resources

MDPI

Article

Carbon Footprint of Additively Manufactured Precious Metals Products

Mario Schmidt [1,*], Jochen Heinrich [2] and Ingwar Huensche [2]

[1] Institute for Industrial Ecology, Pforzheim University, Tiefenbronnerstr. 65, 75175 Pforzheim, Germany
[2] C. Hafner GmbH + Co. KG, Maybachstraße 4, 71299 Wimsheim, Germany
* Correspondence: mario.schmidt@hs-pforzheim.de; Tel.: +49-7231-28-6406

Abstract: Traditionally, precious metals are processed by either lost-wax casting or the casting of semi-finished products followed by cold or hot working, machining, and surface finishing. Long process chains usually conclude in a high material input factor and a significant amount of new scrap to be refined. The maturing of Additive Manufacturing (AM) technologies is advantageous with regard to resources among other criteria by opening up new processing techniques like laser-based powder bed fusion (LPBF) for the production of near net shape metal products. This paper gives an insight into major advantages of the powder-based manufacturing of precious metal components over conventional methods focusing on product carbon footprints (PCF). Material Flow Cost Accounting (MFCA) for selected applications show energy and mass flows and inefficient recoverable losses in detail. An extended MFCA approach also shows the greenhouse gas (GHG) savings from avoiding recoverable material losses and provides PCF for the products. The PCF of the precious metals used is based on a detailed Life Cycle Assessment (LCA) of the refining process of end-of-use precious metals. In the best case, the refining of platinum from end-of-life recycling, for example, causes 60 kg CO_{2e} per kg of platinum. This study reveals recommended actions for improvements in efficiency and gives guidance for a more sustainable production of luxury or technical goods made from precious metals. This exemplary study on the basis of an industrial application shows that the use of AM leads to a carbon footprint of 2.23 kg CO_{2e} per piece in comparison with 3.17 kg CO_{2e} by conventional manufacturing, which means about a 30 percent reduction in GHG emissions and also in energy, respectively.

Keywords: product carbon footprint (PCF); material flow cost accounting (MFCA); precious metal; additive manufacturing; powder bed fusion; precious metal alloys; gold; platinum

Citation: Schmidt, M.; Heinrich, J.; Huensche, I. Carbon Footprint of Additively Manufactured Precious Metals Products. *Resources* **2024**, *13*, 162. https://doi.org/10.3390/resources13110162

Academic Editor: Benjamin C. McLellan

Received: 28 June 2024
Revised: 14 October 2024
Accepted: 12 November 2024
Published: 20 November 2024

1. Introduction

Producing items from precious metals like gold, platinum, palladium, iridium, and similar materials involves significant expense. During conventional processing, these metals undergo numerous stages, including casting, cold or hot forming, machining, and, ultimately, surface finishing. Such processes not only require considerable time but also consume substantial energy, thereby significantly affecting the environmental and carbon footprints. This often results in products containing only a minor percentage of the initial material input, along with large amounts of material needing refinement. Frequently, the material yield is less than 20% [1]. While clean scrap can be directly remelted, refining contaminated chips incurs considerable costs. Even with minimal material loss, this process demands extra energy input. Moreover, the extended processing time for the material escalates capital investment and consequently the costs. Given the value of precious metals, every gram is critical; material yield is a key determinant of not just economic viability but also for the environmental and climate impact of products and the efficient use of natural resources.

Additive Manufacturing (AM) is revolutionizing the way we approach this production process [2,3]. This technique not only enhances resource efficiency but also opens new avenues in applications and material innovation [4,5]. AM facilitates the creation of components through a process of layer-by-layer material addition and fusion. Fundamentally, it can be categorized into two distinct principles of AM [6]. On the one hand, in multi-step sintering-based methods like binder jetting, a blend of binder and metal powder is initially laid out and subsequently thermally converted into the final metal component. On the other hand, with single-step processes such as "laser metal fusion" (a laser powder bed fusion technology provided by the AM machine manufacturer TRUMPF) employed here, metal powder is layered without additives and laser-fused into completed components. The metal powder along the laser's path is melted to form a three-dimensional object, achieving vertical material thicknesses as fine as 200 micrometres depending on the material composition. Sections featuring undercuts, channels, or hollow formations are not melted and stay as loose powder, which can be directly reused.

Ingenious designs can further enhance the resource efficiency of products. For instance, luxury items like rings or watch strap links, traditionally crafted from solid material, can now be fashioned as hollow structures, thereby diminishing both material usage and weight. The near net-shape manufacturing by AM is also a key factor in increasing yield and decreasing the material input factor, respectively. This is especially advantageous for platinum group metal (PGM) alloys where processing and refining is unlike intricate because of the physical and chemical properties [7].

This article aims to highlight the reductions in greenhouse gas (GHG) emissions achievable through the AM of precious metals. Given the substantial carbon footprint of precious metals, AM is expected to show significant benefits in this context. However, precise numerical data on this aspect are currently unavailable.

The carbon footprint of AM is chiefly influenced by two factors: the direct energy consumption of each process step and the material efficiency. Through their literature review, Torvi et al. (2023) identified a gap in established methodologies for tracking energy consumption in AM and suggested a technique for the detailed visualization of energy use via Sankey diagrams [8]. Nevertheless, they did not consider material flow and yield, aspects that are especially critical when dealing with precious metals. In their literature review on the Life Cycle Assessment (LCA) of AM, Kokare et al. (2023) addressed this factor, though their focus was not on precious metals [9]. They noted that AM tends to require more energy than traditional manufacturing processes. However, in cases of intricate product geometries or substantial material loss in conventional methods, AM could offer enhanced sustainability owing to improved material utilization [9,10]. Illustrated by the case of the electron beam melting (EBM) of a titanium alloy product, Lunetto et al. (2021) demonstrated that AM offers distinct advantages over traditional processing, particularly regarding CO_2 emissions [11].

Initially, this article examines the carbon footprint of precious metals, emphasizing those recovered from high-grade scrap (like jewelry). This is necessary because refining is the decisive factor in terms of the use of resources and energy. The study is based on a real case in which end-of-life recycling material is used as input. If primary materials were to be used, the carbon footprint of the product would be higher in both cases. Next, it compares the material and energy inputs of conventional production and AM through a specific case study, determining the savings in carbon footprint. For this analysis, Life Cycle Assessment (LCA), Material Flow Cost Accounting (MFCA), and related software tools are employed. What is special about this analysis is that it shows the process chain in detail, as well as the possible savings potential in each individual process and how these potentials interact in the overall system if they are all realised. This provides valuable information for decision-makers regarding the potential for improvement, which relates to both economic and environmental or resource impacts.

