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Material Flow Cost Accounting as a Resource-Saving Tool for Emerging Recycling Technologies

Caitlin Walls [1,2,*], Almy Ruzni Keumala Putri [2] and Gesa Beck [1,2,3]

1 ABCircular GmbH, Magnusstraße 11, 12489 Berlin, Germany; gesa.beck@ab-circular.de
2 Institute of Applied Resource Strategies IARS, SRH Berlin University of Applied Sciences, Ernst-Reuter-Platz 10, 10587 Berlin, Germany
3 Fraunhofer Applied Research Center for Resource Efficiency ARess, Brentanostr. 2a, 63755 Alzenau, Germany
* Correspondence: caitlin.walls@ab-circular.de

Abstract: Material Flow Cost Accounting (MFCA) is an environmental management accounting method that allocates costs to material and energy flows through a process, thereby enabling a simultaneous reduction in environmental impacts alongside an improvement in business and economic efficiency. This study illustrates the versatility of MFCA beyond its usual application to existing production and manufacturing processes. In this paper, MFCA is used to assess the financial viability of two emerging recycling technologies, IRETA2 (Development and Evaluation of Recycling Routes to Recover Tantalum from Electronic Waste) and ReComp (Development of an Innovative, Economically and Ecologically Sensible Recycling Method for Metallised ABS and PC/ABS Composite Waste). These two projects differ in their process structure. Whilst IRETA2 is a strictly linear recycling process, ReComp consists of two process streams, split according to the treatment of its two material fractions. For both projects, the lab-scale experimental results were used to develop an MFCA model of the recycling process scaled at each project partner's facilities. MFCA was utilised to calculate the projects' overall profit or loss, the impact of the final products' market conditions and processing rate (in the case of IRETA2), or machinery capacity (for ReComp) on the overall results. The results show that neither IRETA2 nor ReComp are financially viable based on the current output products' market value and quantity produced. However, through a sensitivity analysis, it is demonstrated that IRETA2 could become financially viable if the processing rate or market conditions were to improve. Additionally, ReComp could become financially viable if there was an increase in machine capacity. Finally, this paper also explores possible implications of MFCA when applied to emerging recycling technologies on EU policy and strategy, particularly those related to the EU Green Deal, such as extended producer responsibility and supply chain acts.

Keywords: circular economy; circular society; clean production electronic waste; clean technological processes; material flow cost accounting; metallised plastics; recycling

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1. Introduction

Material Flow Cost Accounting (MFCA) is an extension of Material Flow Accounting (MFA) which traces material and energy flows through a process, improving the transparency of material and energy use practices [1]. By associating these material and energy flows with costs, MFCA can identify the costs of material losses at each process step, which in turn assists in reducing environmental impacts and improving overall business efficiency [2].

MFCA first appeared around the late 1980s in Germany and represented the first time that the thermodynamic concept of mass balancing was applied to process flows. The thinking behind MFCA challenged the then-prevailing managerial notion that energy and mass were "consumed" by a process; that is, they were "lost" and not transferred into other forms, for example, products or wastes and emissions [3]. The perceived value of the method was demonstrated through its standardisation in 2011 as part of the Environmental Management Accounting (EMA) methods. Presently, it is guided by the International Standards Organisation (ISO) standard ISO 14051: 2011—Environmental management: material flow cost accounting. The standards define MFCA's key terms and definitions, its fundamental elements and basic steps for its implementation. According to DIN ISO 14051, "MFCA is a management tool that can assist organisations to better understand the potential environmental and financial consequences of their material and energy use practices, and seek opportunities to achieve both environmental and financial improvements via changes in those practices" [4]. The results of MFCA are generally not shared with parties outside the organisation.

In MFCA, inputs (such as materials, energy, water, personnel and machinery) and outputs (such as primary products, byproducts, wastes, wastewater and emissions) are determined within a pre-defined boundary (quantity centre). ISO 14051 defines a quantity centre as a "selected part or parts of a process for which inputs and outputs are quantified in physical and monetary units" [4]. Quantity centres most often represent parts of the process where materials are transformed [5], although they can also represent storage areas or transportation points [4]. The inputs and outputs into a QC are firstly defined in terms of physical units, and then converted to costs [6]. Within each QC, a calculation is undertaken for material, energy and system costs (including, e.g., personnel, rents, depreciation costs of machinery or rental fees) to allocate them to either products and byproducts or material losses [6]. Subsequently, resource efficiency optimisation processes consider the entire system of material flows at a detailed level, enabling impactful improvements to be made.

ISO 14051 provides flexibility in the definition of a product and byproduct. In this study, products are defined as any output that is marketable and can be sold to bring financial value to the process. Byproducts provide some other benefits, e.g., chemicals that can be recycled and thereby reduce waste management and material input costs. Byproducts also include materials obtained that have some financial value, but do not contribute to the profitability of the project because they are already obtained via "business-as-usual" recycling methods. A general MFCA flow chart showing these elements is provided in Figure 1.

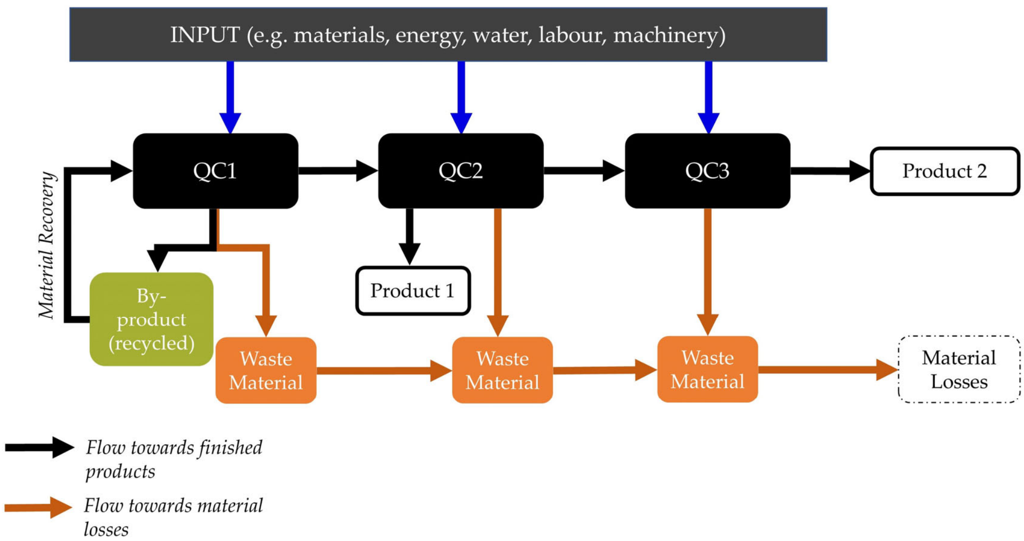

Figure 1. Simplified material flow model for a process with three quantity centres (QC1, QC2 and QC3), one byproduct and two products (Source: Adapted from DIN ISO 14051).

MFCA differs from the conventional cost accounting method, which generally focuses on determining whether any costs incurred are recovered from sales [2]. In conventional cost accounting, there is no differentiation of costs associated with products or wastes and inefficiencies [2]. In comparison, MFCA considers not just input–output differences, but focuses more on resource efficiency and the precise process steps where material losses appear [3]. The costs of the material losses contain the relevant fractions of the system, material and energy costs of all former process steps.

According to Christ and Burritt [1], although the knowledge of MFCA is increasing, the overall understanding of MFCA and its breadth of application is not well known. Additionally, Schaltegger and Zvezdov [7] identified that there is a limited application of MFCA in comparison to its potential, with most of its use focused on assisting with production related decisions. According to Schaltegger and Zvezdov [7], MFCA has the potential to contribute to the sustainable development of organisations, the economy and society. Correspondingly to Christ, Burritt, Schaltegger and Zvezdov's commentary, many studies conducted on MFCA focus on its application to existing production and manufacturing processes, and its contribution to achieving resource efficiency. For example, the Asian Productivity Organisation [2] provided a case example on a Japanese manufacturer of tapes, vinyl, LCDs, insulation and reverse osmosis membranes, Hyršlová et al. [6] demonstrated MFCA using the case study of ceramic tiles manufacturing in the Czech Republic, and Tran and Herzig [8] conducted a literature review of 28 case studies in developing countries all in manufacturing and production industries ranging from the textile industry to wood, plastics, oils and cement. Other study focuses have been, for example, determining the key motivations for applying MFCA. For example, Walz and Günther [9] analysed 73 MFCA case studies to understand why companies apply MFCA, their experiences of the implementation and the outcomes of MFCA regarding financial, environmental and strategic aspects. The authors found that the main reasons for companies to choose MFCA were to reduce costs or identify hidden costs (economic), reduce wastes or reduce the environmental impacts (environmental), or enhance quality and improve processes (organisational). They also found that one weakness of the MFCA method was its application in complex production processes. This is because, in this application, MFCA may not always be followed by the implementation of improvement measures due to the complexity of the process [9]. One possible approach for overcoming this challenge is applying MFCA in the initial stages of process design at the lab-scale. Evidently, there have been limited studies on the application of MFCA to conceptual process design, particularly for emerging technologies.

This study aims to demonstrate the applicability of MFCA to emerging recycling technologies using two case studies, IRETA2 (Development and Evaluation of Recycling Routes to Recover Tantalum from Electronic Waste 2) and ReComp (Development of an Innovative, Economically and Ecologically Sensible Recycling Method for Metallised ABS and PC/ABS Composite Waste). MFCA is used to determine the financial viability of these recycling technologies by modelling the upscaled processes at each respective project partner's companies. Through these two case studies, the importance of obtaining high-purity products and byproducts via green chemistry and avoidance of harmful chemicals is shown. The importance of improving process efficiency and throughput and the sensitivity of project viability to the spot price of primary materials is also demonstrated. Finally, this paper explores the possible implications of MFCA when applied to emerging recycling technologies on the European Union (EU) policy and strategy, particularly those related to the EU Green Deal. The EU Green Deal is Europe's overall growth strategy, outlining the overall ambitions and goals for the region. These strategies focus on achieving climate neutrality in the EU by 2050, economic development without increasing the consumption of natural resources, promotion of the circular economy and zero pollution [10]. This requires consideration of all stages of products and materials, including collection, recycling, and repurposing.

