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Climate Change vs. Circular Economy: Challenges of the Most Common Route for Recycling Gold from WEEE

Benjamin Fritz [1] and Mario Schmidt [2,*]

[1] Institute of Applied Geosciences, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
[2] Institute for Industrial Ecology, Pforzheim University, 75175 Pforzheim, Germany
* Correspondence: mario.schmidt@hs-pforzheim.de; Tel.: +49-7231-28-6406

Abstract: Gold production poses significant environmental challenges, including resource depletion, CO_2 emissions, and toxic chemical usage. Similarly, improper WEEE management harms the environment. However, WEEE contains valuable metals such as gold, making it central to circular economy (CE) strategies and an alternative to mining. This study assesses the climate impact of pyrometallurgical gold recovery from WEEE using life cycle assessment (LCA). The study found that the carbon footprint of producing gold pyrometallurgically from WEEE is 2000 kg CO_2eq/kg. These emissions are largely tied to the carbon content of waste, meaning that low-carbon energy sources have a limited impact. This creates a conflict between CE goals and CO_2 reduction. Scenario analysis shows that utilizing waste heat for district heating significantly lowers emissions. The other strategies used to improve the environmental performance include separating the plastic fraction before smelting, using biogenic plastic in WEEE, and carbon capture and storage (CCS). Transport accounts for just 10% of the total carbon footprint. Future regulations must address multiple factors—EEE production, waste management, smelter infrastructure, global socioeconomic dynamics, and consumer behavior—as higher recycling rates alone will not solve WEEE challenges.

Keywords: LCA; carbon footprint; WEEE; gold; recycling; pyrometallurgy; CO_2; circular economy; metals

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1. Introduction

Waste electrical and electronic equipment (WEEE) poses significant ecological challenges, as does traditional gold production through mining. However, gold can also be produced through the recycling of WEEE, providing a more environmentally friendly alternative that avoids gold mining and reduces WEEE.

According to the UN waste monitor, around 62 billion kg of WEEE was generated in 2022, of which only 13.8 billion was recycled in compliance with official standards [1].

Urban mining offers a huge potential for WEEE. While the concentration of gold in primary ores is just a few grams per ton, in WEEE, gold concentrations as high as 980 g/t in mobile phones or 420 g/t in printed circuit boards (PCBs) are common [2,3]. However, WEEE is a heterogeneous input material, with varying material compositions, forms and particle sizes. It is a complex input that requires different extractive technologies to ores [4]. However, the actual global volumes of gold obtained through recycling are low, with only about 3% of annual gold production coming from WEEE recycling [5]. Furthermore, technology appliances account for only around 7% of the annual global gold demand [6].

The most common route for producing gold from WEEE on an industrial scale involves pyrometallurgical processing using a copper smelting process [7]. Recycling gold from

WEEE is also a prime example of Reuter's "metal wheel", where copper metallurgy serves as the enabler of the circular economy in gold recovery from WEEE [8]. WEEE is typically co-processed alongside sulfide copper concentrates in existing copper smelters, where it is added as an additional feedstock—resulting in the combustion of the plastics contained in the WEEE. The plastic fraction also serves as an energy carrier and reducing agent in the process. The majority of gold recovered from formal recycling comes from around ten companies, including Mitsubishi Materials Corporation (MMC) and DOWA ECO-SYSTEM in Japan, Aurubis in Germany, Boliden Group in Sweden, Glencore in Canada, and Umicore in Belgium (for more details please find Supplement Table S2).

The informal recycling of WEEE, such as in Accra Market, Agbogbloshie (Ghana), involves burning WEEE to remove plastics and recover metals under hazardous conditions. While the exact fate of the recovered metal fractions is not fully known, the UN Waste Monitor states that some valuable materials are sold to companies in the Global North for further recycling. Additionally, some small-scale informal recyclers use toxic chemicals to directly retrieve the gold from, for example, PCBs. This process is carried out in their houses or backyards without sufficient safeguards for human health or the environment [9,10].