2. Materials and Methods

2.1. Carbon Footprint of Secondary Precious Metals

In contrasting AM with conventional processing (CM), it is crucial to consider not only the energy and operational material consumption for each process step but also the input and output volumes of precious metals and their associated carbon footprints. Typical LCA databases contain only general values for precious metals, often derived from limited and estimated data sources. This LCA [12] was compiled following the guidelines of ISO 14040/44 [13,14] and underwent a critical review by Dr. Rolf Frischknecht of Treeze (CH) in 2022.

C.Hafner represents a cutting-edge refining facility located in southern Germany. The facility specializes in refining precious metal scrap post-use (end-of-life scrap) and precious metal-bearing waste (referred to as skimmings or sweepings). In addition to gold, materials like silver, platinum, and palladium are refined into their pure forms. These four precious metals are extracted from both high-grade scrap and lower-grade skimmings. The high-grade scrap undergoes hydrometallurgical processing. A key process involved is the aqua regia method [15]. These refined precious metals are supplied in diverse forms, such as ingots or granules, primarily to industrial clients for further processing.

The Life Cycle Assessment (LCA) was developed using Umberto® software (Version 11), incorporating the Ecoinvent 3.7.1 database for supplementary background data. Such background data encompass elements like electricity supply and operational materials. A cradle-to-gate approach was adopted for the system boundaries, meaning the subsequent utilization of the precious metals was not considered. C.Hafner exclusively employs recycled metals for these types of products, not sourcing from mines, hence the LCA included only metals recycled from end-of-life high-value scrap. An allocation based on the cut-off approach was implemented, disregarding the impacts from the scrap's prior life cycle. This approach is valid for the current analysis, focusing primarily on the recycling of internal scrap. Should an alternative allocation be applied, a varied offset value for the incoming end-of-life scrap would be required, which could be easily correlated with the current findings. Given that refining is a process yielding multiple products, an allocation among the different precious metals was necessary, for which a monetary basis was chosen. The carbon footprints per kilogram of metal are graphically illustrated in Figure 1. For instance, the carbon footprint of recycled gold is approximately 40 kg CO_2 equivalent, varying with the form of the gold. This figure is nearly 500 to 1000 times lower than that of primary gold sourced from mining [16,17].

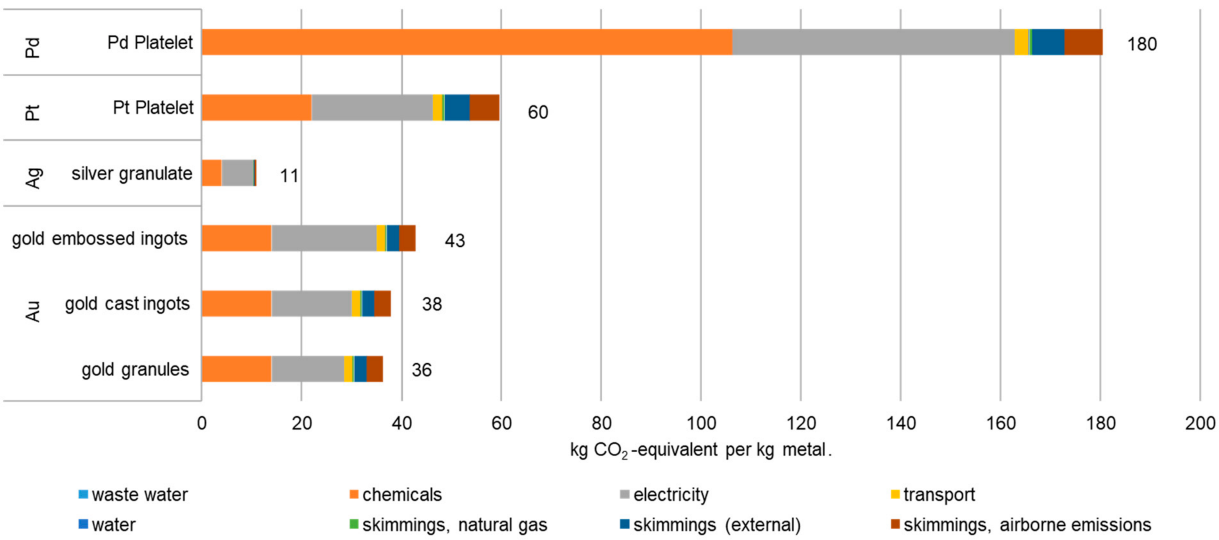

Figure 1. The carbon footprint of various precious metals at C.Hafner, recovered from high value scrap. Source: [12].

A Life Cycle Assessment (LCA) encompasses a broader range of environmental impact categories beyond just climate change. Results pertaining to additional impact indicators for these four metals are consolidated in Table 1. These were derived from impact indicators frequently cited in scientific publications [18] and were benchmarked against other LCAs focusing on precious metals. Fourteen distinct impact categories were chosen for selection and analysis. Consequently, up-to-date data sets for the advanced refining processes of the four distinct precious metals are now accessible.

Table 1. Results for the impact categories of the four different precious metals from state-of-the-art refining (cut-off, cradle-to-gate) [12]. For an explanation of the units, see [18].

