incomplete or of uneven quality, and that inconsistencies may arise between global production data and EU sourcing data with respect to units, contained material, time period, and life-cycle stage [14]. For indium, this means that upstream sustainability assessment is influenced not only by physical supply conditions, but also by the way data are reported and categorized. As a result, processing complexity and data quality should be treated as part of the sustainability assessment problem itself.

For indium-based sensor materials, this has a direct implication. Even if In_2O_3 and ITO are used only in very thin sensor layers, the materials depend on upstream recovery and refining systems that are complex, concentrated, and partly opaque. Therefore, the sustainability assessment of indium-based sensor materials must include processing-stage conditions as a central analytical category.

3.2.2. Metallurgical complexity of indium recovery from zinc-related systems

The metallurgical complexity of indium recovery is closely linked to the treatment of zinc ores and zinc-related intermediate streams. Indium is commonly associated with sphalerite-bearing zinc ores, but it does not usually appear as a separate and easily recoverable material at the early stages of production. Instead, it follows the zinc processing chain and may accumulate in intermediate residues, precipitates, sludges, dusts, slags, or other by-product streams.

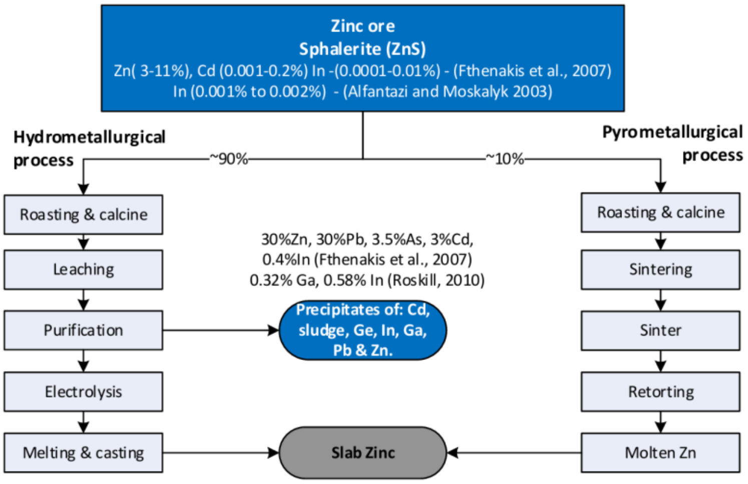

Figure 6. *Smelting of zinc ores to yield zinc slabs and indium precipitate, adapted from Lokanc et al. [13].*

The recycling of indium needs to be understood in a broader zinc processing system. As shown in Figure 6, zinc ore can be treated by hydrometallurgical processing or pyrometallurgical processing routes. In these routes, indium is usually not recycled as the main product. On the contrary, it may be concentrated in intermediate precipitates, residues or other process streams. Lokanc et al. pointed out that many zinc refining processes are based on hydrometallurgical processing. In this process, indium may coexist with cadmium, germanium, gallium, lead, zinc and other elements in the chemical composition of complex streams [13].

This brings practical recycling challenges. Indium must be separated from a multi-element mixture, and these streams are often closer to residues than main products. The recovery result depends on many factors, including process chemistry, residue composition, separation method, refining technology and economic conditions. In this regard, the amount of indium contained in zinc ore only explains part of the problem. It is also important whether the processing system can effectively capture and refine these indiums.

The study of zinc-ferrite-rich residues, zinc leaching residues and jarosite residues show this problem more specifically. The recovery of indium is technically feasible, but it is rarely a simple or unified process. Different residues may require different treatment routes, such as reduction, leaching, purification and precise process control, depending on their composition and behavior during processing [11], [15], [16].

This is very important for evaluating the sustainability of indium-based sensing materials. The upstream correlation of indium cannot be judged only by the ore storage, the estimated value related to the mine or the reserve data. It also depends on whether the existing industrial system can collect, enrich and refine indium. These recycling routes may involve energy use, chemical reagents, waste disposal and process losses. Therefore, even if the final sensing layer contains only a very small amount of indium, its upstream material path may still have sustainability problems that should not be ignored.

3.2.3. Residue handling, secondary supply, and data limitations

Upstream environmental pressure is closely related to the way indium is recovered from zinc-related process streams. In the zinc-indium system, indium is usually found in intermediate materials such as zinc-ferrite-rich residues, zinc leaching residues, jarosite residues, soot, dust, slag and sludge. These streams may contain recyclable indium, but they are usually not materials that can be used directly. Before obtaining indium, heat treatment, leaching, the use of chemical reagents, liquid-solid separation, purification and further residue management are often required [11], [15], [16], [17].

Therefore, residue disposal has become an important component of sustainability assessment. On the one hand, these residues can be used as secondary resources because they may contain indium that would have been lost from the material system. On the other hand, the recovery of indium from these residues is not without environmental impact. Depending on the type and composition of the residue, additional energy, chemicals, process control and waste disposal may be required. Therefore, the upstream characteristics of indium are not only affected by mining and refining, but also by how intermediate streams are produced, processed, reused or finally disposed of.

Secondary supply also needs to be carefully understood. It can improve material efficiency and reduce dependence on primary supply, but the current production of secondary indium is often more related to manufacturing waste than to mature end-of-life recovery. Discarded ITO sputtering targets and other production scraps are important examples. They are produced in a controlled industrial environment, in which relatively high-purity materials are easier to collect, separate and process than indium scattered in waste products [13], [18].

This is different from recovery from end-of-life products. Manufacturing scraps are usually more concentrated and easier to identify. End-of-life products are often more mixed and more difficult to treat. In sensor-integrated engineering products, indium may exist as a very thin layer attached to ceramic, metallic, or composite substrates. This makes separation and recovery much harder.

The same issue creates a data problem. Information on refinery technologies, recovery efficiencies, residue flows, reagent use, energy demand, and process losses is often incomplete, private, or too general for application-specific assessment. The EU criticality assessment also notes problems with sourcing data quality and differences between global and EU data in units, containing material, time periods, and life-cycle stages [14].

3.3. Implications for the sustainability assessment of indium-based sensor materials

The small amount of indium in a sensor layer can make its upstream impact easy to overlook. But In_2O_3 and ITO are not isolated material inputs. They are linked to zinc-related production and refining systems, so the by-product nature of indium has to be part of the assessment.

The main issue is material availability. Indium does not become available just because it exists in ore. It must also be recycled, refined and processed through appropriate processing routes. Therefore, the vulnerability of the processing stage is very important for sustainability assessment.

Secondary supply also needs to be interpreted carefully. Manufacturing waste can support the recovery of indium, but this is not equivalent to the recycling of the mature end-of-life stage. In many final products, indium may exist in a thin layer, which is scattered and difficult to separate. The data gap further increases the uncertainty of the assessment, as information about material sources, refining routes, recovery efficiency and process burden remains limited.