This paper starts with a general overview of the two project case studies, IRETA2 and ReComp in Section 2. In Section 3, the primary methods for this study are presented. Section 4 presents the results and discussion of the analysis, including discussion and analysis of the overall profitability of each project. A sensitivity analysis demonstrates the impact of the primary material's market conditions on each projects' viability. In Section 4.4 the implications of this paper and MFCA as applied to emerging recycling technologies are discussed in the context of EU policy. Finally, in Section 5, the conclusion of this study is presented.

2. Description of Case Studies

2.1. IRETA 2 (Development and Evaluation of Recycling Routes to Recover Tantalum from Electronic Waste 2) Overview

The IRETA2 project, funded by the Federal Ministry of Education and Research (BMBF) via the KMU-Innovativ Programme, Project No. 033RK080F, is the second research project of IRETA [11] with the aim of developing innovative recycling routes to recover tantalum from capacitors located on Printed Circuit Boards (PCBs). The project consortium included: Mairec Edelmetallgesellschaft mbH, smart Services VS GmbH, SLCR-Lasertechnik GmbH, ROBOT-TECHNOLOGY GmbH, Institute of Applied Resource Strategies (IARS) at SRH Berlin University of Applied Sciences, Bifa Umweltinstitut GmbH, Fraunhofer Applied Resource Centre ARess, Tantec GmbH and Tungsten Consulting GmbH.

Tantalum is a widely used metal in modern technologies, the chemical industry, medical industry (as implants) and electronics especially in small devices such as smartphones, tablets, and laptops. According to the EU Criticality Report (2020) [12], 40% of tantalum ores and concentrates are used in capacitors, making it the largest single consumer of tantalum concentrates. Tantalum is identified as a critical raw material for the European Union, primarily due to the high supply risk associated with political instability in The Great Lakes area in central Africa. This region is where more than half of the global supply of tantalum is produced [12]. Additionally, tantalum has an end-of-life recycling rate of less than 1% [13]. This is because the conventional pyrometallurgical process that is used for WEEE (Waste Electrical and Electronic Equipment) recycling mostly only recovers precious metals. In this process, tantalum and other non-precious metals are oxidised and lost in the slag [11]. Further, substitutes for tantalum capacitors are limited [12]. Alternatives include ceramic, standard aluminium or niobium capacitors; however, none provide the same high performance and long-term reliability at a small size [12].

The primary motivation for using MFCA in the IRETA2 Project is to determine the economic feasibility of upscaling the process at Mairec Edelmetallgesellschaft mbH (Mairec) using their existing PCB waste stream. That includes investigating the sensitivity of results to the processing rate, defined as the rate of disassembly of the capacitors from the PCBs, and the spot price of primary sourced tantalum oxide. The process is economically feasible when the recycled tantalum can be sold at a cost equal to or less than the spot price of primary sourced tantalum.

2.2. ReComp (Development of an Innovative, Economically and Ecologically Sensible Recycling Method for Metallised ABS and PC/ABS Composite Waste) Overview

The ReComp project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) via the Central Innovation Programme for Small and Medium Sized Enterprises (ZIM), Project No. ZF4774501CM9. In ReComp a recycling process for metallised plastics was developed in the laboratory of IARS at SRH Berlin University of Applied Sciences and Fraunhofer Applied Research Center for Resource Efficiency ARess together with the industrial partner Krall Kunststoff-Recycling GmbH. The aim of the project was to recover high-purity metals (copper, chromium and nickel) and plastic materials (PC/ABS-Polymer blend) from metallised plastic parts of automobiles from industrial waste. These metallised plastic parts are sourced from production waste due to the relatively high rejection rate in the electroplating process (up to 30%) [14] and from end-of-life vehicles. Another goal of ReComp is to avoid the formation of chromate along the recycling process, which, according to interviews with industry partners, is often formed during other existing hydrometallurgical recycling processes for such waste.

Copper, chromium, and nickel have high economic importance [12]. The production and processing operations of these materials are highly concentrated in a few countries, subjecting the supply to political instability, geopolitical concerns, and prospective export restrictions. Furthermore, the primary production process faces higher costs, emissions, and waste volumes due to decreasing ore quality caused by exploitation. This is a general phenomenon whereby ore quality has declined across commodities as high-quality deposits, and higher-grade regions of the deposits have already been exploited [15]. On the other hand, the use of petrochemical polymers in the production of plastic results in environmental concerns and the depletion of crude oil sources, leading to a volatile plastic market. Crude oil price volatility is primarily caused by political instability, supply and demand imbalances, and seasonal changes [16].

The aim of using MFCA in ReComp is to evaluate the feasibility of upscaling the lab-scale recycling process to industrial scale at the Krall Kunststoff-Recycling GmbH facility. Additional information is also obtained, for example the impact of byproduct recovery on the economic result, and the sensitivity of results to the final products' market conditions.

3. Methods

The MFCA approach used in this study is based on the standard method as outlined in ISO 14051 [2]. This includes the following steps:

- Involve management.
- Determine the necessary expertise.
- Specify the boundary and time period of the study.
- Determine the quantity centres: defined as the parts of the process where materials are transformed [5].
- Quantify the material flows in physical units. Five main categories describe the processes at each quantity centre: materials, energy, system costs (labour and machinery) and waste management.
- Verify via material balance across each QC.
- Cost classification: quantify the material flow in monetary units.
- MFCA data summary and interpretation
- Identification and assessment of improvement opportunities.

One key difference between MFCA applied to existing technologies, compared to emerging ones is that, in the former, processes are already scaled and fully operable. Therefore, data can be collected through financial accounting records, interviews with production staff and meter readings. In comparison, MFCA applied to emerging technologies relies on estimating and predicting future costs based on lab-scale efficiencies, upscaling experiments and characterisations of lab-scale product outputs, alongside a market analysis of available equipment and estimated economies of scale.

The method for applying MFCA to emerging recycling technologies is shown in Figure 2 and described in detail in Section 3.1 to Section 3.7.

3.1. Specify the Boundaries and Time Period of the Study

The project boundaries include all steps encompassed by the emerging recycling technology, starting with the input waste material and finishing with the production of high-quality, marketable products or byproducts.

The project boundaries for the IRETA2 study include all process steps required to recover tantalum from tantalum capacitors located on PCBs, starting with the optical detection of the capacitors and disassembly from the PCBs and finishing with oxidation to obtain high-purity Ta_2O_5 (>99.6%). Recycling of the electrolyte (CH_3SO_3H) for refining electrolysis and recovery of MnO_2 for sale are also included.

The project boundaries for ReComp include all processes following pre-processing (shredding), necessary to produce high-purity (>99.8%) metals and plastics from the shredded metal-coated plastics. The shredding was excluded as this occurs at the consortium partner's facility and would not constitute an extra process step if the technology would be installed. Therefore, the project boundary started with storage (required after shredding) and included QCs such as electrochemical treatment, filtration, and plastic dewatering to obtain deposited Cu, Cr particles, and PC/ABS. Electrolyte recovery was also included for obtaining the purified electrolyte for reuse.

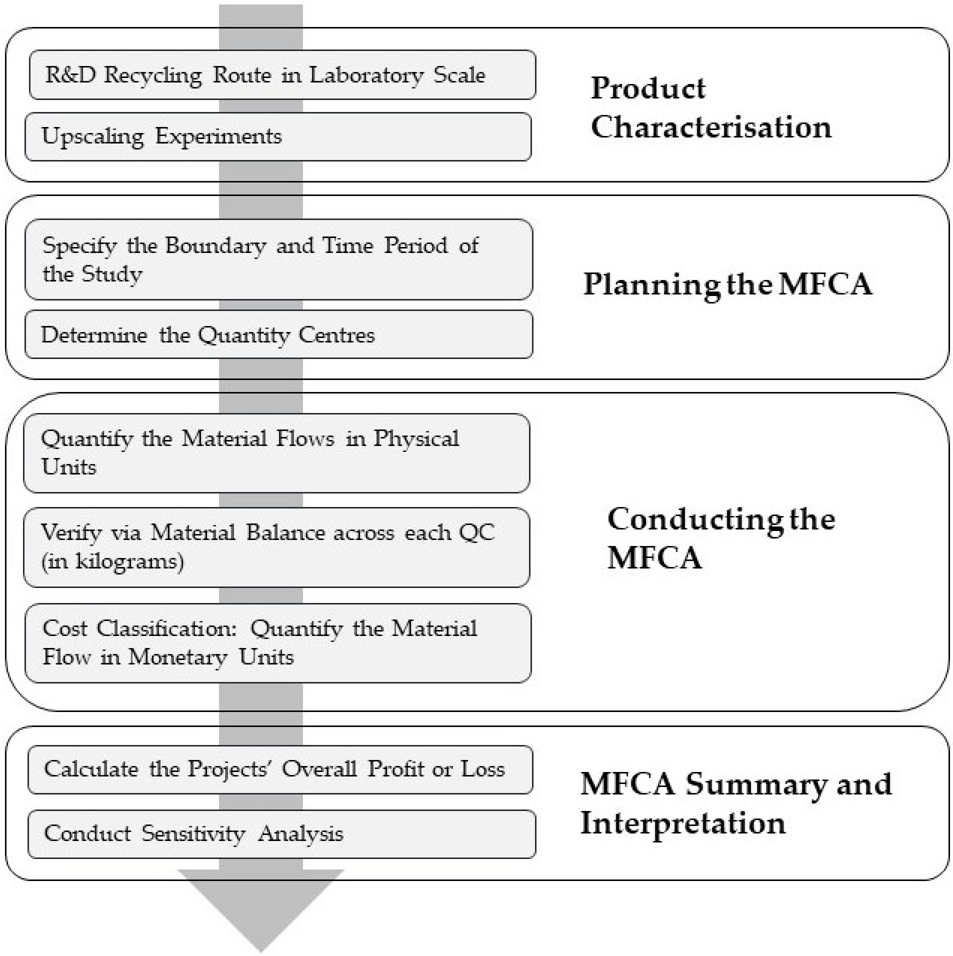

Figure 2. Summary of the MFCA approach for emerging technologies.