According to Nuss and Eckelman, gold is among the metals with the highest specific CO2eq per mass in the periodic table, with a CO_2eq of around 30,000 CO_2eq/kg Au [11,12]. Surprisingly, the annual impact on climate change from copper mining (≈182 Mt CO_2eq/a) 27 billion kg are mined annually similar to the impact of gold mining (236 Mt CO_2eq/a) when using the market datasets in ecoinvent v.3.11 [6,13]. The recycling of high-value EoL scrap on the other hand is known to have a very low carbon footprint of around 40 kg CO_2eq/kg Au [14].

A common method of quantifying environmental impacts along the life cycle of products and materials is life cycle assessment (LCA). A literature screening of LCA studies in the field of WEEE yielded three prior studies performing a thorough analysis of gold. All three studies are comparative LCAs that analyze the environmental impact of different routes of producing gold from WEEE.

In a study that aimed to identify the most eco-friendly recycling technique, He et al. presented LCA results for the mechanical, pyro-, hydro-, electro- and biometallurgical recycling of gold from PCBs [15]. Unfortunately, the study did not include their LCI tables, making it difficult to analyze their results. The impact of the pyrometallurgical recycling route on climate change is reported to be 5840 kg CO_2eq/kg Au. The impact of all the different routes lies between 1420 kg CO_2eq/kg Au and 35,400 kg CO_2eq/kg Au.

Rezaee et al. performed a comparative LCA on six different hydrometallurgical processes used to recycle gold from PCB powder [16]. Their results show that the climate impact lies between 1.17 kg CO_2eq/kg PCB and 46.6 kg CO_2eq/kg PCB. Unfortunately, this study did not report their results per metal. Based on the composition of the input material, we estimated the CO_2eq for the production of gold. Using economic allocation, the carbon footprint is between 10,000 kg CO_2eq/kg Au and 400,000 kg CO_2eq/kg Au. The lowest result is slightly higher compared to those of He et al., who found that for hydrometallurgical recycling, the carbon footprint is 7860 kg CO_2eq/kg Au [15].

Li et al. compared two different recycling methods, the hydro- and the pyrometallurgical routes, with their own novel technique using LCA [7]. The results showed that their novel approach had the lowest CO_2eq, with around 1230 kg CO_2eq/kg Au compared to 17,900 kg CO_2eq/kg Au for the hydro- and 57,900 CO_2eq/kg Au for the pyrometallurgical route. It is not exactly clear why the values for pyrometallurgical recycling in this study are so high. One major difference between this and the other studies is that the authors do not use the cut-off approach; therefore, the copper scrap added to the smelter enters the system with an additional environmental burden.

In this study, we conducted an LCA analysis of the carbon footprint of recycling gold from WEEE through pyrometallurgical recycling in copper smelters, the most commonly used method. We highlight the challenge of decarbonizing WEEE recycling due to the fossil-based plastics embedded within the scrap input, which are burned during processing. As a result, standard decarbonization measures, such as using renewables in the energy mix, have limited effectiveness. We use scenario analyses to explore alternative solutions.

2. Materials and Methods

2.1. LCA Model

This study focuses on an LCA of the Rönnskär smelter, as conducted by Classen et al. [17] (Part IX, 5.2). This process has also been identified by Bigum et al. [18] as the most comprehensive for the smelter phase of WEEE recycling.

Rönnskär is a copper smelter in Sweden run by the company Boliden. The smelter uses Kaldo furnace technology to add WEEE, together with lead concentrates, to their smelter inputs prior to mixing the resulting intermediate black copper with the primary copper route in the converter process (using a PS converter) [4].

Classen et al. provide a detailed description of an LCI system for WEEE recycling in the Rönnskär refinery [17] (IX, 5.2). This system is used in the ecoinvent process for recycling gold from electronic scrap. Because this system is described in such depth and the pyrometallurgical route for WEEE refining is today's most widely used process, we use Rönnskär's system to gain a deeper understanding of the gold recycling process and its environmental impact. In this analysis, we further refined ecoinvent's assessment by subdividing the process into several different steps (see Tables 1–5).