For these reasons, the evaluation of In_2O_3 and ITO should take into account both their functional value and the limitations of upstream material systems.

Table 4. *Main upstream implications for sustainability assessment*

Upstream characteristic	Implication for sustainability assessment
Processing-stage focus	Include processing-stage vulnerability
Zinc-related by-product supply	Consider host-metal dependence
Refining concentration	Assess supply-chain exposure
Multi-stage recovery	Include process burdens
Scrap-based secondary supply	Distinguish from EoL circularity
Limited end-of-life recovery	Avoid overstating circularity
Data gaps and boundaries	Make uncertainty explicit

Table 4 summarizes the main upstream characteristics identified in this chapter and explains how they influence the sustainability assessment of In_2O_3- and ITO-based sensor materials. The table shows that the main upstream concerns are not limited to material scarcity. They also include structural supply dependence, processing-stage bottlenecks, refinery concentration, residue-related recovery challenges, limited circularity, and data uncertainty. These findings provide the basis for the downstream analysis in Chapter 4, where the discussion moves from upstream supply and processing to sensor integration, use-phase relevance, stewardship, toxicity-related issues, and end-of-life treatment.

4. Downstream Sustainability Considerations of Sensor-Integrated Products

4.1. Sensor integration in engineering products

After completing the upstream analysis, the research focus shifted to how indium-based thin-film sensing materials are integrated into the product. The products considered here are not limited to a specific type of equipment. They may include manufacturing tools, mechanical parts, coated surfaces, high-temperature components, and other industrial systems used for monitoring, feedback or control.

This broader product perspective is necessary because this thesis does not analyze a specific product case in detail. On the contrary, the thesis examines how the sensing layer based on In_2O_3 and ITO is integrated into engineering products, and how this integration affects its relevance throughout its life cycle.

For indium-based thin-film materials such as In_2O_3 and ITO, this integration has specific material-system implications. These materials may function as electrically active, thermoelectric, or temperature-sensitive thin films, but their performance is not determined by the functional layer alone. As discussed in Chapter 2, the properties of In_2O_3 and ITO depend strongly on deposition route, film thickness, microstructure, adhesion, and thermal stability. Once incorporated into an engineering product, the sensor layer must work together with the substrate, insulating layer, protective coating, electrical connection, and sometimes additional signal-acquisition components. The sensor material should therefore be understood as part of a multi-material product system rather than as an isolated coating. The multi-material nature of sensor integration can be illustrated by an In_2O_3/ITO thin-film thermocouple probe, in which the functional oxide films are combined with a sapphire support, conductive paste, ceramic protection, and metallic signal wires [19].

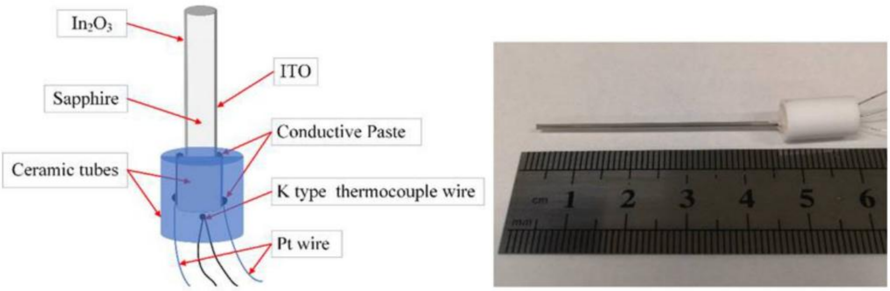

Figure 7. *Schematic and fabricated structure of an In_2O_3/ITO thin-film thermocouple probe, adapted from Deng et al. [19].*

In the structure shown in Figure 7, the In_2O_3 and ITO films are only one part of the sensor system. The probe also includes a sapphire support, conductive paste, ceramic protection, and metallic signal wires [19]. The sensing function comes from this combined structure, not from the functional films alone.

This example helps explain why indium-based sensor materials should be treated as part of multi-material engineering products. Once the sensor layer is integrated into a product, it can support useful functions such as better monitoring, predictive maintenance, longer service life, and less waste from failure or poor process control. At the same time, the added layers, connections, protection materials, and electronic parts can make the product harder to dismantle, separate, and recycle at the end of life.

4.2. Use-phase relevance and functional benefits

Once thin-film sensors are integrated into engineering products, their main value lies in the operating information they are able to provide. Depending on the application, they can detect changes in temperature, strain, vibration, wear, and other process-related conditions. This information allows users to follow the status of a product or process more closely and to react earlier when abnormal behaviour begins to appear.

This functional role is important when assessing In_2O_3 and ITO in sensor-integrated systems. Their relevance should not be judged only by the small quantity of material used in a thin-film layer. It also needs to be considered in relation to the functions that these materials help enable. In other words, the material itself may be minor in mass, but it can support functions that have a much wider effect on the product system.

In manufacturing applications, these functions can bring practical benefits in the use stage. Real-time or near-real-time data can more clearly reflect the status of tools, components and functional surfaces. It can also support fault detection and status assessment, so that maintenance or replacement decisions can be based on actual operating conditions, rather than fixed time plans. This is closely related to predictive maintenance. In predictive maintenance, sensor data is used to determine when intervention is needed and reduce the risk of unexpected failures [1], [2].

From the perspective of sustainability, the benefits of these stages of use are also important. Better monitoring can help reduce avoidable material and energy losses during operation. For example, early detection of degradation may help prevent defective products, unnecessary replacements, excessive tool wear, or sudden failure of parts. In a manufacturing environment, this can help reduce the level of waste and rework, reduce material consumption, and extend the service life of tools and components.

For indium-based thin-film materials, this argument is particularly relevant in applications where conventional external sensing is insufficient. In_2O_3 and ITO thin films can be used in compact sensor structures and may support temperature or thermoelectric sensing in demanding environments. Their potential functional benefit therefore lies not only in signal generation, but also in the possibility of embedding sensing capability close to the relevant surface or process zone. However, these benefits depend on sensor durability, measurement reliability, signal interpretation, and compatibility with the product environment. A sensor that fails prematurely or produces unreliable data may add material complexity without delivering meaningful use-phase advantages [24], [26].

Therefore, the functional benefits of sensor integration should be treated as conditional rather than automatic. The use phase is therefore a potential compensating stage in the life cycle: it may partly justify the introduction of additional functional materials, but only if the sensing function produces measurable improvements in product performance, resource efficiency, or failure prevention.