The period of data collection was each project's research duration, approximately three years. The time period used for the assessment was one year.

3.2. Determine the Quantity Centres

ISO 14051 defines a quantity centre (QC) as a "selected part or parts of a process for which inputs and outputs are quantified in physical and monetary units" [4]. Quantity centres most often represent parts of the process where materials are transformed, although they can also represent storage areas or transportation points [4].

The quantity centres for IRETA2 and ReComp were determined based on the lab-scale procedure. Each quantity centre represents a process step in which the input material was transformed or stored. In some quantity centres, valuable outputs such as products and byproducts were also produced. In this study, products are defined as any marketable output. Byproducts provide some other benefit, e.g., chemicals that can be recycled internally (e.g., by distillation), thereby reducing waste management and material input costs. Byproducts for IRETA2 also include materials obtained that have some marketable value but do not contribute to the overall profitability of the process, as they are already obtained at Mairec from business-as-usual pyrometallurgical recovery methods.

3.2.1. IRETA 2

A total of six quantity centres were chosen for the study, each representing a process step in the lab-scale procedure. No quantity centres for storage were modelled because this is already covered by business-as-usual processes at Mairec. The quantity centres are shown in Figure 3 and described in Table 1.

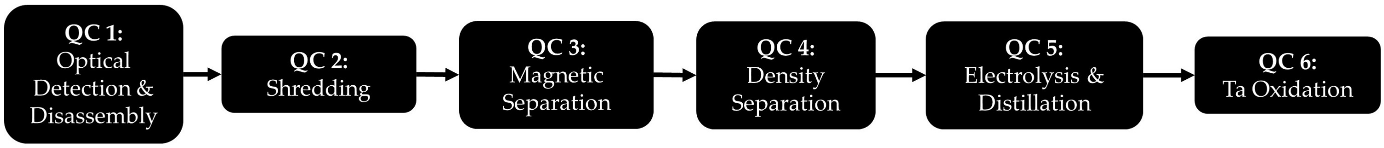

Figure 3. Graphical overview of the IRETA2 Quantity Centres.

Table 1. Description of IRETA2 Quantity Centres.

Quantity Centre	Process Description
QC 1: Optical Detection and Disassembly	Detection of the tantalum capacitors and removal from the PCB utilising a camera, fibre laser, conveyer belt and robots with grippers and accessory items. The capacitors are removed from the PCB via laser and compressed air to achieve the shortest processing rate possible (1 s per PCB + 0.3 s per capacitor). The PCB is turned and the capacitors from the other side are removed.
QC2: Shredding	Mechanical treatment via shredding to achieve comminution and separation of the epoxide resin and the metal contacts.
QC3: Magnetic Separation	Removal of ferrous metal contacts (Ni and Fe) from the shredded product using a permanent magnet and conveyer belt. Ni and Fe are returned to Mairec.
QC4: Density Separation	Removal of the epoxy resin casing (epoxy resin, Ag and C) via density separation with $ZnCl_2$ solution. $ZnCl_2$ solution is recycled. The epoxy resin casing and 90% of the silver (which sticks to the resin after shredding) is removed. The silver is returned to Mairec.
QC5: Electrolysis & Distillation	A 4 step-electrolysis process within a rotary drum electrode in 1-molaric methanesulfonic acid (CH_3SO_3H with sodium chloride) at room temperature is used to deliver mainly deposited Cu, precipitated AgCl, purified MnO_2 and purified Ta. CH_3SO_3H is distilled. Cu and AgCl are returned to Mairec. MnO_2 is sold as a product.
QC6: Oxidation	Oxidation of tantalum via heating to (800–900) °C for to remove traces of resin in air atmosphere to achieve high-purity Ta_2O_5.

3.2.2. ReComp

A total of six quantity centres were chosen for the study, including one quantity centre for storage. After electrochemical treatment, the single product stream is broken into two, one for coarse particles (i.e., the plastic particles that remain in the drum) and the other for fine particles (i.e., the chromium particles) and liquid electrolyte. The quantity centres are shown in Figure 4 and described in Table 2.

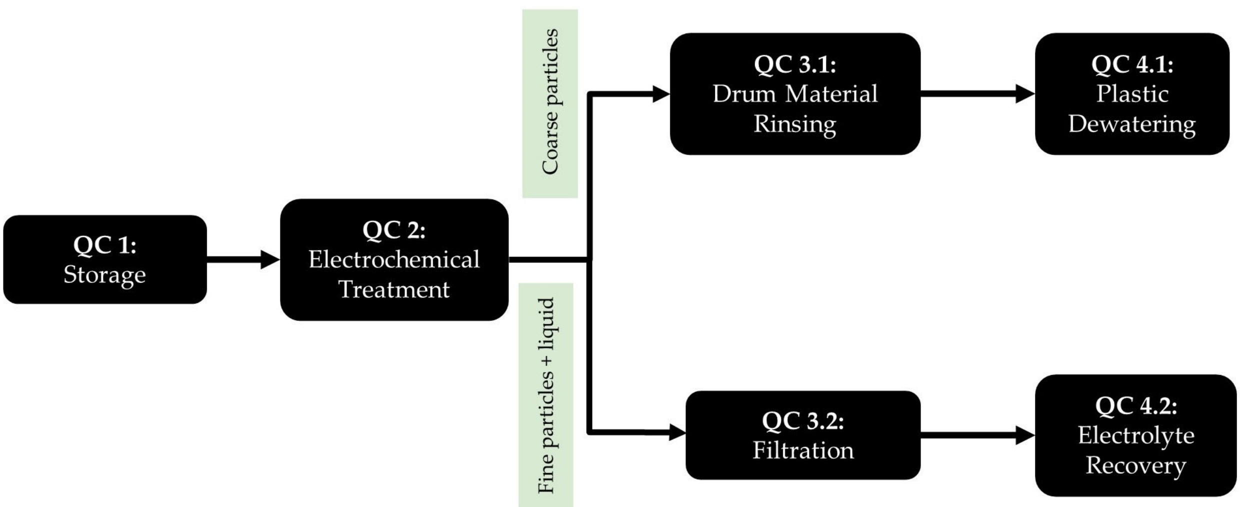

Figure 4. Graphical overview of the ReComp Quantity Centres.

Table 2. Description of the ReComp Quantity Centres.

Quantity Centre	Process Description
QC 1: Storage	The shredded metallised plastics are stored and prepared for the next batch in this quantity centre.
QC 2: Electrochemical Treatment (including Cu Deposition and Recovery of Cr as Flakes)	The pre-processed metallised plastic particles are filled in a rotary drum electrode. The drum is placed in a bath with an electrolyte (methanesulfonic acid, CH_3SO_3H) in a three-electrode setup (the drum is the working electrode, Cu foil as counter and standard-hydrogen as reference electrode). An electrical voltage is used to dissolve copper and nickel from the plastic (PC/ABS). The voltage is applied in a way that copper is deposited and chromium is not dissolved but separated as metal flakes.
QC 3.1: Drum Material Rinsing	Cleaning PC/ABS by using the drum from the former quantity centre and immersing it in water. Thereby the leftover of acid is neutralised and the plastic cleaned. This process can clean large volumes of plastic very effectively.
QC 4.1: Plastic Dewatering	Plastic dewatering is the removal of water from the solid. This process includes vacuum, centrifugation, filtration, solid–liquid separation processes, and removing residual liquids with a filter press.
QC 3.2: Filtration	Filtration is used to separate the Cr flakes from the electrolyte. A ceramic filter is required to carry this out. The solid (chromium) parts remain on the filter, and the liquid passes through the pores.
QC 4.2: Electrolyte Recovery	A distillation system designed to recover electrolyte by distillation. Nickel salt is produced as a waste. The distillation system can purify and concentrate various acids and mixed acid solutions.

3.3. Quantify the Material Flows in Physical Units

First, a material flow model was developed to quantify the material flow through each QC in physical units. The first iteration of the material flow model was based on lab-scale results and included basic qualitative information such as input materials, output materials, energy input type, machinery functionality and wastes. Other information, for example, the purity of the products and the process efficiency of each quantity centre for each product, was determined in the laboratory by using three analytical methods: X-ray Fluorescence (XRF), Inductively Coupled Plasma (ICP) and digital microscopy.

The extent of scaling was then defined in consultation with the consortium partners. In this case, the preferred MFCA model scale for both projects was upscaling at the consortium partners' facilities. Furthermore, upscaling experiments of the different technological steps were conducted in the laboratory.

The material flows for QC2 to QC6 for IRETA2 were calculated using the output (in kg) of capacitors from the optical detection and disassembly stage (QC1). The processing rate was limited by the rate of optical detection and disassembly (0.3 s per capacitor and 1 s for moving between PCBs). In comparison, for ReComp, the material flows for the QCs after QC2 were calculated based on the maximum throughput of the rotatory drum electrode. This machine had capacity up to 10 kg/cycle (i.e., 170 kg/annum) due to contact requirements between the metallised plastic and drum electrodes. The material flow after QC2 was split between the two fractions (coarse plastic particles within the drum, and fine chromium particles and liquid from the bath), as determined during the lab experiments.