Table 1. LCI table for the copper conversion of WEEE based on Classen et al. [17] (Part IX, 5.2).

Conversion			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
WEEE	2.72	kg	all
Electricity from Swedish grid	0.126	kWh	all (changed to ROR in SC2)
Smelter infrastructure	8.35×10^{-11}	unit	all
Quicklime	1.02	kg	in SC1, 2 and 3 adjusted to 0.0969 kg
Output			
Metal values from WEEE in blister copper	1	kg	all
Lead	0.0436	kg	all
CO_2 to air	2.70	kg	SC1, 2, 3
Heat (used for district heating as CH_4 substitute)	23.5	MJ	only SC3

Table 2. LCI table for the electrowinning of cathode copper from WEEE based on Classen et al. [17] (Part IX, 5.2).

Electrowinning			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Metal values from WEEE inblister copper	60.4	kg	all
Anode refinery infrastructure	5.65×10^{-9}	unit	all
Electricity	12.5	kWh	all (changed to ROR in SC2)
Natural gas	1.47	MJ	in SC2 adjusted to 0.0123 kg of H2
H_2SO_4	1.40	kg	all
Water	7.80	kg	all

Table 2. *Cont.*

Electrowinning			
Flow	**Amount**	**Unit**	**Scenarios**
Output			
Precious metals in anode slime	1	kg	all
Copper cathode	39	kg	all
Nickel	5.49	kg	all

Table 3. LCI table for pressure leaching of anode slimes based on Classen et al. [17] (Part IX, 5.2).

Pressure Leaching			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Precious metals in anode slime	35.8	kg	all
Electricity	16.2	kWh	all (changed to ROR in SC2)
Natural gas	6.12	MJ	in SC2 adjusted to 0.051 kg of H2
Oxygen	1.87	kg	all
Refinery infrastructure	1.69×10^{-6}	unit	all
Output			
Au, Ag, Pd in intermediate	35.7	kg	all

Table 4. LCI table for Moebius electrolysis based on Classen et al. [17] (Part IX, 5.2).

Moebius Electrolysis			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Au, Ag, Pd in intermediate	35.7	kg	all
Electricity	16.2	kWh	all (changed to ROR in SC2)
Refinery infrastructure	1.69×10^{-6}	unit	all
Output			
Au, Pd in anode slime	2.82	kg	all
Silver	32.9	kg	all

Table 5. LCI table for Wohlwill electrolysis based on Classen et al. [17] (Part IX, 5.2).

Wohlwill Electrolysis			
Flow	**Amount**	**Unit**	**Scenarios**
Input			
Au, Pd in anode slime	2.82	kg	all
Electricity	16.2	kWh	all (changed to ROR in SC2)
Refinery infrastructure	1.69×10^{-6}	unit	all
Output			
Gold	1	kg	all
Palladium	1.82	kg	all

The LCA was modelled and calculated using the open-source software Brightway2 v.2.5 and the graphical user interface add-on Activity Browser v.2.11.1 [19,20]. For the impact assessment, we used the database ecoinvent cut-off v.3.10. The functional unit is 1 kg of gold. A list of the ecoinvent processes used can be found in Supplement Table S1.

Tables 1–5 show the LCI used by ecoinvent, as well as the adjustments made to account for different scenarios. A detailed description of the scenarios and the underlying assumptions can be found in Section 2.2. In the interest of clarity, flows that are not relevant to CO_2, such as particulate matter or emissions to water, were omitted.

2.2. Scenarios

For this study, four scenarios were developed to evaluate the environmental impact of gold recycling from WEEE under varying process conditions and assumptions, with a focus on identifying opportunities to improve emissions, energy efficiency and resource use. Additionally, inconsistencies in the ecoinvent process were addressed, including the omission of emissions from plastic combustion [17] (Part IX, 5.1.). This was also not included in the work of Bigum et al. [18].