Per Kg of Metal Impact Indicator	Silver Granulate	Gold Cast Ingots	Gold Embossed Ingots	Gold Granules	Palladium Platelet	Platinum Platelet	Unit
Climate change	1.10×10^{1}	3.79×10^{1}	4.28×10^{1}	3.63×10^{1}	1.83×10^{2}	5.96×10^{1}	kg CO_2 eq.
Human toxicity, cancer	3.50×10^{-7}	2.11×10^{-6}	2.20×10^{-6}	2.09×10^{-6}	7.35×10^{-6}	3.64×10^{-6}	CTUh
Human toxicity, non-cancer	6.34×10^{-6}	5.21×10^{-5}	5.25×10^{-5}	5.19×10^{-5}	1.46×10^{-4}	1.01×10^{-4}	CTUh
Particulate matter	2.50×10^{-7}	1.57×10^{-6}	1.61×10^{-6}	1.56×10^{-6}	5.50×10^{-6}	1.92×10^{-6}	disease incidence
Ozone depletion	2.24×10^{-6}	6.47×10^{-6}	6.61×10^{-6}	6.43×10^{-6}	4.28×10^{-5}	1.08×10^{-5}	kg CFC-11 eq.
Photochemical ozone formation	2.20×10^{-2}	8.83×10^{-2}	9.49×10^{-2}	8.62×10^{-2}	4.08×10^{-1}	1.40×10^{-1}	kg NMVOC eq.
Ecotoxicity, freshwater	1.45×10^{1}	9.78×10^{1}	9.95×10^{1}	9.73×10^{1}	3.69×10^{3}	6.97×10^{2}	CTU
Eutrophication, freshwater	1.17×10^{-3}	3.19×10^{-3}	3.96×10^{-3}	2.95×10^{-3}	1.36×10^{-2}	4.99×10^{-3}	kg P eq.
Eutrophication, marine	8.02×10^{-3}	2.51×10^{-2}	2.72×10^{-2}	2.44×10^{-2}	1.58×10^{-1}	4.64×10^{-2}	kg N eq.
Acidification	3.90×10^{-2}	2.35×10^{-1}	2.46×10^{-1}	2.31×10^{-1}	8.57×10^{-1}	2.91×10^{-1}	mol H^+-eq
Resource use, minerals and metals	1.10×10^{-4}	4.40×10^{-4}	4.82×10^{-4}	4.27×10^{-4}	2.46×10^{-3}	7.16×10^{-4}	kg Sb eq.
Land use	7.70×10^{1}	4.63×10^{2}	4.86×10^{2}	4.56×10^{2}	1.36×10^{3}	5.22×10^{2}	Points
Water use	5.25×10^{0}	1.87×10^{1}	1.96×10^{1}	1.84×10^{1}	1.27×10^{2}	2.85×10^{1}	m^3 water eq.
Cumulative energy demand	1.77×10^{2}	6.17×10^{2}	7.03×10^{2}	5.90×10^{2}	3.21×10^{3}	9.98×10^{2}	MJ eq

2.2. System Boundaries of the Internal Refining

A significant challenge lies in accurately determining the carbon footprints associated with the internal scrap flows. Within C. Hafner's operations, it is essential to differentiate among three distinct system areas. Skimmings or sweepings, which are waste with a minimal content of precious metals, undergo incineration and subsequent refining, resulting in a relatively high specific carbon footprint. This process is identified as system A in Figure 2. Metals derived from the direct refining of high-value scrap exhibit a low carbon footprint. Representing the bulk of the mass flow, these are designated as System B in Figure 2. Materials from both these areas are subsequently utilized in processing, encompassing both AM and CM, which is referred to as system C. Figure 2 shows fictitious carbon footprints for these mass flows, illustrating the management of internal scrap requiring re-refinement. The material emerging from refining carries a cumulative carbon footprint of 90 kg CO_2 equivalent (comprising 75 kg + 15 kg). An additional 10 kg CO_2 equivalent accrues during processing, culminating in a gross carbon footprint of 100 kg CO_{2e}. In total, 40 percent of this re-enters the refining cycle as waste, resulting in a net carbon footprint of 60 kg CO_{2e} for the metal product. Given that this system encompasses material recursion and the aggregate emissions from systems A and B also depend on inputs from System C, a simultaneous solution (via a linear system of equations) is required, which the Umberto® software automatically accomplishes.

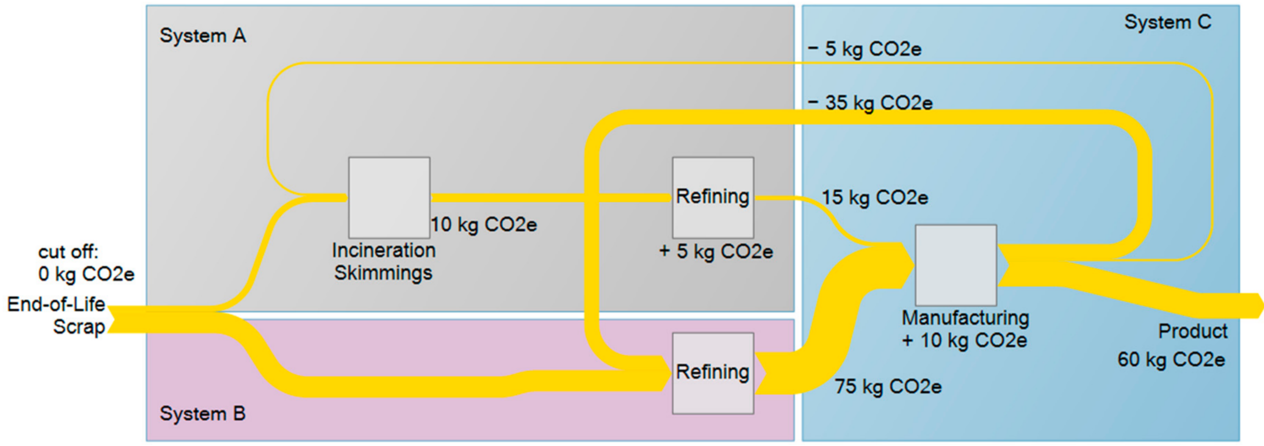

Figure 2. The illustrative scheme for the treatment of internal returns of material with notional figures for the carbon footprint of metal flows (in yellow).

2.3. Use of Material Flow Cost Accounting (MFCA)

Material Flow Cost Accounting (MFCA) as defined by ISO 14051 [19], is a technique used to quantify the lost added value resulting from material losses. Losses can be recoverable waste, chips and recirculated material, defective products, or emissions—all materials that are not used in the product and do not add value and can be avoided. This approach encompasses not only the initial material costs but also the expenses accrued during processing, which include energy, operational materials, labor, and machinery. Hence, this method is particularly apt for comparisons between AM and CM, given the critical role of material yield in these processes. Standard conventional cost accounting systems typically do not reflect these types of savings. Such analyses are immensely valuable, as they indicate which reduction strategies are economically feasible.

Nevertheless, two modifications are necessary to adapt the ISO 14051 standard. Due to competitive considerations, this article focuses on the carbon footprint of the products or recoverable material losses instead of disclosing specific costs. MFCA has also been proven effective for assessing the carbon footprint of material losses, as has already been demonstrated [17,20]. In this approach, the prices of raw materials and fuels are substituted with their respective carbon footprints, and process costs are represented by the direct or indirect emissions produced during the process.