The machinery and number of personnel required were determined in consultation with the consortium partners to ensure that the machinery met the technical requirements of the process and that the number of personnel reflected industry practice (including safety requirements). The machinery at each QC was generally sized based on the expected material throughput. Machinery costs were determined from quotes obtained from retailers and contractors. Based on the chosen machinery, the expected electricity usage was calculated.

The material model flows and units of measurement are summarised in Table 3.

The material flow diagrams with a qualitative description of the inputs and outputs for the categories of energy, materials, labour, wastes, products and byproducts for IRETA2 and ReComp are shown in Figures 5 and 6, respectively.

Table 3. Material model flows and units of measurement.

Energy	Materials (Input/Output)	Labour	Machinery	Wastes	Products	Byproducts
Kilowatt Hour	Kilogram	Hours	Quantity	Kilogram	Kilogram	Kilogram

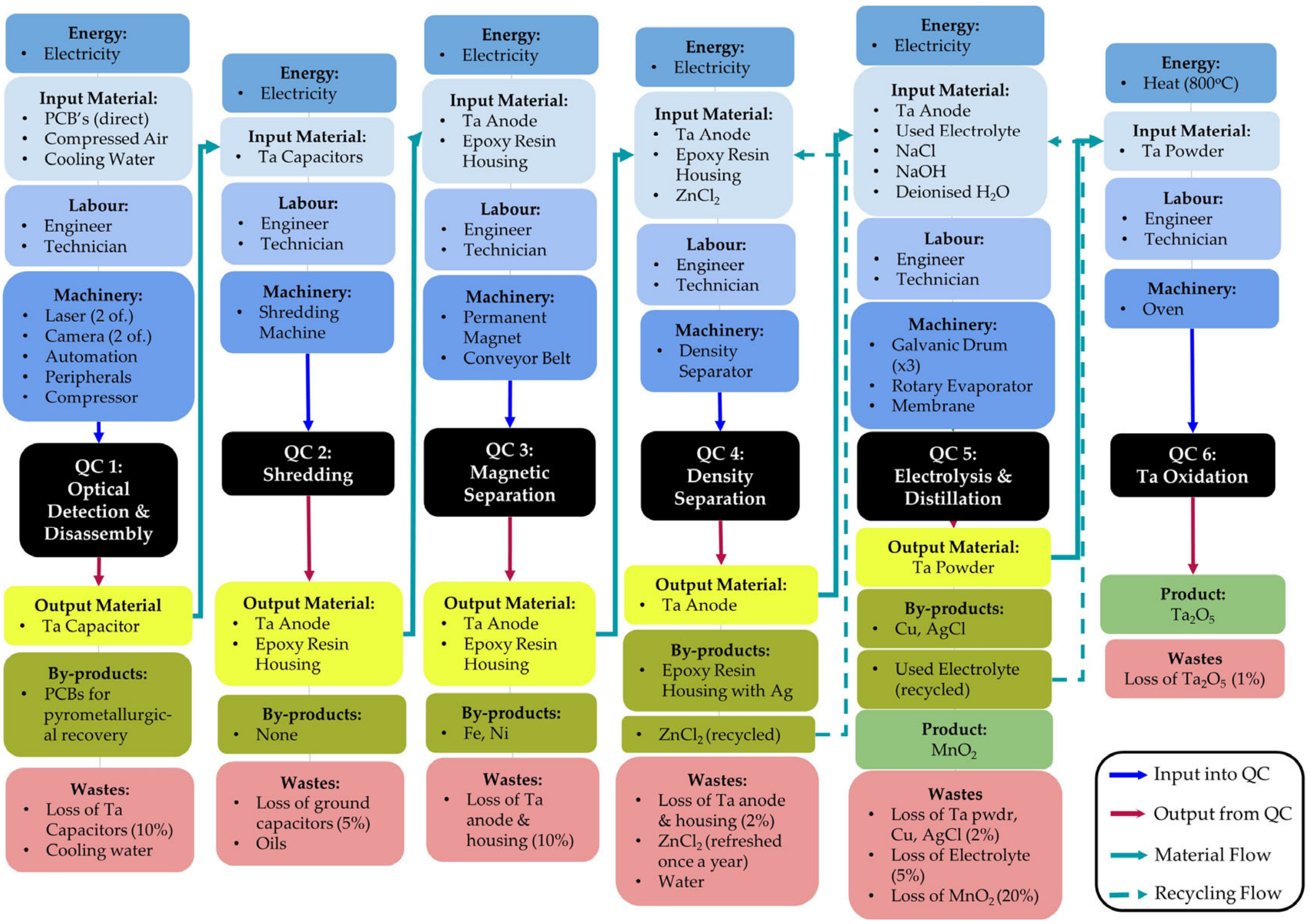

Figure 5. Qualitative material flow diagram for IRETA2.

3.4. Verify via Material Balance across Each QC

Following the definition of the quantity centres and material flows in physical units, a mass balance check (material balance) was conducted at each QC. This mass balance check required the input materials to be balanced with output materials, byproducts and wastes across each quantity centre.

The material balance required consistency of measurement units. In this study, the material balance was calculated using the measurement unit of mass (kilograms).

3.5. Cost Classification: Quantify the Material Flow in Monetary Units

Both studies classified the costs as material, energy, labour, machinery, and waste management costs. Machinery and labour costs are sometimes classified together as "system costs", which capture all costs associated with the in-house handling of the material flows excluding material, energy and waste management costs [4]. However, the two were separated in this study to allow for more granularity in the results.

The assumptions for developing each cost classification are listed as follows:

- Material costs: The material cost comprises two types: direct and indirect. Direct materials are generally those materials that are input at the beginning of the process (QC1). For IRETA2 the direct materials are the PCBs; for ReComp, the direct materials are the metallised plastics. Indirect materials are materials added at intermediary steps to facilitate the process in that quantity centre, for example, cooling water, compressed air and chemicals such as CH_3SO_3H or NaCl.

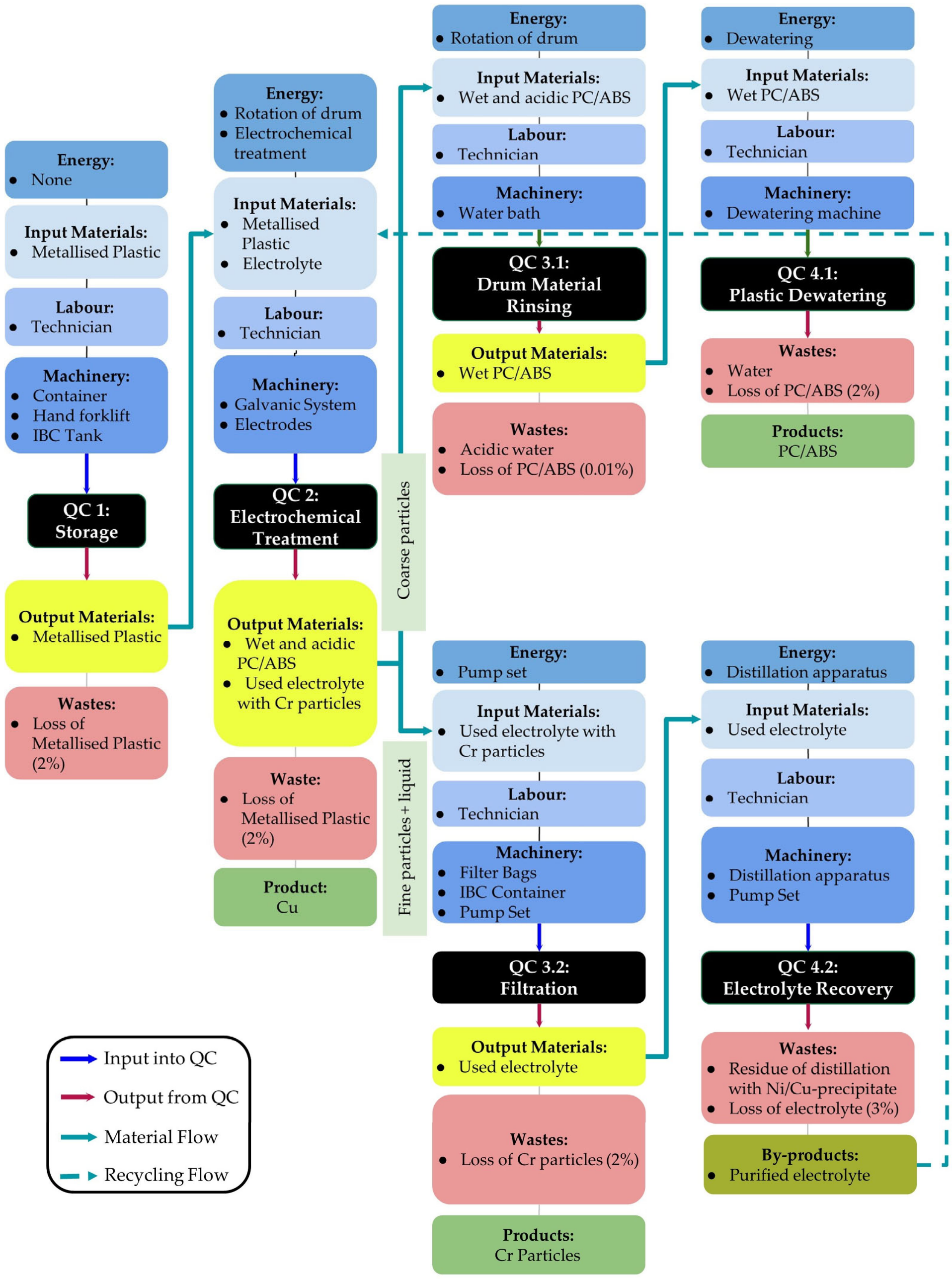

Figure 6. Qualitative material flow diagram for ReComp.