2.2.1. Scenario SC0

Scenario SC0 represents the base case, modeling gold recycling from WEEE following ecoinvent's guidelines but disaggregating it into five distinct process steps. To isolate individual contributions in the gold refining process, we further subdivided it into three subprocesses: pressure leaching, Moebius electrolysis and Wohlwill electrolysis. The electricity consumption and refinery infrastructure were assumed to be equally distributed among the three subprocesses, while natural gas and oxygen were allocated exclusively to pressure leaching.

2.2.2. Scenario SC1

Scenario SC1 is modified to account for CO_2 emissions from the plastic fraction in WEEE and modifies the amount of flux used. In the ecoinvent model, CO_2 emissions from plastics combustion were omitted. In this study, theoretical emissions were estimated based on the stochiometric average carbon content of the plastic fraction, assumed to consist of polyethylene (C_2H_4), polypropylene (C_3H_6) and polystyrene (C_8H_8), with an average carbon content of 88% [21]. According to Classen et al., the WEEE input contains approximately 30% plastics [17] (Part IX, 5.2). The carbon content was estimated by multiplying the plastic carbon content (88%) by the plastic share in WEEE (30%) and the WEEE input required per kilogram of gold [17] (Part IX, 5.2). Based on the principles of stoichiometry, the CO_2 emissions were calculated from the carbon amount by multiplying it with a factor of 3.67. Additionally, the flux (quicklime) amount in ecoinvent, approximately 1.58 kg CaO/kg Cu, was revised [17] (Part IX, Figure 5.13). The study by Sanjuan-Delmás et al. states that in the Rönnskär smelter, quicklime and limestone are used together at 0.142 kg flux/kg Cu [22]. The Rio Tinto Kennecott smelter (USA) reports a value of around 0.03 kg CaO/kg Cu [23]. In a general LCA study on copper production, 0.15 kg CaO/kg Cu was used, which is comparable to the value of Sanjuan-Delmás et al. [22,24]. As a conservative estimate, the highest value of 0.15 kg CaO/kg Cu was adopted for all subsequent scenarios (SC1 to SC3).

2.2.3. Scenario SC2

Scenario SC2 models a transition to renewable energy. Electricity was assumed to come from hydropower, while "green" hydrogen replaced natural gas in the furnaces. The hydrogen demand was calculated using a heat value of 120 MJ/kg, and its production was associated with emissions of 4 kg CO_2eq/kg H_2 [25–27]. Considering Rönnskär's coastal location, offshore wind or tidal energy could also be viable electricity sources. However, the choice of renewable energy source depends on site-specific factors, which vary across refineries. Montanwerke Brixlegg, for example, already use ROR.

2.2.4. Scenario 3 SC3

Scenario 3 SC3 explores the potential for utilizing waste heat from plastic combustion for district heating. The energy content of the plastic fraction was calculated based on the plastics content used in SC1 and the average heating values of polyethylene, polypropylene, and polystyrene, as reported by Huang [28]. To estimate how much heat could be utilized for district heating, the heat needed for the smelting process was first estimated. The specific heat capacities of copper and silica—the major constituents of WEEE aside from plastics—were considered, along with their respective melting enthalpies to calculate the energy demand for smelting the copper. This energy demand was subtracted from the total potential energy content of the plastics, giving the theoretical heat surplus after smelting the copper. An 80% efficiency factor was applied, resulting in a net usable heat of 23.5 MJ (see Table 1 and Supplement Tables S5–S8). This value was used to estimate the CO_2 emissions avoided from natural gas heating based on ecoinvent data (see Supplement Table S1). The calculated emission savings were subsequently subtracted from the total carbon footprint of gold recycling. Note that this calculation is a very simplistic and theoretical approach and can only give a first rough estimate of the district heating potential of WEEE.

2.3. Allocation

In the product system this study is based upon, a total of six products are produced in different process steps: copper, gold, lead, nickel, palladium and silver. In four of the five process steps, more than one product or intermediate is produced (see Tables 1–5). In a multi-output system, environmental impacts have to be allocated to each product or intermediate. The two most common methods used to allocate these impacts in metals and mining systems are calculating the share of the product mass (mass allocation) or calculating the economic value of the product (economic allocation) [29,30]. In the present case, the copper cathode has the highest production volume, with around 1400 kg Cu/kg Au (see Table 6). However, in revenue creation, copper ranks fourth after silver, gold (1 kg) and palladium (1.8 kg Pd/kg Au). In this study's prime example, where base metals such as lead or copper as well as precious metals such as gold or palladium are produced, economic allocation better reflects the reason behind the product system. This is because the precious metal by-products significantly contribute to the revenue of the system. The following table shows the prices used for economic allocation.