An additional modification is required to accurately represent recycling systems, as is the case here. The existing calculation algorithm of ISO 14051 does not facilitate this. Nonetheless, the LCA software Umberto® has been enhanced to enable this seamlessly. This involves a scenario comparison, where the system's original state, including recoverable material losses, is contrasted with a desired state where these losses are diminished by a specified amount. The outcomes of this comparison can be presented in numerical or graphical form.

Sankey diagrams prove to be an invaluable tool in the analysis of these systems. In this context, they are employed to graphically represent not just the quantitative aspects of energy and material flows but also, pertinent to this article, how these flows contribute to the carbon footprint of the final product. Consequently, every energy and material flow is assigned a carbon footprint value, depicted in the form of a Sankey arrow. This visualization enables immediate identification of the processes that contribute most significantly. Furthermore, it can be expanded to illustrate which processes offer the most substantial opportunities for savings. The findings are presented in this manner in Section 3.

2.4. Specification of the Conventional Manufacturing (CM) Processes

Standard processing steps in the creation of precious metal products include casting, annealing, rolling, punching sheet metal, milling, drilling with CNC machines, and ultimately surface treatment and cleaning. These procedures are largely similar to those in traditional metalworking. The most energy-intensive among these are the thermal processes, specifically casting and annealing. Accurately measuring the energy consumption for each individual process poses a challenge, particularly when attributing the consumption to a specific product. Typically, consumption data are only available for extended periods, encompassing a range of different products. In this study, energy measurements were conducted to assess these processes. The measurements included recordings of power consumption for several real time production cycles for each work step for each technology. The energy consumption was normalized by the corresponding output quantity of products.

In conventional machining, key operating materials include oils, detergents, and tools, all of which experience varying degrees of wear. The usage of these materials was also documented.

The primary emphasis, however, was placed on recoverable material losses incurred at each stage of processing. Precise records were kept of the input and output quantities for each process relative to the product being analyzed. Typically, large quantities of punching waste or chips are produced here. In the case of precious metals, even the smallest quantities of dust are relevant, which accumulate in the waste from hall cleaning and are recovered by filter systems. Nearly all these metal losses can be recycled, a key benefit of working with precious metals. But the effort involved is still great: after metal processing, many products have a high material input factor. As a result, a lot of material is tied up in the system, which is almost constantly being recycled.

It is crucial to distinguish whether material losses are pure and can be easily remelted, or if they are contaminated and require re-refinement. The need for re-refinement not only escalates costs and energy consumption but also prolongs the retention of these valuable precious metals within the company. This extended retention translates to increased capital tied up in the inventory.

2.5. Specification of the Additive Manufacturing (AM) Processes

In AM, products are '3D printed' in a manner that closely adheres to their final three-dimensional shape. This method omits numerous conventional processing steps, like in investment casting [21], rolling, or punching. Nonetheless, these processes cannot be entirely eliminated, as the products frequently require additional milling, grinding, and cleaning to attain their finished form.

The key distinction in AM is the nature of the input material, which needs to be in the form of high-quality metal powder. The crucial factor here is the powder's morphology and particle size distribution. This metal powder is derived from alloyed metal through a process known as powder inert gas atomization. Subsequently, the desired particle size is classified using sieving and centrifugal separation techniques.

The AM process itself is executed through laser-based powder bed fusion (LPBF). In this method, a laser selectively melts layers of metal powder to form the near net shape. Any unused powder can be directly recycled, ensuring there is minimal material wastage needing re-refinement. Recoverable material losses are primarily confined to the post-processing phase and are significantly less compared with traditional manufacturing methods. Typically, these losses constitute a small percent of the initial material input.

Differing from traditional metal processing, Additive Manufacturing relies on highly advanced machinery. A key component is the powder inert gas atomization system, which is crucial for producing the spherical metal powder used in AM. This process involves detailed mechanisms for sizing and creating pure metal particles. The second critical piece of equipment is the 3D printer itself, which employs a continuous laser beam with a computerized numerically controlled (CNC) optical system guaranteeing a defined laser spot and path throughout the working plane to precisely melt and shape the metal powder.

This laser technology necessitates intricate calibration, parameterization, and control in relation to the metallurgy of the powder to achieve an economical process stability and the desired microstructural and dimensional quality of the products. The investment in these systems is notably higher in contrast to conventional metalworking equipment and is comparable to modern computer aided machinery (CAM) like CNC precision machining centers. With regard to technical autonomy, robustness, and performance, state-of-the-art 3D printing systems are able to execute series of build jobs. Times for setup and maintenance are similar to those of other CAM equipment.

3. Case Study

3.1. Specification of the Product

As a case study, a real industrial application of an electrode head made of a Pt-Ir alloy was selected, which is commonly used in aggressive conditions such as highly corrosive environments and/or in combination with thermal and mechanical burdens. Electrode heads were produced using either the conventional method versus powder technology for comparisons (Figure 3). The end product weighed 4.4 g. The alloy consisted of 800‰ platinum and 200‰ iridium. The platinum was supplied by the company's own refinery. The carbon footprints determined in Section 2.1 were used for this. The required iridium was purchased externally. The carbon footprint of iridium was conservatively estimated at 600 kg CO_{2e} per kg.

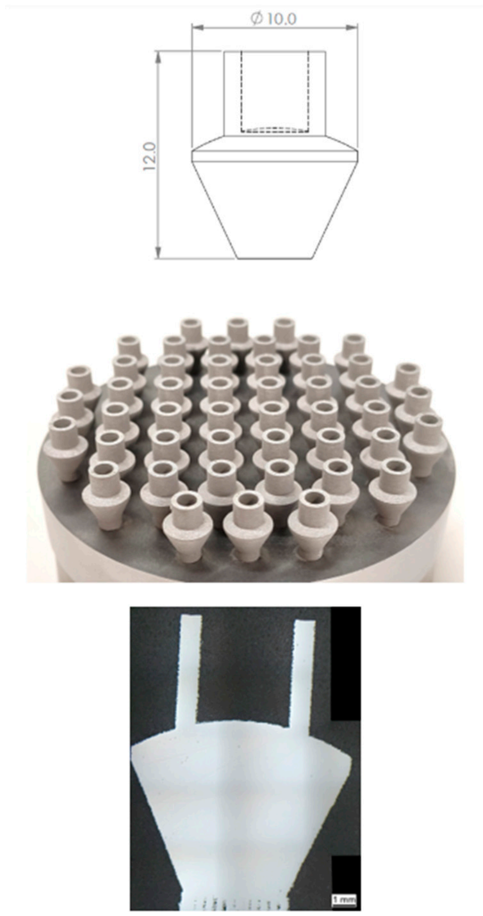

Figure 3. Near net shape AM electrode head (numbers in mm), AM batch production, and cross section.