4.3. Stewardship and toxicity-related issues

The downstream sustainability assessment of indium-based sensor materials should not only consider their functional benefits during use, but also how these materials are managed across later life-cycle stages. In this thesis, stewardship is understood as the practical responsibility to document, control, and handle indium-containing sensor materials during fabrication, use, maintenance, dismantling, and recycling. Product stewardship is commonly interpreted as a form of shared responsibility across actors in the product chain, rather than as a responsibility assigned to one single stage or actor [20]. This perspective is particularly relevant for In_2O_3- and ITO-based sensor layers because they are typically thin, spatially dispersed, and embedded in multi-material engineering products. Once incorporated into a product structure, they may be difficult to identify visually and may not be treated as a separate material stream at the end of life.

Product stewardship is useful here because the potential risks of indium-based sensor materials depend strongly on material form, exposure route, and life-cycle stage. During normal use, In_2O_3 or ITO may exist as stable and protected thin films. In contrast, higher exposure relevance may arise during deposition, cutting, polishing, maintenance, dismantling, or recycling, where respirable particles or dust may be generated. SCRREEN2 reports that industrial exposure to insoluble indium compounds, including indium arsenide, indium phosphide, and ITO, may lead to interstitial lung damage and other respiratory problems. In several European countries, occupational exposure to indium is strictly regulated. The same report states that Germany applies an occupational exposure limit of 0.0001 mg/m^3 for respirable indium-containing dust, while higher occupational exposure limit values of 0.01 mg/m^3 are reported for Korea and Japan [18].

Occupational exposure evidence is relevant to this thesis because indium-containing materials may be handled in forms that differ from stable thin films in finished products. However, exposure relevance may increase during fabrication, target production, deposition, cutting, polishing, dismantling, or recycling, where respirable particles or dust may be generated. Table 5 summarizes selected occupational exposure indicators reported for indium-exposed workers and controls. The table is used here to support the need for exposure control and material stewardship, rather than to suggest that finished sensor-integrated products necessarily present the same level of risk.

Table 5. *Selected occupational exposure evidence relevant to indium-based material stewardship, adapted from Liu et al. [21], [22].*

Indicator	Controls	Exposed workers
Urinary indium, ng/g creatinine	2.23 ± 0.25	11.00 ± 1.67
Serum indium, µg/L	4.93 ± 0.35	39.26 ± 3.39
%FEV_1	95.63 ± 11.96	91.46 ± 7.05
%FVC	95.42 ± 13.34	91.03 ± 9.67
SP-A, µg/L	117.09 ± 8.59	178.96 ± 20.11
LDH, µg/L	211.28 ± 11.32	349.00 ± 16.75

Note: Values are reported for occupationally exposed workers and controls. They should be interpreted as evidence of exposure relevance in production or processing environments, not as direct evidence of risk during normal use of protected In_2O_3/ITO thin-film sensor layers.

Table 5 shows that exposed workers had higher urinary and serum indium levels than controls, indicating that occupational exposure can occur in indium-related production environments. The exposed group also showed lower average %FEV_1 and %FVC values and higher SP-A and LDH values, which suggests that respiratory-related and biological response indicators may be affected under occupational exposure conditions. These findings should be interpreted cautiously because production exposure is not equivalent to the normal use of protected In_2O_3/ITO sensor layers. Nevertheless, the evidence supports the need for traceability, safe handling, and exposure-control measures during fabrication, maintenance, dismantling, and recycling.

These findings are important for the present thesis because they show that toxicity-related concerns should be linked to exposure scenarios rather than to the mere presence of indium in a product. A protected In_2O_3 or ITO thin film embedded in an engineering product is not equivalent to respirable indium-containing dust in a production or recycling environment.

Overall, stewardship provides a practical framework for connecting toxicity-related evidence with product-level sustainability assessment. The implication is not that In_2O_3- and ITO-based sensor materials should be avoided in all applications. Rather, their use-phase benefits should be assessed together with occupational exposure risks, early biological indicators, environmental data gaps, and downstream handling responsibilities. This supports a balanced assessment in which indium-based sensor materials are recognized as functionally valuable, but also requiring careful management across the product life cycle.

4.4. End-of-life challenges and recycling implications

For indium-based thin-film sensor materials, the main challenge of the end-of-life stage does not necessarily come from manufacturing waste. Production waste and ITO-related manufacturing waste usually arise in a controlled industrial environment. These streams tend to be more concentrated and easier to identify, which is one of the reasons why previous studies have focused on the recovery of indium from such sources.

Products with integrated sensors present different situations. When these products reach the end of their service life, indium-containing layers may be distributed in mixed engineering products instead of being collected as clean and concentrated material streams. These thin layers themselves may also be extremely thin, hidden inside the product structure, and difficult to identify during sorting or disassembly. This makes recycling from end-of-life products more uncertain, and in many cases, it is more difficult than from production waste.

The recovery challenge is therefore not only related to the small amount of indium present in each product. It is also linked to the physical form and location of the material. In_2O_3 or ITO may exist as a very thin layer attached to a substrate and combined with ceramic, metallic, conductive, protective, or electronic components. Such layers may be hard to identify visually, difficult to separate mechanically, and unattractive to recover economically when the total indium content per product is low. As a result, indium in sensor-integrated engineering products may fail to enter a dedicated recycling route and may instead be lost during conventional waste treatment.

This issue should be clearly distinguished from manufacturing-scrap recycling. Spent ITO sputtering targets and process scrap can be more suitable for recovery because they are relatively concentrated and generated within controlled production systems [17], [18]. By contrast, post-consumer or end-of-life sensor layers are likely to be thinner, more dispersed, more strongly integrated with other materials, and less visible within the product structure. Therefore, the existence of secondary indium supply should not be interpreted as evidence that end-of-life recovery is mature for all indium-based applications.

End-of-life uncertainty has direct implications for sustainability assessment. If the indium-containing sensor layer cannot be identified, separated, or recovered after use, then its circularity potential is limited. At the same time, the sensor may still provide sustainability benefits during use if it helps reduce scrap, rework, downtime, premature tool replacement, or unnecessary resource consumption. The key issue is therefore not whether indium-based sensor materials are inherently sustainable or unsustainable, but whether their functional benefits are meaningful enough to justify the introduction of a material system with uncertain end-of-life recovery.

Overall, the downstream sustainability profile of In_2O_3- and ITO-based sensor materials is shaped by both potential use-phase benefits and unresolved end-of-life challenges. Sensor integration may improve monitoring and operational efficiency, but it may also increase product complexity and make later recovery more difficult. These considerations provide the basis for Chapter 5, where the upstream and downstream findings are synthesized in relation to sustainability hotspots, uncertainties, and trade-offs.