For both projects, the input materials have no initial cost associated with them. In IRETA2, the PCBs are waste materials currently processed by the company. Once the tantalum capacitors are removed, the PCBs are processed via business-as-usual pyrometallurgical recycling. Similarly, in ReComp, the metallised plastic materials have zero cost associated with them because they would be sourced from industrial production waste streams and, a small portion, from end-of-life vehicles.

The costs for the auxiliary materials are shown in Table 4.

Table 4. Costs for auxiliary materials used in IRETA2 and ReComp.

Auxiliary Material	Project	Quality	Provider/Manufacturer	Price EUR/kg (excl. VAT)
Water	IRETA2/ ReComp	Deionised Water	Berlin Wasserbetriebe (BWB)	0.05182 [17]
$ZnCl_2$	IRETA2	Purity ≥ 97.0% p.a.	Carl Roth GmbH Co. KG.	99.90 [18]
CH_3SO_3H	IRETA2/ReComp	Purity 99.5% p.a. ACS	Carl Roth GmbH and Co. KG	94.90 [19]
NaCl	IRETA2	Purity 99.5% p.a. ACS, ISO	Carl Roth GmbH Co. KG.	20.50 [20]
NaOH	IRETA2	Purity 99.0% p.a.	Carl Roth GmbH Co. KG.)	18.18 [21]

- Energy costs: The energy cost consists of electricity costs required to operate the machinery at each QC. Mairec provided the adopted electricity rate for IRETA2. This company currently purchases electricity from the power market at 0.40 EUR/kWh (source: Mairec). The electricity rates for ReComp were taken from the average industrial prices including tax in Germany for 2022 [22]. The current average industrial rates for 2022 are 0.27 EUR/kWh [22].
- Labour costs: the labour costs were obtained from each company's average production worker hourly rate (employer's gross) and were categorised as either a technician at 20 EUR/hr or engineer at 30 EUR/hr (source: company data).
- Machinery costs: The machinery cost calculation consists of three parts: the purchase price of the equipment, salvage value and depreciation rate. The purchase prices were obtained from vendor quotes. The depreciation rate and salvage value were determined based on advice from the various quantity centre owners regarding the operating environment (for example, in dusty environments, the equipment is expected to have a shorter lifespan). All machinery was given a zero-salvage value, with five or ten years of depreciation.
- Waste management costs: The waste management costs include all fees associated with the handling and disposal of waste by third parties. The cost of disposal of wastes other than wastewater was obtained from the Berliner Stadtreinigung (BSR) price list for disposal from trade, crafts, commerce and services with volumes less than 500 kg per producer and year [23]. The costs for disposing chemicals (for example, $ZnCl_2$) were obtained from waste disposal company quotes. The cost of wastewater was obtained from BWB and priced at 0.0022 EUR/kg [17].

3.6. Calculate the Projects' Overall Profit or Loss

The financial viability of each respective project was determined through consideration of all costs associated with material, energy, labour, machinery, and waste management, offset by the sale of products and byproducts.

3.6.1. IRETA2

The product outputs from IRETA2 are tantalum pentoxide and manganese dioxide. Although iron, nickel, copper and silver are also obtained from the process, they are not considered revenue-building as they would already be obtained via business-as-usual pyrometallurgical methods at Mairec.

The selling price for manganese dioxide was obtained from chemical manufacturing companies (e.g., Carl Roth). At the time of writing, the price of Manganese (IV) oxide, 1 kg (purity ≥ 98%) was EUR 135 (source: Carl Roth [24]).

As there is no existing and established recycling process for tantalum, the sale price of the primary sourced (mined) tantalum was used as the reference price. Price information for tantalum for this study was obtained from the commercial database AsianMetal, as published on the Preismonitor on the DERA Website [25]. This database represents the "spot price" of tantalum and provides prices for tantalum concentrate in the form of tantalum pentoxide at both 99.5% and 30% purity. The price of 99.5% purity tantalum pentoxide of 263 EUR/year (Jan 2023 prices) [25] was adopted for this study.

3.6.2. ReComp

The main product outputs from ReComp are high-purity copper electrodeposited on the copper electrode, chromium flakes, and PC/ABS around 2–8 mm long. Although nickel in salt form was also obtained from the process, it was not of high enough purity to be considered revenue and instead treated as a waste.

The main results for ReComp were calculated using each mineral's average price over 24 months (January 2021 to December 2022). These were 2.36 EUR/kg, 8.18 EUR/kg, and 1548 EUR/kg for PC/ABS (source: Plasticker [26]), copper (source: Gold.de [27]), and chromium (source: Institute for Rare Earths and Metals [28])

3.7. Sensitivity Analysis

A sensitivity analysis is one process by which the importance and dependency of the model inputs on the model outputs are determined [29]. In particular, the purpose of conducting a sensitivity analysis in the context of an MFCA for emerging recycling technologies is to determine the impact of the spot price of primary materials and, in the case of IRETA2, the processing rate on the project's financial viability.

The impact of the processing rate on IRETA2's financial viability was conducted by varying the optical detection and disassembly time in the critical path quantity centre, QC1. The purpose of this analysis was to determine a "breakeven" processing rate, whereby profit/loss of the process was EUR 0. This analysis was an iterative one, as after revising the processing rate, the capacity of all downstream machinery had to be verified and updated (if required) to ensure capacity for the additional throughput.

Another interesting sensitivity analysis variable was the primary product's spot price. Particularly for IRETA2, the spot price of tantalum has been subject to short-term extreme price increases primarily due to periods of rapid development in the electronics sector and concerns regarding supply shortages. For example, the "DotCom" boom in early 2001 led to a short-term boom in tantalum ore pricing from 75 EUR/kg to in 2000 to over 432 EUR/kg (Ta_2O_5) in 2001. This price quickly dropped back to 75 EUR/kg in 2002 due to increased inventory levels, less demand from the electronics sector than expected and a global downturn [13]. By varying the selling price of tantalum pentoxide in the MFCA, a "breakeven" spot price was determined, whereby the profit/loss of the process was EUR 0.

The impact of market conditions on ReComp was analysed by adjusting the selling price of the sellable products (PC/ABS, copper, and chromium) according to the 24-month ((January 2021 to December 2022) minimum, average, and maximum product spot prices. The adopted prices for the various materials and sources of information are shown in Table 5.

Table 5. Price developments of PC/ABS, Copper and Chromium over a 24-month period (January 2021 to December 2022). (Source: as shown in table).

Material	Price	Source
PC/ABS	Min: 1.27 EUR/kg	Plasticker [26]
	Max: 2.88 EUR/kg	
	Ave: 2.36 EUR/kg	
Copper	Min: 7.00EUR/kg	Gold.de [27]
	Max: 9.36 EUR/kg	
	Ave: 8.18 EUR/kg	
Chromium	Min: 1260 EUR/kg	Institute for Rare Earths and Metals [28]
	Max: 1836 EUR/kg	
	Ave: 1548 EUR/kg	

4. Results and Discussion

This section is divided into four main parts. Firstly, Section 4.1 contains an overview of the cost flow results through the quantity centres for IRETA2 and ReComp. Following this, Section 4.2 discusses the cost allocation and overall profit/loss results (main results). In Section 4.3, the results from the sensitivity analysis are analysed. Finally, in Section 4.4 the implications of MFCA applied to emerging recycling technologies on EU policy and the research industry are discussed.

4.1. Cost Flow Results

The cost flow results are shown in graphical form for IRETA2 and ReComp in Figures 7 and 8, respectively. These diagrams summarise the results of the cost allocation step of the MFCA procedure and show the cost input into each quantity centre, broken down by type (material, energy, labour and machinery). The costs are distributed to either the product or material loss cost according to the nominated efficiency for each quantity centre, as shown in Table 6 for IRETA2 and Table 7 for ReComp The waste management cost is the cost associated with the disposal of the material losses or any indirect materials that cannot be recycled.

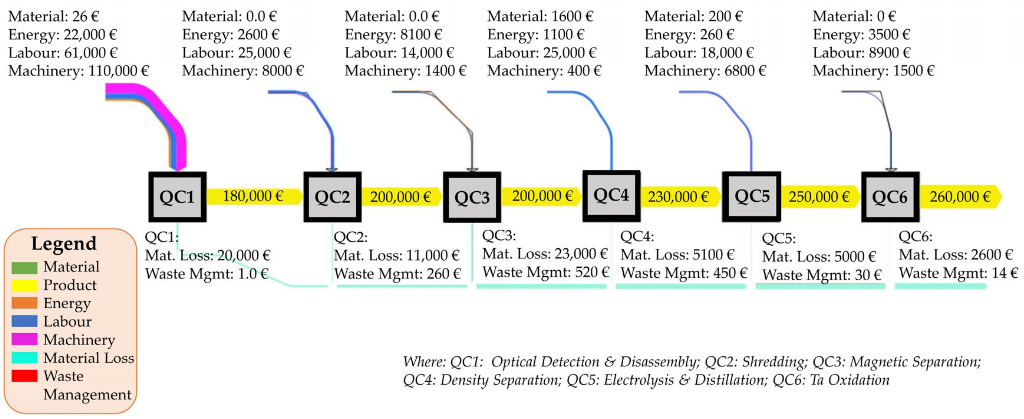

Figure 7. IRETA2 Cost Flow Diagram.