The conventional manufacturing of the semi-finished product included the work steps of (1) vacuum casting, (2) hot pressing, (3) turning and iterations of (4) wire drawing, and (5) annealing. Within the powder technological alternative, steps (2–5) were substituted by powder atomization, classification, and 3D printing. These steps formed the basis for the analysis. All energy and material flows of the individual processes were taken into account but cannot be disclosed for reasons of confidentiality. However, they were evaluated in an external review process. In Figures 4 and 5, the process steps with their respective contributions to the carbon footprint are shown as a Sankey diagram. Similar representations are also possible with the energy and material flows, with other environmental impacts or even with the costs, making this representation a very powerful analysis tool.

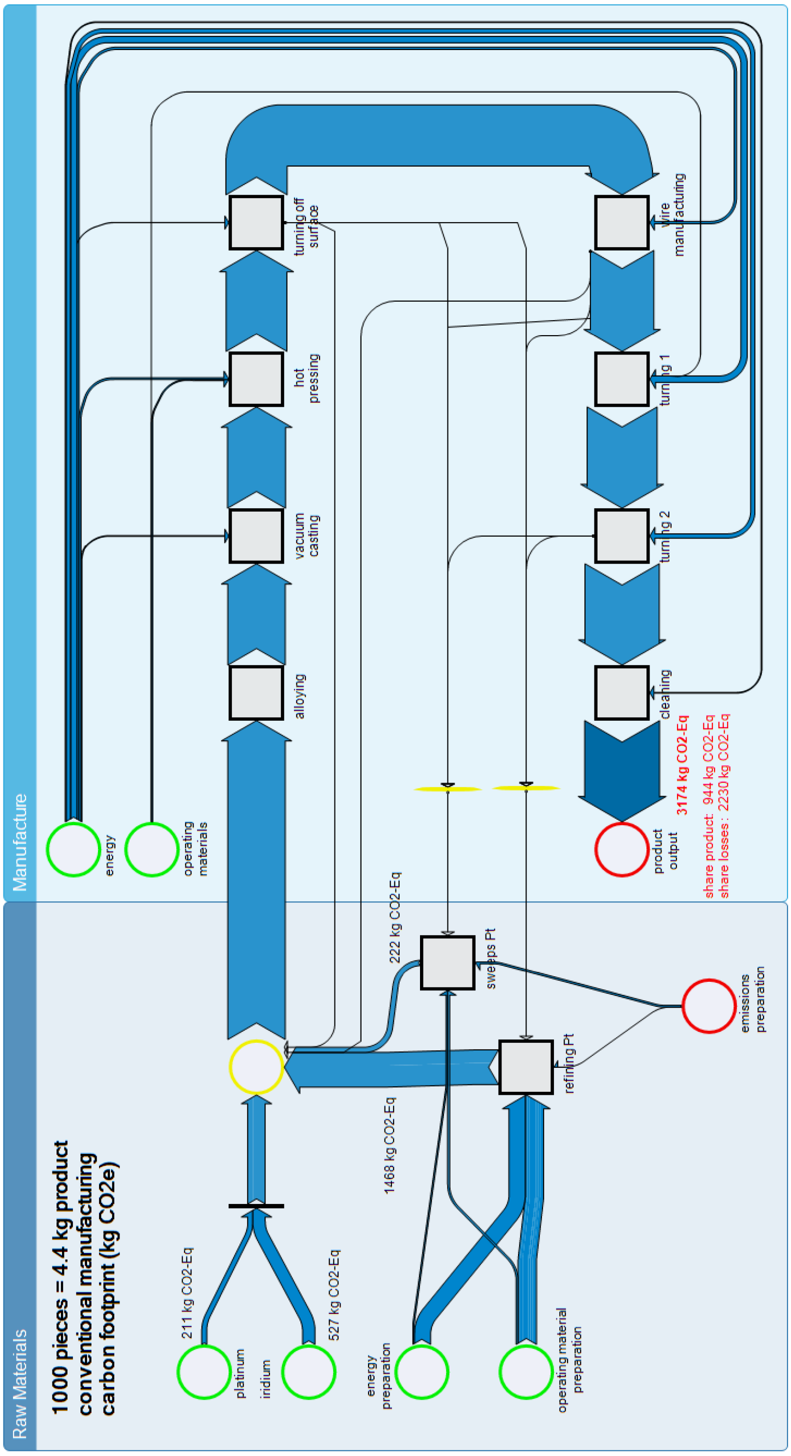

Figure 4. Sankey diagram of the conventional manufacturing of electrode heads made of Pt-Ir 200‰. The width of the arrows indicates the amount of the carbon footprint of the various energy and material flows in kg CO_{2e}.