5. Discussion of Sustainability Trade-offs and Key Hotspots

5.1. Main sustainability hotspots identified from the European indium cycle

The upstream and downstream analysis developed in Chapters 3 and 4 shows that the sustainability relevance of indium-based sensor materials cannot be assessed only from the mass of In_2O_3 or ITO used in a final sensor layer. Instead, these materials need to be interpreted as part of a broader material system that includes upstream sourcing, refining, processing, product integration, use-phase function, and end-of-life treatment. This section synthesizes these findings by using the European indium cycle as a broader material-flow perspective.

The European relevance of indium-related sustainability hotspots can be illustrated by the anthropogenic indium cycle in the EU-28. Unlike a process-specific flowchart, this figure presents a regional material-flow perspective and describes how indium moved through production, fabrication and manufacturing, use, and waste-management stages in 2014. The dashed boundary represents the EU-28 system boundary. Flows inside this boundary refer to indium movements occurring within the European system, while arrows crossing the boundary indicate imports and exports. All numerical values in the figure are expressed in tonnes of indium [23].

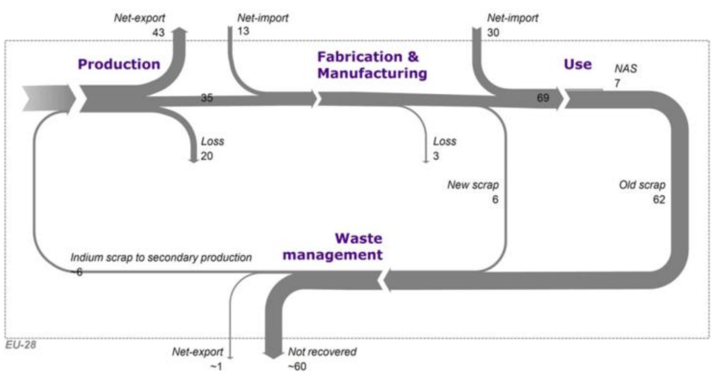

Figure 8. *The 2014 anthropogenic indium cycle in the EU-28. NAS: net addition to in-use stock. Values are given in tonnes of indium, adapted from Ciacci et al. [23].*

Figure 8 illustrates the anthropogenic indium cycle in the EU-28 in 2014. The dashed boundary represents the EU-28 system boundary, while flows crossing this boundary indicate imports and exports. The figure includes several life-cycle stages, including production, fabrication and manufacturing, use, and waste management. The values shown in the figure are expressed in tonnes of indium, and the NAS indicator refers to the net addition of indium to in-use stock. In this way, the figure provides a regional material-flow perspective rather than a process-specific flowchart for In_2O_3- or ITO-based sensor production.

The figure is relevant to this thesis because it shows that indium use in Europe is connected to both internal material flows and international trade. For example, Figure 8 indicates that approximately 35 tonnes of indium moved from production to fabrication and manufacturing within the EU-28, while approximately 69 tonnes entered the use phase. This difference suggests that the European use phase was not supplied only by internal production and manufacturing, but also depended on imported indium-containing products or materials. Therefore, the sustainability relevance of indium-based sensor materials cannot be understood only at the level of the final sensor layer; it must also be considered in relation to wider material-flow systems.

More importantly, Figure 8 shows that the presence of indium in products does not automatically lead to effective circularity. A significant amount of indium may enter the use phase and later become old scrap, but recovery from end-of-life products remains limited. This is directly relevant to In_2O_3- and ITO-based sensor materials because thin-film sensor layers may be even more difficult to identify, separate, and recover than indium-containing layers in more established product streams such as displays or flat-panel devices. Therefore, the figure supports one of the main downstream findings of this thesis: end-of-life recovery should not be assumed simply because indium recycling exists in manufacturing or display-related contexts.

From this material-flow perspective, several sustainability hotspots can be identified. First, indium supply remains connected to upstream production and refining systems outside the final application. Second, product use can accumulate indium in forms that are difficult to recover. Third, recycling is stronger for manufacturing scrap and concentrated ITO-related waste streams than for dispersed end-of-life products. Finally, the lack of application-specific data makes it difficult to determine whether indium-based sensor materials can be effectively recovered after use. These points provide the basis for the following trade-off discussion, where the potential use-phase benefits of sensor integration are interpreted in relation to upstream burdens and end-of-life uncertainty.

5.2. Use-phase trade-offs in machining workshop applications

The previous section identified several material-system burdens associated with indium-based sensor materials, including by-product supply dependence, processing complexity, limited end-of-life recovery, and data uncertainty. However, these burdens should not be interpreted in isolation. In sensor-integrated manufacturing applications, the sustainability relevance of In_2O_3- and ITO-based sensor materials also depends on whether the sensor function can generate meaningful benefits during use.

In machining workshop applications, sensor integration can support process monitoring, tool condition monitoring, chatter detection, fault detection, and predictive maintenance. These functions are relevant because machining processes may generate material waste, rework, tool wear, downtime, and unnecessary energy consumption when abnormal process conditions are not detected early. Sensor-integrated tooling systems may therefore provide sustainability benefits if they help reduce scrap, prevent premature tool failure, improve process stability, or extend tool life [1], [2].

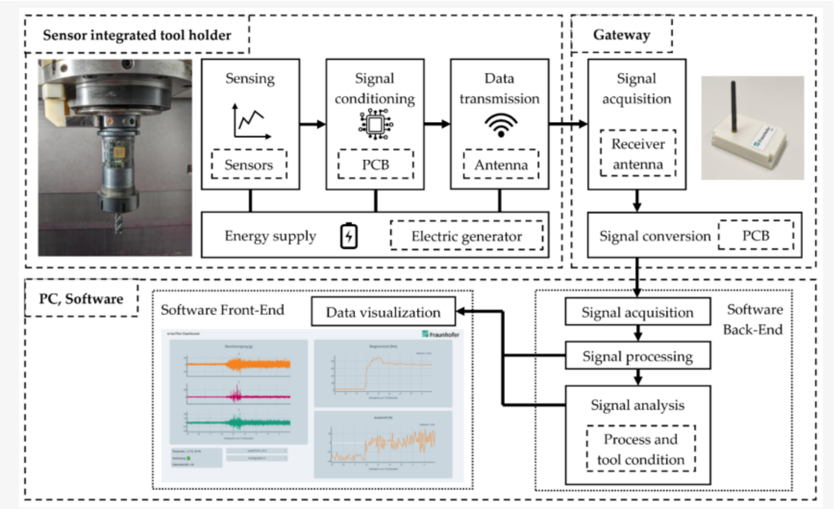

Figure 9. *Monitoring system based on a sensor-integrated tool holder, adapted from Schuster et al. [24].*

Figure 9 shows an example of an integrated sensor tool holder system for machining process monitoring. In such systems, the sensor is integrated in a position close to the tool-workpiece interaction area so that it can capture processes-related signals, such as force, vibration or responses related to vibration during operation. This figure is relevant to this thesis because it shows how sensing materials and sensing structures become part of the functional tooling system, rather than just staying in the isolated laboratory-scale film form.