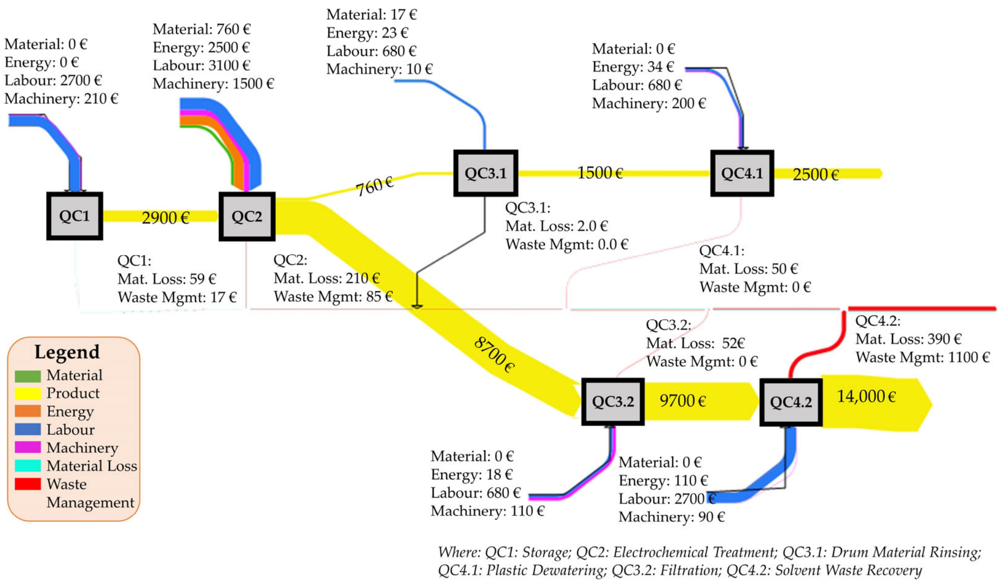

Figure 8. ReComp Cost Flow Diagram.

Table 6. Efficiency of IRETA2 QCs for producing intermediate and final products.

QC1	QC2	QC3	QC4	QC5	QC6
Ta capacitors 90%	Ground capacitors 95%	Ta anode & housing 90%	Ta anode & housing 98%	Ta pwdr, Cu, AgCl 98% Electrolyte 95% MnO_2 80%	Ta_2O_5 99%

Table 7. Efficiency of ReComp QCs for producing intermediate and final products.

QC1	QC2	QC3.1	QC4.1	QC3.2	QC4.2
Metallised plastic 98%	Metallised plastic 98%	PC/ABS 99.99%	PC/ABS 98%	Cr particles 98%	Electrolyte 97%

As shown in Figure 7, the costs for IRETA2 are dominated by the capital costs of the machinery in QC1. There are no material costs for QC2, QC3 and QC6 as there are no additional material inputs into these mechanically based QCs [shredding (QC2), magnetic separation (QC3) and oxidation (QC6)].

The cost flow results for ReComp are shown in Figure 8. According to the material flows, the product costs for ReComp are predominately attributed (90%) to the product costs which flow from QC2 to QC3.2 and QC4.2 (the fine particles and liquid fraction). Waste management and material losses contribute minimally to the overall cost of the process.

4.2. Main Results

In this section, further results of the cost allocation step are shown, alongside a discussion of the overall profit/loss for each project. Section 4.2.1 focuses on the results for IRETA2, whereas Section 4.2.2 on the results for ReComp.

4.2.1. IRETA2

Based on the current processing rate of 2.9 s per PCB in QC1 and 254 working days per year, 2.5 million PCBs (550 tonnes) or 16 million capacitors are processed per year. The current processing rate has been calculated assuming 0.3 s of disassembly time per capacitor + 1 s for moving between each PCB, with an average of 6.4 capacitors per PCB, according to a statistical analysis of the PCBs conducted by Mairec. Mairec currently receives in the order of 2000 tonnes of PCBs per year, indicating that there is a significant surplus in available feedstock for this process. Based on the current processing rate in QC1, around 980 kg of tantalum pentoxide can be obtained per annum. The overall efficiency of the IRETA2 process is 73%.

Figure 9 provides a breakdown of the total costs against each quantity centre. As shown in this graph, the quantity centre with the highest costs across all categories (materials, energy, labour, machinery and waste management) is QC1. This is primarily due to the high capital cost of machinery, including the laser, camera, automation and peripherals. These equipment costs constitute 60% of the total costs in QC1. Comparatively, the second highest cost contributor, QC2, consists of 70% labour costs.

Figure 10 provides a breakdown of costs for each cost category in IRETA2. As shown in this figure, labour costs contribute 50% of all costs of the IRETA2 process, followed by machinery and then energy. Waste management and materials contribute less than 2% combined to the overall cost of the process due to the development of highly efficient process steps and in-house recovery of used chemicals (electrolyte CH_3O_3H and $ZnCl_2$ solution). Materials contribute very little to the overall cost of the process because the input materials (PCBs) are obtained cost-free. Additionally, indirect materials are only required in QC4 and QC5. QC1, QC2, QC3 and QC6 require no additional indirect material inputs. Reducing the amount and toxicity of indirect materials also reduces the costs associated with waste management. In this case, costs are mostly attributed to disposing of material losses due to inefficiencies and are generally small (ranging from EUR 1–EUR 3 per kg) because of their low toxicity. The recycling of $ZnCl_2$ in QC4 and of electrolyte in QC5 also reduces the costs associated with regular chemical disposal. For example, instead of disposing of $ZnCl_2$ daily in QC4, it is cleaned and recycled and only disposed of and refreshed once a year.

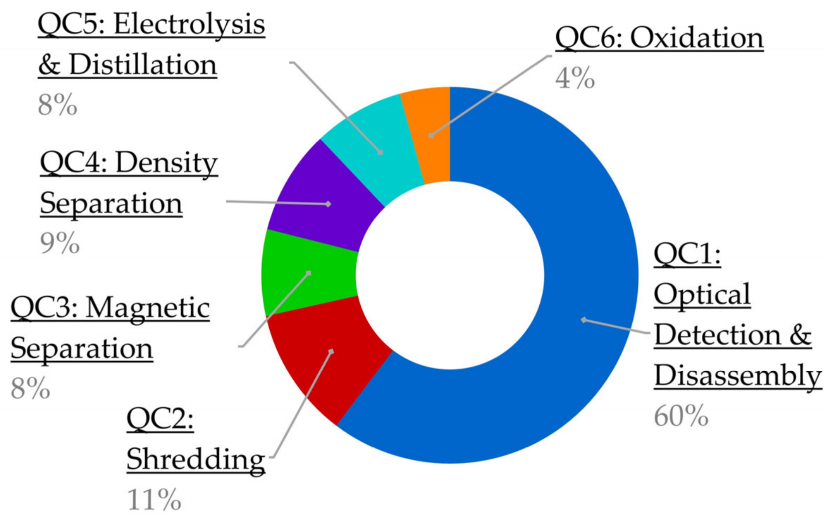

Figure 9. Breakdown of costs for each quantity centre, where the value indicates the percentage of the total cost for IRETA2.

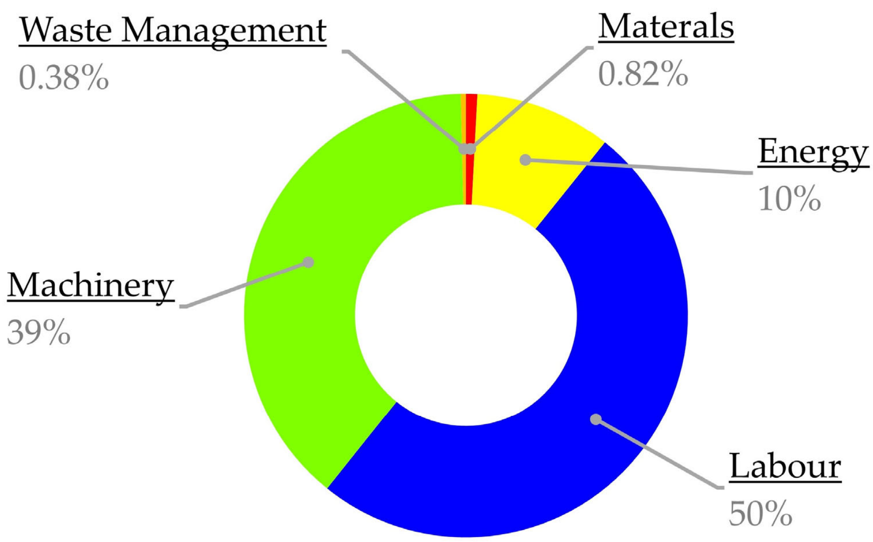

Figure 10. Breakdown of costs for each cost category in IRETA2, where the value indicates the percentage of the project's total cost.

A breakdown of the total costs and earnings associated with IRETA2 is summarised in Table 8. As shown in this table, based on the current operating costs of around 320,000 EUR/annum and the sale of MnO_2 and Ta_2O_5 at 135 EUR/kg and 263 EUR/kg, respectively, the upscaled process would make a loss of around 17,000 EUR/annum. This result is also shown visually in Figure 11, which shows the cumulative profit/loss graph. This graph shows a continuous output (loss) until QC5, during which manganese dioxide is sold.

Table 8. IRETA2 Process Costs and Earnings.

Process	Quantity Produced kg/annum	Costs/Earnings EUR/annum
Cost of Total Process	-	−320,000
Earnings from Ta_2O_5 (Sold at 263 EUR/kg)	980	260,000
Earnings from MnO_2 (Sold at 135 EUR/kg)	320	43,000
Profit/Loss	-	−17,000

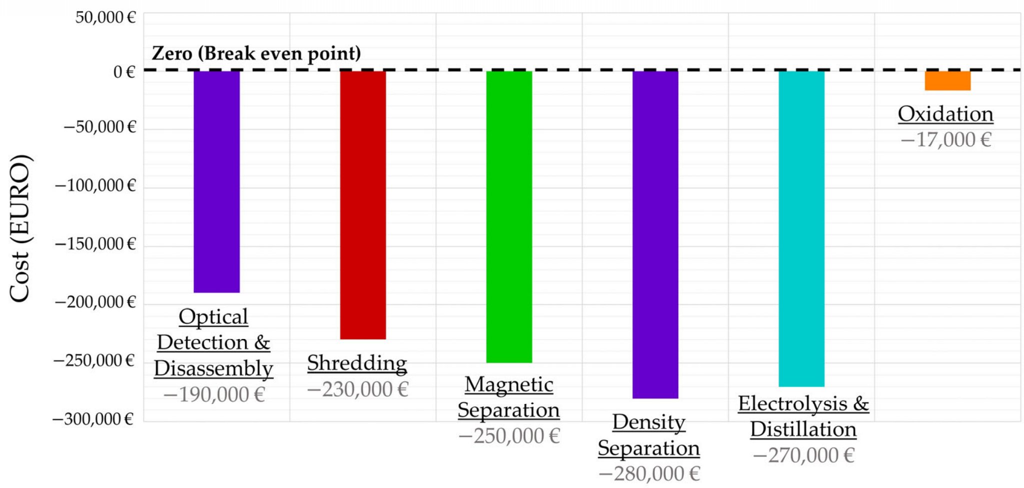

Figure 11. Cumulative profit/loss diagram for IRETA2.