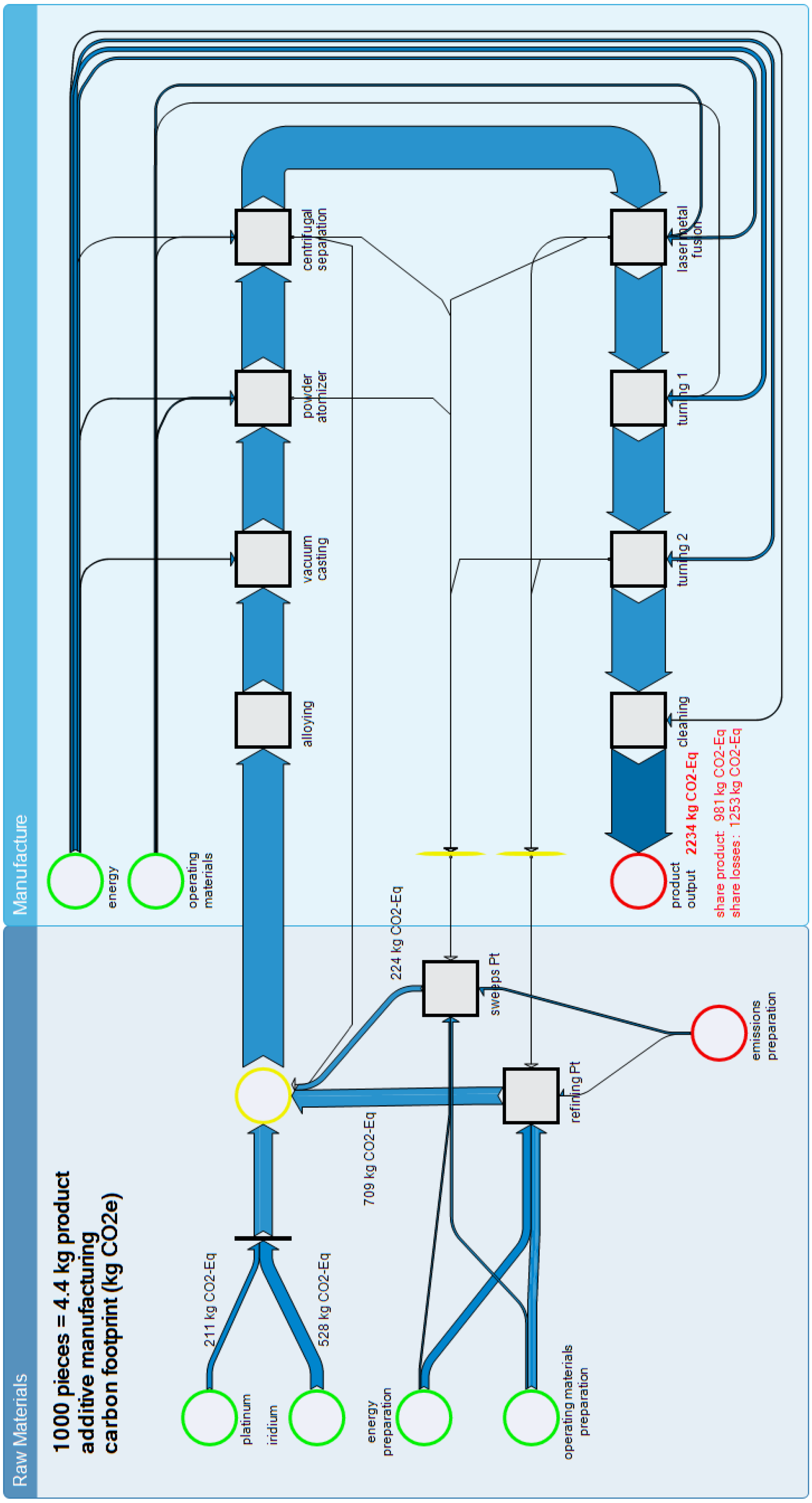

Figure 5. Sankey diagram of the Additive Manufacturing of electrode heads made of Pt-Ir 200‰. The width of the arrows indicates the amount of the carbon footprint of the various energy and material flows in kg CO_{2e}.

While the obtained semi-finished products do not show differences in quality, it is important to mention the different shapes. The conventional cylindrical wire leads to an essentially larger material input compared with the near net shape AM part. Unfused powders can be reused immediately after sieving. In addition to savings of resources and capital employed for the semi-finished products, near net shape AM parts reduce the machining time, chip and refining volumes, as well as the resource consumption in the final manufacturing step of precision milling. The final parts based on powder are indistinguishable from parts made from wires. Quality assurance testing procedures confirm equal quality regarding dimensional accuracy, monolithic structure, surface, and physical properties.

3.2. Results from the Analysis

Figure 4 shows the energy and material flows of the process route for conventional processing. It is divided into the actual manufacturing (right) and the provision of metals (left), whereby the data from Section 2.1 are used. The distinction between refining from high-quality secondary material and from sweepings, as explained in Figure 2, is important here. During manufacturing, the metal undergoes the processes of alloying, casting, wire processing, annealing, milling, and cleaning.

In this case, the green arrows already indicate the carbon footprint of the respective energy and material flows. This adds up to 3.17 kg CO_{2e} per piece for the end product. The Sankey diagram clearly shows that about half of it (1.47 + 0.22 kg CO_{2e}) is related to refining. In contrast, the energy and resources required for machining only make a small contribution to the carbon footprint. In total, 70% (2.23 kg CO_{2e}) are caused by recoverable material losses. In other words, if the process steps with inherently high resource consumption and therefore large footprint contributions such as refining and material input could be completely avoided, the carbon footprint could be reduced significantly, as far as this is technically possible.

Figure 5 shows the Sankey diagram corresponding to the AM of the electrode heads for comparison. The scaling of the arrows is the same as in Figure 4 and it is immediately apparent that the carbon footprint is significantly lower. This is due to the near net shape manufacturing and the smaller amount of material that has to be used in the system or that has to be re-refined. The carbon footprint of the end product is 2.23 kg CO_{2e} per piece which is about two thirds of that of conventional processing (3.17 kg CO_{2e}). In total, 56% (1.25 kg CO_{2e}) are caused by the recoverable material losses. It is particularly noticeable here that sweepings account for a significantly larger proportion of the carbon footprint. This is due to the fact that unused high-quality metal powder can be used directly in the cycle and does not have to be refined. Accordingly, the refining of contaminated residues is more prominent in the carbon footprint, as is the energy consumption of the various processing steps.

This analysis, which for reasons of confidentiality is only presented here using the example of the carbon footprint, can also be carried out with the costs. Equally interesting is the lead time of a product and the absolute amount of material required in the system, as this is of great relevance for the capital commitment due to the limited precious metal stock.

Figure 6 presents a breakdown of the carbon footprint for both additive and conventional manufacturing methods. In the case of AM, there is a notably reduced need for refining secondary materials, although the processing of sweepings remains similar to conventional methods. While AM is relatively energy-intensive, its total energy consumption is still lower compared with traditional manufacturing. A notable aspect of AM is the increased usage of operating materials, primarily attributed to the utilization of specialized gases like argon and nitrogen.