For this discussion, the importance of Figure 9 mainly lies in the use stage function realized by sensor integration. If embedded or tool-integrated sensors can provide reliable process information, they may help detect unstable cutting conditions, tool wear, vibration or other abnormal process states at an earlier stage. In the actual manufacturing environment, this kind of information can support better process control and may help reduce waste products, rework and accidental tool failure.

Related studies on sensor-integrated tooling and tool condition monitoring point in a similar direction. They show that embedded sensors, as well as sensing systems integrated at the machine level, can support machining process monitoring and fault detection [24], [26].

The energy dimension is also important. A machining process consumes electricity not only during material removal, but also during non-cutting or production-ready states. HEIDENHAIN reports that, in a milling-machine example, auxiliary components such as pallet changer, cooling, hydraulics, and automation require approximately 2.5 kW in the production readiness condition. The same source notes that the CNC control package with feed-axis and spindle motors accounts for only 25–30% of the total required power in many metal-cutting processes, which underlines the importance of auxiliary and non-cutting energy demand [25]. Therefore, if a sensor-integrated tool helps avoid unnecessary downtime or unstable process states, the benefit may include not only reduced scrap and rework, but also avoided auxiliary electricity consumption.

The potential auxiliary electricity saving from avoided tool-wear-related downtime can be expressed as:

$$E_{\text{aux,saved}} = H_{\text{year}} \times r_{\text{downtime}} \times \eta_{\text{sensor}} \times P_{\text{aux}}$$

where:

- $E_{\text{aux,saved}}$ is the auxiliary electricity saved by reducing tool-wear-related downtime, expressed in kWh/year;
- H_{year} is the annual machine operating time, expressed in h/year;
- r_{downtime} is the share of tool-wear-related unplanned downtime;
- η_{sensor} is the share of this downtime that can be avoided by the sensor system;
- P_{aux} is the auxiliary-component power in the production readiness condition, expressed in kW.

Assuming that a machine operates for 8 hours per day and 220 working days per year:

$$H_{\text{year}} = 8 \times 220 = 1760 \text{ h/year}$$

Using the auxiliary-component power of 2.5 kW reported by HEIDENHAIN [25], the equation becomes:

$$E_{\text{aux,saved}} = 1760 \times r_{\text{downtime}} \times \eta_{\text{sensor}} \times 2.5$$
$$E_{\text{aux,saved}} = 4400 \times r_{\text{downtime}} \times \eta_{\text{sensor}}$$

Considering the tool-wear-related unplanned downtime range of 7% to 20% reported in tool condition monitoring literature [26], the auxiliary electricity saving would depend directly on the effectiveness of the sensor system. Under the assumptions above, each 10% improvement in avoiding tool-wear-related downtime would correspond to approximately 30.8–88.0 kWh/year of avoided auxiliary electricity per machine. If the sensor system avoided 50% of such downtime, the saving would increase to approximately 154–440 kWh/year per machine. This estimate remains conservative because it only includes auxiliary electricity in the production readiness condition and does not include avoided scrap, rework, tool replacement, cutting-fluid use, compressed air demand, or repeated machining.

In addition to downtime-related electricity savings, the most direct workshop-level benefit of sensor integration may be reduced scrap. Since this thesis does not conduct a full quantitative LCA of a specific sensor-integrated tool, the additional annual burden of the sensor system is treated as an unknown variable B_S. This makes it possible to calculate how much the scrap rate would need to decrease in order to compensate for a given sensor burden.

Let:

$$B_S = \text{additional annual burden of the sensor system}$$

where B_S includes the burden of the sensor material, thin-film fabrication, system integration, and end-of-life limitation, expressed in kWh-equivalent/year.

If a workshop needs to produce a fixed number of accepted parts per year, the number of parts that must be started depends on the scrap rate. Without sensor integration, the number of started parts is:

$$N_0 = \frac{Q}{1 - s_0}$$

where N_0 is the number of started parts required before sensor integration, Q is the annual number of accepted parts required, and s_0 is the initial scrap rate.

After sensor integration, the number of started parts becomes:

$$N_1 = \frac{Q}{1 - s_1}$$

where N_1 is the number of started parts required after sensor integration, and s_1 is the scrap rate after sensor integration.

The number of avoided started parts is therefore:

$$N_{\text{avoided}} = \frac{Q}{1 - s_0} - \frac{Q}{1 - s_1}$$

The avoided environmental burden from scrap reduction can then be expressed as:

$$B_{\text{saved}} = B_{\text{part}} \times \left(\frac{Q}{1 - s_0} - \frac{Q}{1 - s_1}\right)$$

where B_{saved} is the burden avoided through scrap reduction, and B_{part} is the burden per started part, expressed in kWh-equivalent/started part.

At the break-even point, the burden avoided through scrap reduction equals the additional annual sensor burden:

$$B_S = B_{\text{part}} \times \left(\frac{Q}{1-s_0} - \frac{Q}{1-s_1}\right)$$

Now, let's define:

$$d = s_0 - s_1$$

The absolute reduction in scrap rate is the difference between the initial scrap rate and the scrap rate after sensor integration. So:

$$s_1 = s_0 - d$$

Substitute $s_1 = s_0 - d$ into break-even equation:

$$B_s = B_{part} \times \left(\frac{Q}{1-s_0} - \frac{Q}{1-(s_0-d)}\right)$$

Because:

$$1-(s_0-d) = 1-s_0+d$$

So:

$$B_s = QB_{part} \times \left(\frac{1}{1-s_0} - \frac{1}{1-s_0+d}\right)$$

For simplicity, let's assume:

$$A = 1 - s_0$$

So:

$$B_s = QB_{part} \times \left(\frac{1}{A} - \frac{1}{A+d}\right)$$

Fractionation within parentheses:

$$\frac{1}{A} - \frac{1}{A+d} = \frac{A+d-A}{A(A+d)} = \frac{d}{A(A+d)}$$

So:

$$B_s = QB_{part} \times \frac{d}{A(A+d)}$$

Multiply both sides by $A(A+d)$:

$$B_sA(A+d) = QB_{part}d$$

Expand the left side:

$$B_sA^2 + B_sAd = QB_{part}d$$

Move the terms containing d to the right side.

$$B_sA^2 = QB_{part}d - B_sAd$$

$$B_sA^2 = d(QB_{part} - B_sA)$$

So:

$$d = \frac{B_sA^2}{QB_{part} - B_sA}$$

Since:

$$A = 1 - s_0$$

Finally:

$$d(B_s) = \frac{B_s(1 - s_0)^2}{QB_{part} - B_s(1 - s_0)}$$

The corresponding final scrap rate after sensor integration is:

$$s_1(B_S) = s_0 - d(B_S)$$

This equation is useful because it expresses the required process improvement directly as a function of the additional sensor burden B_S. A larger sensor burden requires a larger reduction in scrap rate, while a lower sensor burden can be compensated by a smaller process improvement.