Table 6. Product prices used for economic allocation based on the World Bank's pink sheet for the year 2023 [31]. Palladium price is based on (https://macrotrends.net, accessed on 22 February 2025).

Product	Price [USD/kg]	Production Volume [kg/kg Au]
Copper	8.49	1400
Gold	62,500	1
Lead	2.14	94.3
Nickel	21.5	197
Palladium	42,000	1.82
Silver	752	32.9

SKARN Associates provides a comprehensive database that includes information on the energy demand and climate impact of more than three thousand mining assets producing various metals, including gold, copper and nickel [32]. The database uses a special method of impact allocation. According to SKARN, for mines producing gold within a base metal concentrate, all emissions associated with the freight and pyrometallurgic smelting of the concentrate are allocated to the primary metal in that concentrate (e.g., copper). The emissions from the subsequent refining of anode slimes are allocated by economic value. The SKARN allocation method was applied as a third method to the present LCA model.

2.4. Transport

A recurrent theme in the media is how recycling WEEE takes place around the globe and as a result requires global shipping, part of which is illegal [1,33]. In this study, we estimate the impact of the transportation associated with recycling gold from WEEE on climate change. A method similar to the "bee-line measures" employed by ecoinvent was used [17] (Part IX, 5.5). First, the amount of WEEE created by different countries was used to provide masses in tons for each country [1] (Annex 2). Distances were calculated by using the haversine formula, to measure the distance from the capital city of each country to ten major pyrometallurgical refineries (see Supplement Table S2) [34,35].

The total WEEE generation of each country was then multiplied by the distance to the closest refinery to estimate the ton-kilometers (TKM) for each country. Subsequently, each TKM value was multiplied by the CO_2eq per TKM for trucks (0.19 kg CO_2eq/TKM) and container ships (0.010 kg CO_2eq/TKM), based on ecoinvent data v.3.10. It was assumed that 20% of each distance was covered by trucks (16–23 tons, EURO4) and 80% by container ships. This resulted in a total of 7.3 Mt CO_2eq per year for transporting the annual global generation of WEEE to the major smelters, or 0.11 kg CO_2eq per kilogram of WEEE.

It should be noted that the assumption that all WEEE worldwide is transported to refineries likely overestimates the actual situation. However, since the total CO_2eq is normalized by the total scrap amount, this error should not be significant. Also, the real shipping distances are unknown, and it is unlikely that every country exports the total mass of its WEEE (e.g., heavy fractions such as refrigerators) to the nearest WEEE recycling copper smelter.

For the transportation of gold from the refineries to the market, ecoinvent assumes that gold is first transported by truck over a fixed average distance of 250 km to an airport and then distributed to the market via plane. As none of the smelters contacted provided us with primary data, transport had to be approximated. For this, the distance from each refinery to the nearest airport was calculated using Google Earth (https://earth.google.com), accessed on 24. February 2025) (see Supplement Table S3), a tool widely used for estimating the distances for transport processes in LCA [36–38]. Since the exact amount of gold produced from WEEE by each refinery is unknown, an estimate was made based on the refinery capacities (see Supplement Table S2). The total annual amount of gold recovered from WEEE, ≈150 tons, was then distributed proportionally to the capacity of each refinery [39].