4.2.2. ReComp

The MFCA calculation is based on the current throughput of 170 kg of metallised plastic per year. The throughput is currently limited to 10 kg per cycle by the capacity of the rotatory drum electrode in QC2. ReComp recovers approximately 13 kg of high-purity copper, 300 g of high-purity chromium, and almost 130 kg of the polymer blend PC/ABS.

As shown in Figure 12, QC2 is the highest cost QC (making up 47% of the total cost of ReComp), even with the recovery of electrolyte, due to the relatively high amount of labour and equipment (barrel electroplating machine, copper cathode and platinised titanium) needed to separate and recover high-purity copper, chromium and PC/ABS from the metallised plastic. QC4.2 has the second highest cost of all QCs (24%) due to labour costs incurred during the distillation process to recover the electrolyte and waste management costs associated with the disposal of the nickel salt. By recycling the electrolyte, this QC reduces the overall material costs by around 40,000 EUR/annum and waste management costs by around 3000 EUR/annum. The costs associated with QC1 comprise mainly of labour costs due to the manual transfer of input material into QC2, checking and receiving input and auxiliary materials and transferring the output materials and waste. QC3.1, QC3.2 and QC4.1 contribute the smallest amount to the overall process cost. These QCs have low machinery costs, low energy demand and require minimal labour.

Figure 13 provides a breakdown of costs for each cost category in ReComp. As shown in this figure, labour accounts for the largest percentage of total costs (61%) across the entire process, followed by costs for energy (15%), machinery (12%), waste management (6.9%) and material (4.5%). Of all the quantity centres, QC1, QC2 and QC4.2 require the highest amount of operator input. Material and waste disposal costs are kept low thanks to the recovery of the electrolyte in QC4.2 for reuse in QC2, as well as high efficiencies of all QCs (all $\geq$ 97%). Additionally, no toxic materials (for example chromate) are produced, therefore keeping waste management costs relatively low.

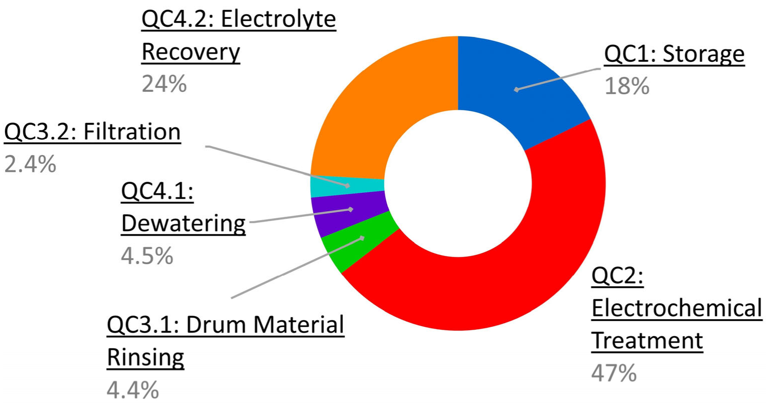

Figure 12. Breakdown of costs for each quantity centre in ReComp, where the value indicates the percentage of the total cost of the project.

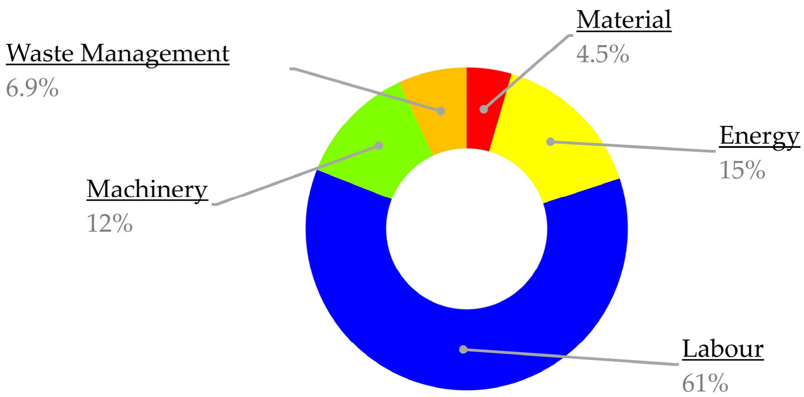

Figure 13. Breakdown of costs for each cost category in ReComp, where the value indicates the percentage of the total cost of the project.

Figure 14 and Table 9 presents the costs and earnings of each QC in ReComp. As shown in this figure, QC2 is the highest-cost QC. Chromium contributes the greatest revenue to ReComp, accounting for 54% of all revenue, followed by PC/ABS and then copper. Although only 0.32 kg of chromium is produced per annum, it is the most valuable product due to its high market value. ReComp currently makes a net loss of around 16,000 EUR/annum.

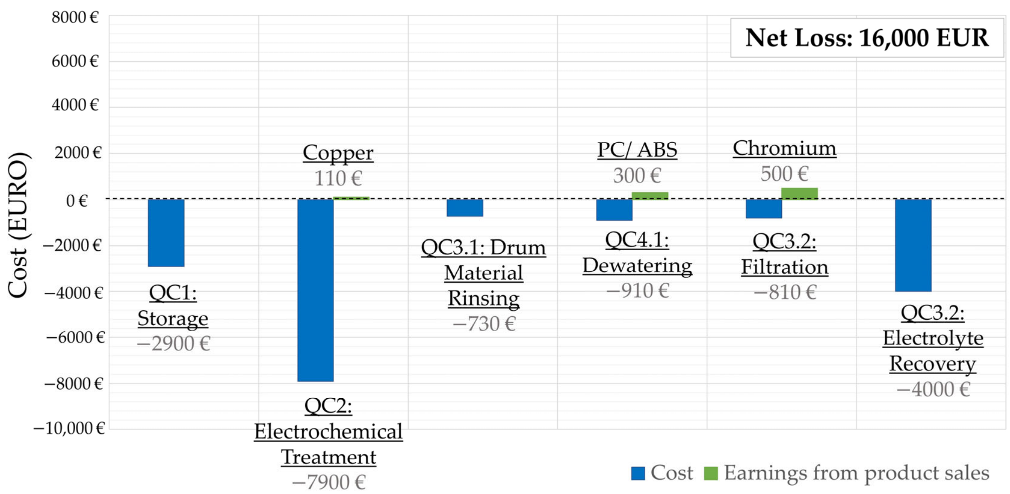

Figure 14. Costs and earnings from products and byproducts in ReComp.

Table 9. ReComp Process Costs and Earnings.

Process Costs/Earnings	Quantity Produced kg/annum	Costs/Earnings EUR/annum
Cost of Total Process	-	−17,000
Earnings from Copper (Sold at 8.18 EUR/kg)	13	110
Earnings from PC/ABS (Sold at 2.36 EUR/kg)	130	310
Earnings from Chromium (Sold at 1548 EUR/kg)	0.32	500
Profit/Loss	-	−16,000

4.3. Sensitivity Analysis

This chapter details the sensitivity analysis results for IRETA2 and ReComp. Section 4.3.1 outlines the results for IRETA2, namely, the breakeven selling point for tantalum pentoxide, and detection and disassembly rate in QC1. Section 4.3.2 discusses the impact of the final products' (copper, PC/ABS and chromium) market conditions on the financial viability of the ReComp project.

4.3.1. IRETA2

The purpose of the sensitivity analysis for IRETA2 was two-fold. The first was to demonstrate the sensitivity of the results to the spot price of tantalum pentoxide. Like many other technology metals, tantalum's market value is highly volatile. To demonstrate that the process could still be profitable under certain market conditions, the spot price of tantalum pentoxide that would cause the process to "break even" was determined. The second part of the sensitivity analysis involved exploring the impact of throughput on the project's financial viability by varying the processing rate of the optical detection and disassembly in QC1.

Based on the results for part one of the sensitivity analysis, the breakeven spot price of tantalum pentoxide was determined to be 286 EUR/kg. Based on historic data (refer to Figures 15 and 16), the spot price of tantalum has reached this breakeven point three times in the past fifty years. As shown in these figures, these events occurred in the year 2001, March to June 2017 and April to July 2022. Except for the 2001 prices, which was driven by the "DotCom" boom, the market prices did not significantly surpass the breakeven value. Additionally, the market prices only remained at this breakeven value for a few months, indicating that there would likely need to be other improvements to the overall process to achieve consistently favourable financial outcomes.

Such improvements to the process could come from reducing the processing rate, which would in turn enable a higher throughput of tantalum capacitors and, subsequently, a greater output of tantalum pentoxide. Based on the current spot price of 263 EUR/kg, the process would "breakeven" if the processing rate was reduced from 2.9 s to 2.7 s per PCB. Consequently, this results in an increase in tantalum capacitor throughput from 12.6 kg/day to 13.5 kg/day. All downstream machinery in the current MFCA model has the capacity for this increase in throughput. For example, the shredder in QC2 could comfortably process throughput up to 27 kg/day.