To illustrate the scale of this relationship, a simple screening scenario is used. The assumptions are:

$Q = 10{,}000$ accepted parts/year
$s_0 = 5\% = 0.05$
$B_{\text{part}} = 1.2$ kWh-equivalent/started part

Under these assumptions, the break-even equation becomes:

$$d(B_S) = \frac{B_S(1 - 0.05)^2}{10{,}000 \times 1.2 - B_S(1 - 0.05)}$$
$$d(B_S) = \frac{0.9025B_S}{12000 - 0.95B_S}$$

Table 6 shows the required scrap-rate reduction for four illustrative levels of additional sensor burden: 50, 100, 250, and 500 kWh-equivalent/year. This value is used only as an illustrative burden per started part, not as a measured value for a specific machining process.

***Table 6.** Break-even scrap-rate reduction under illustrative additional sensor-burden scenarios.*

Additional sensor burden B_S	**Required scrap-rate reduction $\boldsymbol{d}(B_S)$**	**Required final scrap rate $\boldsymbol{s_1}(B_S)$**
50 kWh-eq/year	0.38 percentage points	4.62%
100 kWh-eq/year	0.76 percentage points	4.24%
250 kWh-eq/year	1.92 percentage points	3.08%
500 kWh-eq/year	3.92 percentage points	1.08%

The break-even results can be read as required scrap-rate targets. If the extra sensor burden is 50 kWh-eq/year, the scrap rate has to decrease from 5.00% to 4.62%. If the burden is 100 kWh-eq/year, the final scrap rate has to reach 4.24%. If the burden is 250 kWh-eq/year, the final scrap rate has to reach about 3.08%.

These numbers should be treated as threshold values, not as measured sensor performance. They show the level of improvement needed for scrap reduction to offset the extra material and life-cycle burden of the sensor system.

Auxiliary electricity savings can also be added to this logic. If reduced downtime already saves electricity, then only the remaining sensor burden needs to be offset by scrap reduction:

$$B_{S_{\text{residual}}} = B_S - E_{\text{aux,saved}}$$

where $B_{S_{\text{residual}}}$ is the remaining sensor burden after accounting for auxiliary electricity savings. If $B_{S_{\text{residual}}} \leq 0$, then avoided auxiliary electricity alone is sufficient to offset the additional sensor burden in this screening calculation. If $B_{S_{\text{residual}}} > 0$, then additional benefits such as scrap reduction, rework reduction, longer tool life, or reduced inspection demand are needed.

This calculation supports the central trade-off of this section. Indium-based sensor materials may be environmentally defensible when the sensor function leads to measurable workshop-level improvements, including reduced scrap, lower rework, avoided downtime, reduced auxiliary electricity use, or longer tool life. However, if the additional sensor burden is high and the operational improvement is small or difficult to verify, the use of a critical and poorly recoverable material such as indium becomes more difficult to justify.

5.3. Model description, rationale, and limitations

5.3.1. Model description and rationale

The calculation in this section should be understood as a preliminary screening model, not a complete life cycle assessment model. Its purpose is not to predict the actual environmental performance of a specific sensor-integrated tool, but to estimate how much improvement the use stage needs to be achieved assuming that there is an additional sensor burden to offset this burden.

The reason for adopting such a model design is that the specific application data for In_2O_3 and ITO sensor systems is still limited. A complete evaluation requires detailed data, including sensor material usage, film deposition process, process electricity consumption, material loss, system integration, maintenance, sensor life and end-of-life treatment method. Since these data are not yet available in specific industrial cases, this paper expresses the additional annual sensor burden as (B_S) and uses it as a assumed aggregate variable.

The model starts from a fixed annual demand for accepted parts. If the scrap rate is reduced after the sensor is integrated, the number of parts that actually need to start production will be reduced in order to obtain the same number of accepted parts. The reduction in the number of starting parts corresponds to the avoidance of part of the production burden. At the break-even point, the avoided burden from scrap reduction is equal to the assumed additional annual sensor burden. Therefore, the model is used to calculate how much waste rate needs to be reduced to achieve break-even under different hypothetical sensor burden scenarios.

5.3.2. Model limitations

There are several limitations of this model. First, (B_S) is not the actual measured value of a specific sensor system, but a assumed aggregate burden. It is not further divided into different parts such as material production, film manufacturing, sensor integration, maintenance or end-of-life treatment. Second, the model mainly focuses on the reduction of the scrap rate, while other potential use-phase benefits in the use stage, such as reducing rework, avoiding downtime, extending tool life or reducing auxiliary electricity, are not fully quantified in the main break-even equation. Third, the annual output, initial scrap rate and the burden of each starting part used in the example scenario do not come from a specific machining case. Therefore, the calculation results should be understood as threshold values, not the actual measured sensor performance.

In addition, upstream supply risk, material value, toxicity-related handling needs and life-end uncertainty are mainly discussed as qualitative sustainability hotspots in this thesis and have not been transformed into quantitative impact indicators in the model. Therefore, the model cannot directly judge whether a specific sensor integrated product is sustainable. It can only show how much the use stage improvement needs to be under the selected hypothetical conditions to offset the hypothetical sensor burden.

5.3.3. Requirements for a thorough trade-off assessment

A more complete trade-off assessment would require, you need specific application data from the material system and manufacturing process. In terms of burden, it is necessary to include data such as sensor material mass, deposition efficiency, sputtering target or precursor usage, process electricity, post-treatment, wires, electronic components, integration steps, maintenance, replacement and life end processing. In terms of benefit side, actual measurement data is needed, including reduced scrap rate, reduced rework, reduced downtime, extended tool life, reduced inspection demand, reduced auxiliary electricity consumption and long-term reliability of sensors.

A complete evaluation also requires a real life-end scenario, including whether the indium-containing sensing layer can be identified, disassembled, separated and recycled after use. Finally, the sensor-integrated case should be compared with the no-sensor baseline, and, if possible, with alternative sensing materials or other monitoring schemes.

5.4. Knowledge gaps and broader sustainability implications

The previous sections show that the sustainability assessment of indium-based sensor materials remains affected by several important knowledge gaps. Although the upstream and downstream analysis has identified key environmental hotspots, the available evidence is still not sufficient to support a complete quantitative conclusion for a specific sensor-integrated tool. This is particularly relevant because the environmental justification of In_2O_3- and ITO-based sensor layers depends on a balance between additional material burdens and measurable use-phase benefits. Therefore, future assessment should focus not only on material criticality, but also on fabrication data, workshop performance, end-of-life traceability and application-specific recovery scenarios.