The corresponding TKM and the specific CO_2eq for truck transport (based on ecoinvent) were multiplied $\left(TKM \times \frac{CO_2eq}{TKM}\right)$, resulting in a climate impact of 2600 kg CO_2eq, or approximately 0.02 kg CO_2eq per kilogram of gold for the transportation of the annual gold produced from WEEE to the nearest airport. According to Eurocontrol, the average distance of flights was around 1000 km in 2020 [40]. In order to not underestimate this issue, a value of 2000 km was used. This distance, the total amount of gold recovered from WEEE and the specific impact of air transport (0.83 kg CO_2eq/TKM) on climate change from ecoinvent v.3.10 were used to estimate the TKM. The resulting emissions for distributing the gold by air to the market amount to around 250,000 kg CO_2eq per year, or 1.66 kg CO_2eq per kilogram of gold.

3. Results

3.1. The Impact of Quicklime

Figure 1 shows the global warming potential (GWP) of recycling WEEE in Boliden's Rönnskär facility in Sweden by the contribution of conversion, electrowinning, pressure leaching, moebius electrolysis and Wohlwill electrolysis. The figure shows the impact of producing the whole product basket, which consists of 1 kg Au, 1.82 kg Pd, 32.9 kg Ag, 197 kg Ni, 1400 kg Cu and 94.3 kg Pb. The lower bar in the chart labelled quicklime shows the material with the highest contribution to the CO_2eq.

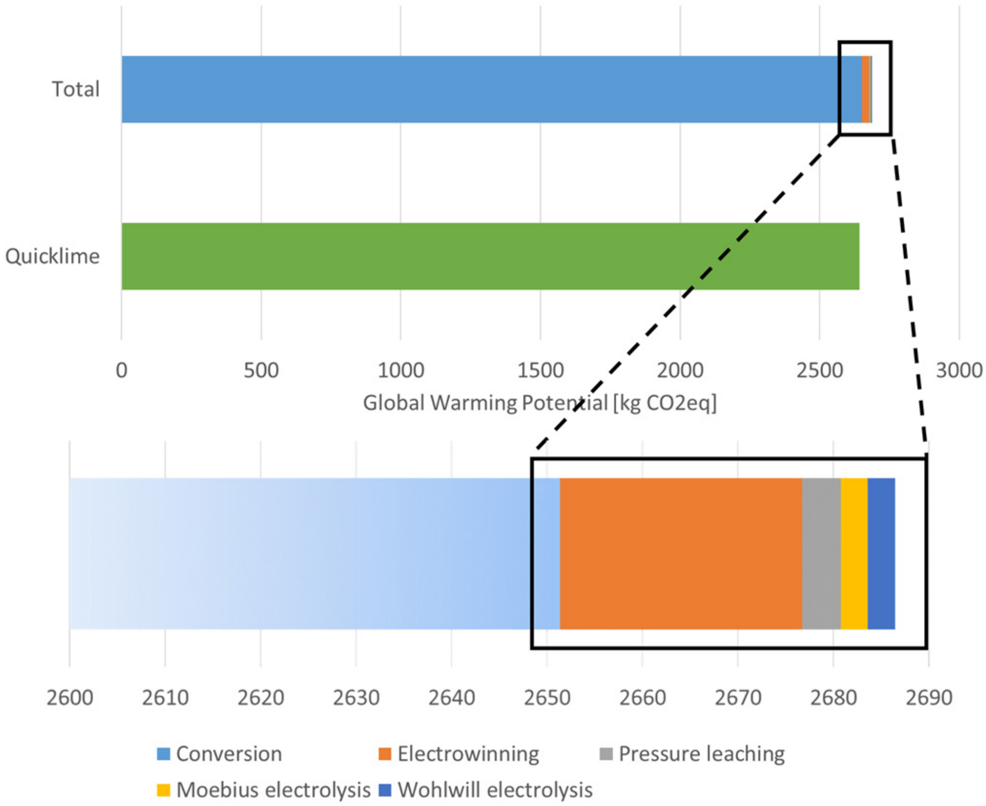

Figure 1. Process contribution of WEEE recycling for the whole product basket in SC0 highlighting the role of quicklime.