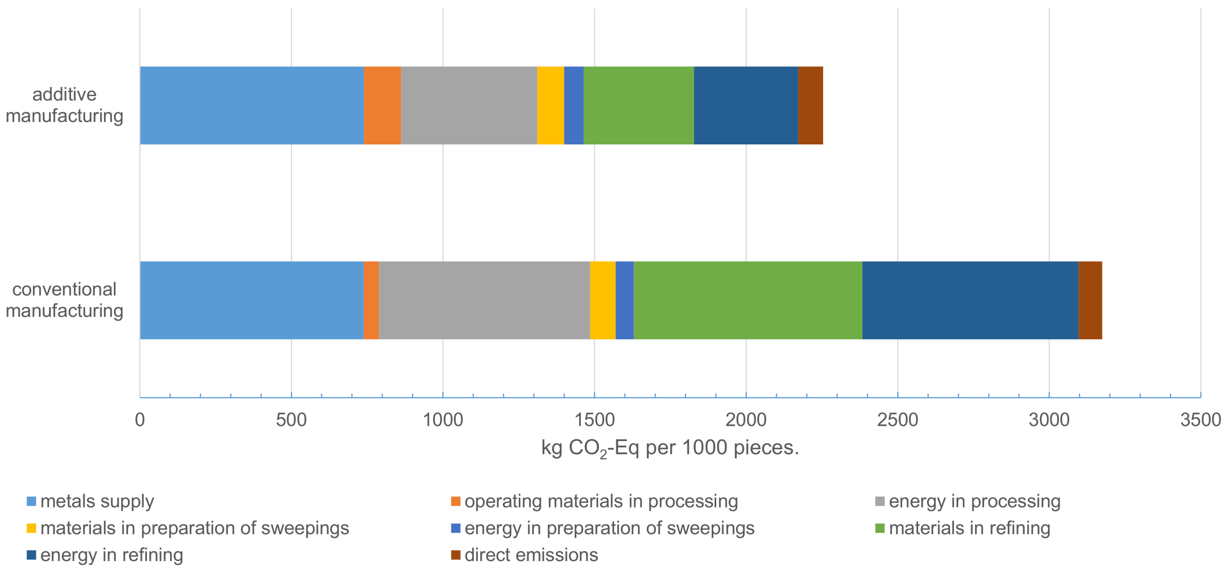

Figure 6. Carbon footprint (in kg CO_2 equivalent) of electrode heads made of Pt-Ir 200‰ and the contributions of various sources. Comparison of Conventional and Additive Manufacturing.

3.3. Reduction in the Carbon Footprint Through Less Material Loss

Utilizing the MFCA method within the Umberto® software enables a detailed analysis of individual process steps, centering on the query: What savings could be achieved if this process incurred no losses? Such an analysis offers valuable insights into which areas should be prioritized for implementing improvement measures.

Table 2 presents a summary of such calculations. It addresses the reduction in the product carbon footprint (PCF) if the production of chips during turning are eliminated. It shows both the maximum effects of the selected individual measures and if they are all implemented together. It should be noted that the savings potential of the individual measures cannot be added together because the measures influence each other. However, this is taken into account by the MFCA method applied. Of course, not all savings potentials can be realized for technical reasons. It may only be possible to reduce the shavings by half in a process, for example. However, the presentation enables a prioritization of measures. In a further step, concrete measures or combinations of measures can then be calculated with their effects. This is an essential extension to the MFCA method as described in the ISO 14051 standard.

Table 2. Hypothetical reduction in the carbon footprint by avoiding material losses.

kg CO_{2e}/Piece	Conventional Manufacturing	Additive Manufacturing
Carbon footprint (PCF)	3.17	2.23
e.g., individual savings potential if no cuttings are produced during turning	1.9	1.1
Individual savings potential if no more losses are produced overall	2.23	1.25
Minimal PCF of all measures together	0.94	0.98

In the case of conventional manufacturing, the PCF could be reduced by more than half. With AM, almost half of the emissions can still be reduced, of course at a lower level of total emissions. Should all material losses be prevented, the PCF in conventional manufacturing might be further improved. Yet, achieving complete loss prevention is technically unfeasible.

4. Discussion

In the presented case study, all calculations were demonstrated using the carbon footprint as a primary metric. It is important to emphasize generally that the measures of carbon dioxide equivalents, resource units, and costs are dependent on each other in most cases. To the same extent that CO_{2e} is saved, the use of fossil fuels and of auxiliary and operating materials is also reduced, which in turn require less resources in the process chain. Since this is a real industrial product, the absolute figures cannot be published, but they have been verified by an independent expert in a peer review process. Nonetheless, these calculations can also be applied to financial costs or other environmental indicators, offering a broad range of assessment possibilities geared towards both economic and ecological optimization. As an illustration, the calculations outlined in Section 3 could inform decisions regarding the cost-effectiveness or investment viability of initiatives aimed at reducing recoverable material losses.

We use the MFCA approach according to the ISO 14051 standard. However, we enhance the approach by analyzing the process chain in detail according to the energy and material flows, taking into account the carbon footprint (and other environmental impacts) and considering the costs in detail. MFCA according to ISO 14051 is not able to consistently map internal recirculation because the approach always assumes that material losses leave the system. Here, however, they remain in the system, thus representing an inefficiency in production. With our approach, this can be consistently mapped.

This aspect is particularly critical for climate protection efforts. As demonstrated, the refining of material losses contributes to a carbon footprint, and the process inefficiencies essentially result in greenhouse gas emissions that ideally should be minimized. These emissions are especially problematic since they do not confer any direct benefit. Reducing such emissions, like through decreasing material refining, typically incurs costs, including additional investments or operational expenses. Conversely, greenhouse gas emissions carry their own costs, whether directly through a CO_2 pricing mechanism or indirectly when seeking to achieve climate neutrality via financial compensation. Assessing whether internal reduction strategies are more cost-effective than offsetting becomes straightforward with this approach.

The case study concerns the impact on the carbon footprint by employing specialized, costly machinery such as powder atomization units, AM systems, or state of the art CNC machining centers. These complex machines also require manufacturing and cause emissions. In this analysis, we estimated the carbon footprint of these machines and assessed their significant influence on the overall results. This impact is closely linked to machine utilization. Given the current usage rate and projected lifespan of these machines, the AM process contributes approximately 0.2 kg CO_{2e} per electrode head to the carbon footprint. If machine utilization is low, this value could increase markedly, which would then necessitate inclusion in the overall carbon footprint calculation. Conversely, however, the carbon footprint of providing machines (e.g., CNC precision machining centers) for conventional machining would also have to be included in the comparison.

5. Conclusions

Overall, it becomes evident that near net shape Additive Manufacturing can substantially enhance material efficiency in the creation of precious metal products. This efficiency becomes noticeable not only in the overall lower material input, the capital employed, and the manufacturing resource needs, it essentially reduces the refining efforts that are the major contribution to the total product carbon footprint and energy demand by up to 70%, as shown. Depending on the application design, the rate of internal recoverable material losses requiring refining can be drastically lowered. This reduction significantly affects the carbon footprint of these products, which, with Additive Manufacturing, is reduced to two thirds of that from conventional manufacturing methods as presented in this exemplary case study. The overall footprints accumulate to 2.23 by AM and 3.17 kg CO_{2e} conventionally, respectively. The differences are mainly caused by chemicals and energy consumptions in refining as well as energy needs for processing. Impacts vary depending on the complexity of the design and process chain. As a guideline, footprint savings increase with increasing complexity. Thus, Additive Manufacturing is an effective technology in promoting resource efficiency and contributing to climate protection efforts.