A first knowledge gap concerns the lack of sensor-specific life cycle inventory data. Existing studies on indium and ITO provide useful information on raw material supply, thin-film applications, transparent conductive coatings and recycling from display-related products. However, these data do not directly represent sensor-integrated engineering tools. For a more accurate assessment, future studies would need inventory data for sensor-layer deposition, target or precursor use, film yield, process electricity, post-treatment, wiring, integration steps, maintenance, and replacement. Without these data, the additional burden of the sensor system can only be treated as a scenario variable rather than as a measured value. This limitation is consistent with broader critical-material assessment literature, which emphasizes that data availability, system boundaries and methodological choices can strongly affect sustainability conclusions for minor and by-product metals [7].

A second knowledge gap concerns the quantification of use-phase benefits. In principle, sensor-integrated tools may reduce downtime, scrap, rework, tool replacement and non-productive energy use. However, these benefits are highly application dependent. The calculation in Section 5.2 shows that even a relatively small reduction in scrap rate may compensate for a low additional sensor burden, while a higher sensor burden requires much stronger workshop-level improvement. This means that future studies should measure not only whether a sensor functions technically, but also whether it reduces rejected parts, shortens downtime, increases tool life, lowers inspection requirements or reduces electricity consumption per accepted part. For this reason, the key data needed for future sustainability assessment include scrap-rate reduction, avoided rework, avoided tool failure, reduced machine idle time and sensor lifetime relative to the lifetime of the host tool.

A third knowledge gap is related to end-of-life recovery from sensor-integrated tools. Most available indium recycling studies focus on larger and more established product streams, such as LCD panels, flat-panel displays or spent ITO sputtering targets. These cases are useful as analogies, but they do not fully represent thin and spatially dispersed sensor layers attached to durable engineering substrates. In sensor-integrated tools, the indium-containing layer may be difficult to identify visually, may be strongly bonded to the substrate, and may be present in quantities too small to justify selective recovery under normal waste-management conditions. Therefore, the recovery assumptions used for display products or manufacturing scrap should not be transferred directly to sensor-integrated engineering products [18], [23].

A fourth knowledge gap concerns material traceability and product information. The European indium cycle discussed in Section 5.1 shows that the presence of indium in products does not automatically lead to recovery. For sensor-integrated tools, this problem may be even more pronounced because recyclers may not know that a thin indium-containing layer is present. Future sustainability strategies should therefore include material documentation, product labelling, design for disassembly, and information transfer between manufacturers, users, and waste handlers.

This issue is also consistent with a broader policy direction toward better material transparency, recycling, and product information. These developments do not solve the recovery problem by themselves, but they indicate an important direction for future product design. If engineering tools contain critical or difficult-to-recover functional materials, then product design should not only optimize sensing performance, but also consider material traceability and end-of-life handling. Replaceable sensor modules, clearer material declarations, recoverable functional layers, and product-level documentation could help reduce the information barrier that currently limits recovery.

These policy developments do not solve the recovery problem by themselves, but they indicate the direction in which sensor-integrated products may need to develop. If future engineering tools contain critical or difficult-to-recover functional materials, then product design should not only optimize sensing performance, but also consider material transparency and end-of-life handling. For example, replaceable sensor modules, clear material declarations, recoverable functional layers, and digital product records could help reduce the information barrier that currently limits recovery. Such measures would be particularly important for materials like indium, where the technical amount used in one product may be small, but the broader supply and recycling system remains environmentally significant.

Overall, the main implication is that indium-based sensor materials should be evaluated through a combined performance-and-circularity perspective. A purely material-based assessment may overemphasize the small mass of the sensor layer, while a purely functional assessment may overstate the environmental benefit of sensor integration. A more balanced approach should ask whether the sensor provides measurable workshop-level improvements, whether its fabrication burden is proportionate to those benefits, and whether the material can be identified and responsibly managed at the end of life. Until more application-specific data are available, In_2O_3- and ITO-based sensor layers should be considered most defensible in high-value or high-risk machining applications where reductions in scrap, downtime, tool failure or rework are likely to be substantial enough to offset the additional material burden.

Taken together, these gaps show that the sustainability of indium-based sensor materials cannot be fully determined from present evidence alone. The most important future task is to connect material-level assessment with application-specific performance data. Only by combining information on fabrication burden, workshop savings, sensor durability and end-of-life recoverability can future studies determine whether indium-based sensor integration leads to a net sustainability benefit.

6. Conclusions

6.1. Main conclusions

This thesis examines indium-based sensor materials from a life-cycle-oriented perspective, with particular attention to indium oxide (In_2O_3) and indium tin oxide (ITO) used as thin-film sensor materials in industrial and manufacturing systems. Since detailed, application-specific data are still limited, the study does not attempt to perform a full quantitative Life Cycle Assessment. Instead, it develops a qualitative assessment of the main sustainability hotspots, challenges, trade-offs, and knowledge gaps associated with the use of these materials in engineering products.

One important point emerging from the analysis is that the small mass of a sensor layer does not, by itself, capture the sustainability relevance of In_2O_3 and ITO. Although these materials may be present only as thin functional films, they are connected to a much wider material system. This system includes by-product recovery, metallurgical processing, high-purity material preparation, thin-film fabrication, product integration, use-phase performance, material stewardship, and end-of-life management. In other words, the material quantity in the final product may be small, but the life-cycle context behind that material can still be significant.

The assessment therefore needs to consider both sides of the issue: the function enabled by the sensor material and the material pathway required to make that function possible. In high-value or high-risk manufacturing applications, the use of In_2O_3 and ITO may be easier to justify if sensor integration helps reduce scrap, rework, downtime, premature tool failure, non-productive energy use, or unnecessary material consumption. In lower-risk applications, however, the argument becomes less straightforward. If process losses are already limited, or if the benefits of sensor integration cannot be clearly measured, the sustainability case for using indium-based thin-film materials becomes more uncertain.

6.2. Answers to the research questions

Research Question 1:

How are indium-based sensor materials positioned within the upstream value chain, and what sustainability concerns arise from the by-product nature, supply concentration, and processing complexity of indium?

Indium-based sensing materials are associated with an upstream value chain strongly influenced by zinc-related production. Indium is usually not extracted through special native mining routes. On the contrary, it is mainly recycled as a by-product, which means that its availability depends on the production, recycling efficiency, refining capacity, processing restrictions and residue disposal of the associated metal.

This supply structure raises a number of sustainability concerns. The source of materials is not always easy to trace, and the supply data may be incomplete or mainly based on estimates. Environmental assessment has also become more complex because indium recovery is embedded in a broader metallurgical system rather than an independent production chain. Even if only a very small amount of indium is used in the film sensing layer, its upstream material path is still relevant.