4.3.2. ReComp

The first part of the sensitivity analysis for ReComp focused on understanding the project's economic viability with respect to the volatility of the market value of PC/ABS, copper, and chromium. The likely profit obtained per year based on the minimum, average and maximum selling price of these materials was determined. Based on this analysis, it was found that the changing market price has no significant impact on the economic outcome of the project. In each case, the annual loss remains around 16,000 EUR/annum.

This is because only small amounts of the high-value products, for example chromium, are produced. In comparison, PC/ABS which make up most of the final product (over 90%) only fluctuates less than 2 EUR between the minimum and maximum price points.

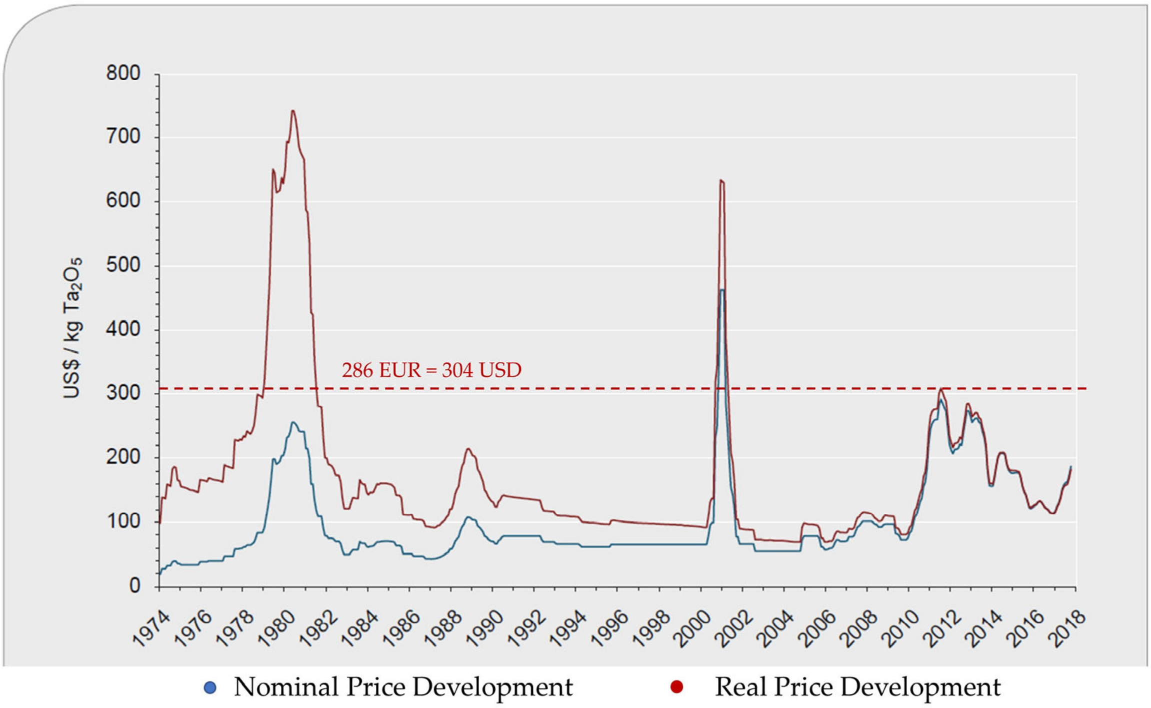

Figure 15. Historical price developments of Ta_2O_5 (99% quality) (Adapted from DERA [13]).

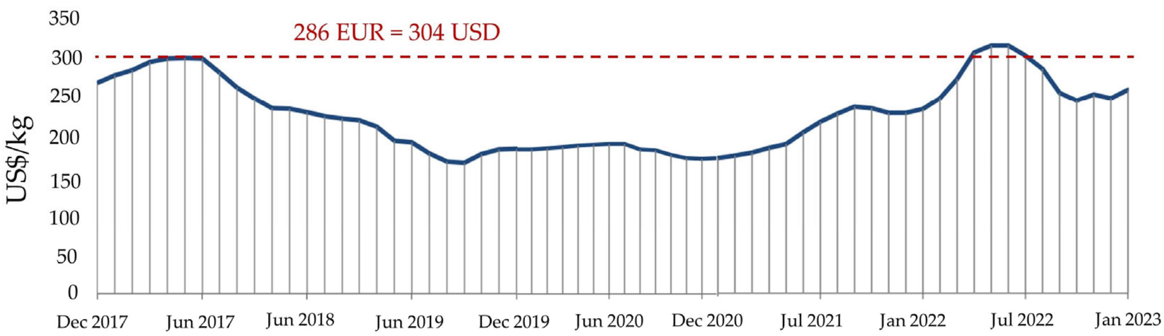

Figure 16. Recent price developments in Ta2O5 (99% purity) (Adapted from DERA [30]).

This process could become profitable by increasing the throughput of metallised plastic by about 10-fold, from 170 kg/annum to 1700 kg/annum. This increase in throughput would require an upgrade in machinery size, prompting an associated increase in labour and electricity use, all slightly offsetting the benefits from the increase in product output. This will be explored as part of a running second part of the project, ReComp 2.

4.4. Implications of the Results for Research, Industry and Policy

The results of this work, through the demonstration of the applicability of MFCA to emerging recycling technologies, has ongoing implications for the research and manufacturing industries as well as policy.

Particularly for the research and manufacturing industries, this paper demonstrates that MFCA is suitable for analysing emerging technologies and is not just limited to existing processes. Using MFCA, lab-scale projects can be modelled to analyse scenarios under which the process could be profitable at industrial scale. This can assist in guiding researchers to focus their efforts in improving efficiencies (that is, reducing the amount of material losses at each process step), avoiding waste formation, and improving the purity of output products, because high-purity products constitute the greatest economic gains. Consequently, the greatest economic output correlates to the smallest ecological impact, since waste does not require specialised disposal methods and the large amount of high-purity secondary materials (products produced through the recycling process) can be used in the same or similar products that produced the waste. Therefore, down-cycling is avoided and the route for close-looped recycling is strengthened. Accordingly, MFCA contributes to the EU Green Deal as it provides transparency to the recycling process. This is beneficial in communicating the technological and economic challenges associated with recycling, and the importance of considering "design for recycling" strategies (for example through improving product disassembly capabilities). MFCA also demonstrates that "green chemistry" can reduce the environmental and economic burden that can come with recycling using harmful chemicals due to the formation of toxic waste that is expensive to process and dispose of.

Furthermore, MFCA contributes to policy developments towards a more comprehensive regulatory framework on extended producer responsibility, which has already been seen in European and German policies surrounding products such as packaging, cars, WEEE or batteries. For example, the new European battery directive has focused on improving recycling efficiency and purities for all built-in materials and requires manufacturers, distributors or importers of batteries to contribute to the cost of recycling [31]. With similar directives of extended producer responsibility expected in the future, MFCA could be used to demonstrate the cost of recycling to companies and policy makers to assist them in planning and understanding expected costs.

The demand for recycled materials is expected to increase due to the overarching strategies of the EU Green Deal, that not only target improved recycling efficiency and material recovery, but also come with the consideration of social risks associated with the extraction, processing, and trading of raw materials. For example, the Supply Chain Act (Lieferkettengesetz) was established in Germany to better human rights protection, by making companies responsible for human rights treatments in their supply chains [32]. Companies will also be responsible for environmental protection, where environmental risks can lead to human rights violations. The law applies from 2023 to companies with a workforce of greater than 3000, and from 2024 to companies with at least 1000 employees [32]. Such laws will make recycled materials a much more attractive sourcing material. MFCA in this respect can contribute to demonstrating that it is possible to obtain high-purity, marketable products without the ecological and social issues associated with the primary sourced material.

5. Conclusions

MFCA, when applied to emerging recycling technologies, is a practical tool that enables a clear understanding of a project's financial viability when scaled from lab to project scale. It allows for a detailed analysis of the production process and can raise awareness of possible process inefficiencies that have both an economic and environmental impact. The profitability of these recycling processes can vary significantly depending on factors such as the processing rate and capacity of machinery, as well as the output products' market value, particularly for high-value products. Other factors such as the quality of the output product, the amount of waste and the process efficiency also play an important role in determining the profitability of the process.

The financial viability of IRETA2 was shown to be highly dependent on the spot price of the final product, tantalum pentoxide and the optical detection and disassembly rate. Based on a current spot price of 263 EUR/kg and a processing rate of 2.9 s per capacitor, the process is currently not financially viable and makes a loss of around 17,000 EUR/annum. However, if the spot price of tantalum were to increase to over 286 EUR/kg, or the processing rate would reduce to 2.7 s per capacitor, the process would break even. Any spot price higher than this point or improvement in processing rate would produce profit and make the process financially viable.

The implementation of MFCA in ReComp has demonstrated that the process is not yet financially viable based on the current throughput of 170 kg/annum of metallised plastic. This is limited by the capacity of the rotary drum electrode in QC2. Price developments in the marketable products (PC/ABS, chromium and copper) within the last 24 months do not change the overall result, because of the small amounts of high-value products (chromium) produced. Comparatively, plastic, which constitutes over 90% of the final product output, has a relatively low market value. The project could become profitable with an approximate 10-fold increase in the processing capacity. This will be explored in the running second part of the project, ReComp 2.

Overall, if recycling processes are to be competitive to primary product production methods, recycling needs to produce high-purity products (at least as high as the primary product) and the process needs to be profitable under various primary product market conditions.

Finally, this paper demonstrates that MFCA can provide insightful information for industries involved in developing emerging recycling technologies and policy makers in improving the uptake of recycling. One of the key benefits of MFCA is that it provides transparency to material flows during the recycling process, as well as the costs associated with recycling processes. This contributes to assisting industry to understand the implications of meeting demands from policies developed particularly under the EU Green Deal. For example, MFCA can help industry and policy makers plan for the economic implications associated with the anticipated widening of extended producer responsibility regulatory frameworks and social risk management policies for supply chains.

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