Author Contributions: Methodology, calculation, original draft preparation: M.S.; Conceptualization, data curation, validation, writing—review and editing, J.H. and I.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are partly available on request from the corresponding author. The data are not publicly available due to corporate confidentiality.

Conflicts of Interest: The authors declare that this study received funding from C. Hafner GmbH + Co. KG. The funder was not involved in the study design, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

References

1. Heinrich, J.; Laag, T.; Copponnex, T. The advantages of Additive Manufacturing for the processing of platinum group metals. *Met. Addit. Manuf.* **2021**, *7*, 165–172.
2. Fischer-Buehner, J.; Basso, A.; Bertoncello, R.; Poliero, M. Rapid Jewelry Manufacturing by Laser Melting of Precious Metal Powders. In *Santa Fe Symposium on Jewelry Manufacturing Technology*; Met-Chem Research: Albuquerque, NM, USA, 2012.
3. Cooper, F. Sintering and additive manufacturing: Additive manufacturing and the new paradigm for the jewellery manufacturer. *Prog. Addit. Manuf.* **2016**, *1*, 29–43. [CrossRef]
4. Ferraro-Cuda, M. Innovation and differentiation: Precious metal Additive Manufacturing in the jewellery sector. *Met. Addit. Manuf.* **2020**, *6*, 107–117.
5. Fryé, T. Mechanical Properties and Microstructures of Additively Manufactured 950 Platinum Ruthenium Alloy. In *Additive Manufacturing with Powder Metallurgy Conference (AMPM) Proceedings*; Metal Powder Industries Federation: Princeton, NJ, USA, 2022.
6. Strauss, J. Additive Manufacturing of Precious Metals. In *ASM Handbook: Additive Manufacturing Processes*; Bourell, D.L., Frazier, W., Kuhn, H., Seifi, M., Eds.; ASM International: Materials Park, OH, USA, 2020. [CrossRef]
7. Laag, T.; Heinrich, J. Advantages and Challenges of Platinum Group MetalsPowder Processing. In *Santa Fe Symposium on Jewelry Manufacturing Technology*; Met-Chem Research: Albuquerque, NM, USA, 2018; pp. 327–343. Available online: https://www.santafesymposium.org/2018-santa-fe-symposium-papers/2018-powder-processing-of-platinum-group-metals-advantages-and-challenges (accessed on 14 November 2024).
8. Torvi, S.P.; Nepal, B.; Wang, J. Energy Mapping of Additive Manufacturing Processes Using Sankey. *Int. J. Adv. Manuf. Technol.* **2023**, *128*, 4551–4560. [CrossRef]
9. Kokare, S.; Godina, R.; Oliveira, J.P. Life Cycle Inventory of Additive Manufacturing Processes: A Review. In *Quality Innovation and Sustainability. ICQUIS 2022*; Springer Proceedings in Business and Economics; de Oliveira Matias, J.C., Oliveira Pimentel, C.M., Gonçalves dos Reis, J.C., Costa Martins das Dores, J.M., Santos, G., Eds.; Springer: Cham, Switzerland, 2023; pp. 77–86. [CrossRef]
10. Pusateri, V.; Olsen, S.O.; Kara, S.; Hauschild, M.Z. Life Cycle Assessment of metal additive manufacturing: A systematic literature review. In Proceedings of the 8th International Conference on Sustainable Design and Manufacturing (KES-SDM 2021), Split, Croatia, 15–17 September 2021.
11. Lunetto, V.; Priarone, P.C.; Kara, S.; Settineri, L. A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case. *Procedia CIRP* **2021**, *98*, 406–411. [CrossRef]
12. Schmidt, M.; Fritz, B. Life Cycle Assessment and Carbon Footprint of Precious Metal Recycling by C.HAFNER. 2022. Available online: https://www.c-hafner.de/fileadmin/user_upload/pdf/Life_Cycle_Assessment_and_Carbon_Footprint_of_precious_metal_recycling_by_C.HANFER_-_Summary_INEC___treeze_en.pdf (accessed on 31 October 2023).
13. *ISO 14040:2006 + Amd 1:2020*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2020.
14. *ISO 14044:2006 + Amd 1:2017 + Amd 2:2020*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2020.
15. Corti, C.W. Recovery and refining of gold jewellery scraps and wastes. In *The Santa Fe Symposium on Jewelry Manufacturing Technology*; Met-Chem Research: Albuquerque, NM, USA, 2002; pp. 1–20.
16. Skarn_Associates_Limited. *Skarn Gold GHG & Energy Q4 2023 v1.0 27-Oct-2023*; Skarn_Associates_Limited: London, UK, 2023.
17. World Gold Council. *Gold and Climate Change: Current and Future Impacts*; World Gold Council: London, UK, 2019.
18. Hauschild, M.Z.; Goedkoop, M.; Guinée, J.; Heijungs, R.; Huijbregts, M.; Jolliet, O.; Margni, M.; De Schryver, A.; Humbert, S.; Laurent, A.; et al. Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2013**, *18*, 683–697. [CrossRef]

19. *ISO 14051:2011*; Environmental Management—Material Flow Cost Accounting—General Framework. International Organization for Standardization: Geneva, Switzerland, 2011.
20. Nishitani, K.; Kokubu, K.; Wu, Q.; Kitada, H.; Guenther, E.; Guenther, T. Material flow cost accounting (MFCA) for the circular economy: An empirical study of the triadic relationship between MFCA, environmental performance, and the economic performance of Japanese companies. *J. Environ. Manag.* **2022**, *303*, 114219. [CrossRef] [PubMed]
21. Zito, D.; Allodia, V.; Trevisan, F.; Rossini, M.G.M.; Rossini, A.; Mazza, M. Potential and Innovation of the Selective Laser Melting Technique in Platinum Jewelry Production. In *Santa Fe Symposium on Jewelry Manufacturing Technology*; Met-Chem Research: Albuquerque, NM, USA, 2018; pp. 625–684. Available online: https://www.santafesymposium.org/2018-santa-fe-symposium-papers/2018-potential-and-innovation-of-the-selective-laser-melting-slm-technique-in-platinum-jewelry-production (accessed on 14 November 2024).