Therefore, the supply risk is not only determined by geological scarcity. The concentration of refining capacity, geopolitical exposure, processing complexity and limited data transparency all affect whether indium can be supplied in a reliable way. Against this background, the EU's key framework is of reference value because it evaluates indium at the processing stage and emphasizes that recovery and refining are the core links in the upstream value chain.

Research Question 2:

What downstream sustainability considerations are relevant when In_2O_3- and ITO-based thin-film sensor materials are integrated into engineering products, particularly in relation to use-phase relevance, stewardship, toxicity-related aspects, and end-of-life recovery?

When In_2O_3 and ITO films are integrated into engineering products, they become part of a broader multi-material system. Their function is no longer just functional coating. In suitable applications, these materials can help achieve process monitoring, tool status monitoring, early fault detection, predictive maintenance, reduce waste products, reduce rework, extend tool life and improve process control.

However, these potential benefits should not be regarded as the automatic result of sensor integration. They depend on whether the sensor can work reliably for a long time, whether the signal quality is sufficient, and whether the information generated is really used for process decision-making. The sensing layer can provide technical capabilities, but its sustainability significance becomes clear only when this capability brings measurable improvements in the use stage.

Downstream sustainability also involves questions of stewardship and exposure control. A protected In_2O_3 or ITO thin film inside a finished engineering product is not the same as respirable indium-containing dust that may occur in production, maintenance, dismantling, or recycling environments. Toxicity-related concerns therefore need to be considered in relation to material form, exposure route, and life-cycle stage. The occupational exposure evidence discussed in Chapter 4 suggests that worker exposure may be relevant during material handling, powder processing, target production, deposition, maintenance, dismantling, and recycling.

End-of-life recovery is another major issue. Indium-containing sensor layers are thin, dispersed, strongly integrated with substrates, and difficult to identify or separate from larger engineering products. Recovery from manufacturing scrap and ITO sputtering targets is possible, but this does not mean that mature end-of-life recovery exists for sensor-integrated tools or durable engineering products.

Research Question 3:

Given the limited availability of application-specific environmental impact data, how can the identified upstream and downstream sustainability hotspots be interpreted in relation to the potential functional benefits of sensor integration?

The identified hotspots should be interpreted through a trade-off view. They should not be treated as simple evidence for or against indium-based sensor materials. The main burdens include by-product dependence, processing complexity, refining concentration, limited end-of-life recovery, toxicity-related handling needs, and data uncertainty.

These burdens need to be considered together with possible use-phase benefits. Sensor integration may reduce scrap, rework, downtime, auxiliary electricity use, tool failure, and other process losses. The workshop-level calculations in Chapter 5 show that even small improvements may help offset a low additional sensor burden, especially in high-value or high-risk machining applications.

The strength of this trade-off depends on the scale of the sensor burden and the size of the operational benefit. If the sensor burden is low and the use-phase improvement is measurable, the sustainability case becomes stronger. If the burden is high and the benefit is small or difficult to prove, the case becomes weaker.

For this reason, indium-based sensor materials need to be assessed through both performance and circularity. A mass-based view may miss upstream and end-of-life concerns. A function-based view may overstate the benefits of sensor integration. The assessment needs to ask whether the sensor provides measurable workshop-level improvements, whether its material and fabrication burden matches those improvements, and whether the indium-containing layer can be identified and managed at end of life.

6.3. Contributions of the thesis

This thesis contributes to the assessment of indium-based thin-film sensor materials by connecting their technical function with broader life-cycle concerns. Rather than viewing sensor materials only as technical components, the study places them within a wider material and product system. This system includes upstream supply, metallurgical processing, product integration, use-phase value, material stewardship, and end-of-life recovery.

A central contribution of the thesis is the life-cycle-oriented framework developed and applied throughout the study. This framework is useful in situations where full quantitative data are limited, which is often the case for emerging or specialised sensor-integrated manufacturing applications. It provides a structured way to identify where sustainability issues may arise across the material system, without requiring the level of inventory data needed for a full quantitative Life Cycle Assessment.

Another contribution lies in the attention given to material scale and material context. The thesis shows that the small mass of In_2O_3 or ITO in a sensor layer should not automatically be interpreted as low sustainability relevance. Even when used in very thin films, these materials remain connected to by-product supply, zinc-related recovery systems, refinery concentration, processing complexity, and limited circularity.

The thesis also develops a trade-off logic between material-system burdens and possible use-phase benefits. The machining workshop discussion illustrates this point in a practical way. Sensor integration may be more reasonable when it leads to measurable improvements, such as reduced scrap, lower downtime, reduced auxiliary electricity use, or longer tool life. Where such benefits are uncertain or difficult to demonstrate, the sustainability argument for using indium-based thin-film sensor materials becomes less straightforward.

6.4. Limitations and future outlook

The main limitation of this thesis is the type and detail of the data currently available. For In_2O_3 and ITO-based sensing layers used in industrial tooling and manufacturing products, the life cycle inventory data for specific applications is still limited. Therefore, this thesis does not quantify the complete environmental burden related to the preparation of sensing layers, the use of targets or precursors, deposition energy consumption, post-treatment, product integration, maintenance, replacement or recycling. Therefore, this assessment should be understood as a preliminary analytical framework rather than a complete quantitative sustainability evaluation.

The use stage also needs more detailed research. This thesis discusses the possible benefits, such as reducing waste, reducing downtime, extending tool life and saving auxiliary electricity. However, these benefits have not been measured in specific industrial cases. Future research needs to test the tools of integrated sensors in an experimental or industrial environment and collect data on their actual performance improvement during use. Relevant indicators can include reducing the scrap rate, avoiding rework, avoiding tool failure, shortening the idle time of the machine, reducing the energy consumption of each qualified product, and comparing the life of the sensor and the life of the host tool.

Recycling at the end of life is another area where the existing evidence is still relatively weak. Existing recycling research mainly focuses on LCD panels, flat panel displays, manufacturing waste and ITO sputtering targets. Thin sensing layers embedded in industrial tools or durable engineering substrates receive less attention. Therefore, future research should establish a more realistic end-of-life scenario for products with integrated sensors. At the same time, it is also necessary to examine whether material identification, modular design, product document recording or improved recycling technology can improve the feasibility of indium recycling.

On the basis of this work, a complete life cycle assessment study can be combined with upstream material data, detailed fabrication inventories, measured workshop performance data, and realistic assumptions about the treatment of the end stage of life. Such research will help move from a qualitative understanding of sustainability hotspots to a more quantitative assessment of the trade-offs involved in the use of indium-based thin film sensing materials.

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