The significant effect that quicklime, which is used as flux in the converter, has on the overall impact is notable in Figure 1. This applies in scenario SC0, the base case in ecoinvent, in which the combustion of the plastic in WEEE does not emit CO_2. Including this in our calculation would raise the absolute impact and hence lower the relative contribution of quicklime. Another possible explanation for the high impact of quicklime might be that the amount of quicklime that Classen et al. assumed was used as flux is too high (for more details, see Section 2.2) [17]. As illustrated in the magnified section of the upper bar in Figure 1, the electrowinning of the copper cathodes (SC0) is the second most impactful process after the conversion.

3.2. Different Allocation Models

Figure 2 illustrates the impact of allocation methods on climate change when considering the recycling of WEEE in Boliden's Rönnskär facility in Sweden for the scenario SC1 model. The figure also depicts the difference between primary (ecoinvent v.3.11 cut-off) and secondary productions of the product basket from WEEE (for more details see Supplement Table S4.)

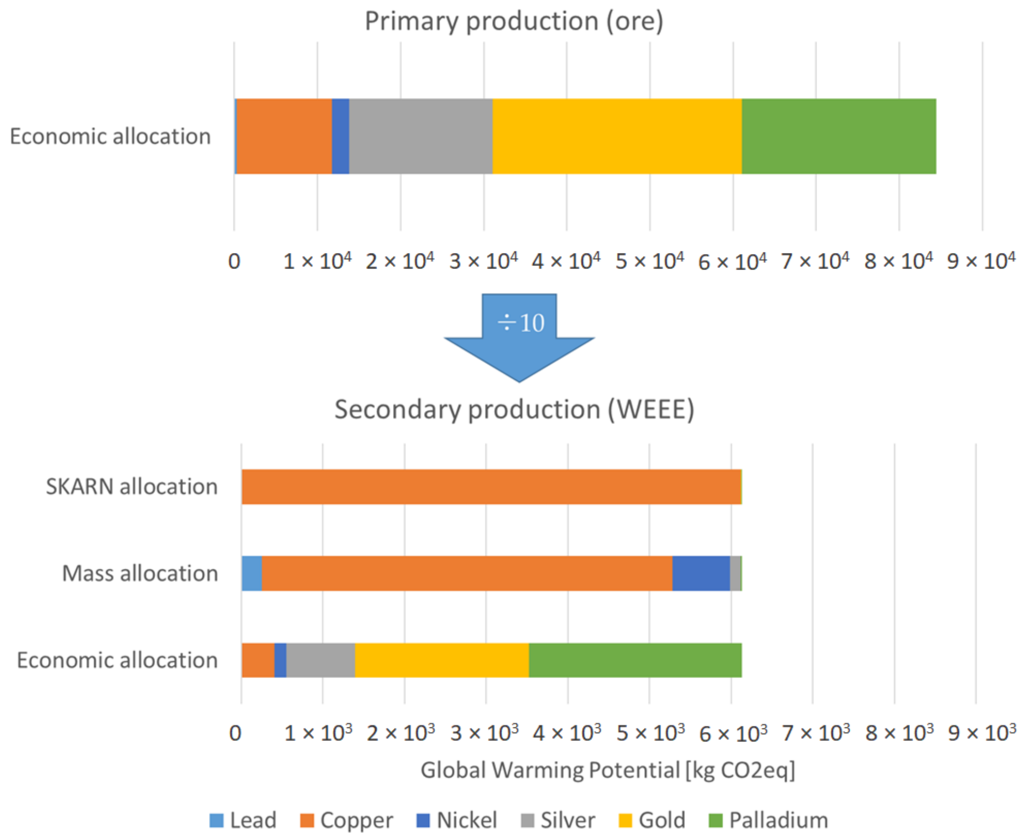

Figure 2. Allocation analysis based on the contribution of each metal to the carbon footprint of the whole product basket and comparing the results to the literature results (Supplement Table S4).

The most striking fact in Figure 2 is the difference in the impact that primary and secondary production have on climate change. If, theoretically, the product basket of WEEE were instead produced from mining (ecoinvent v.3.11. cut-off), the impact would be more than ten times higher. No metal in the product basket could be mined and produced with a lower carbon footprint than that produced through WEEE recycling.

As can be seen from the three bars at the bottom of Figure 2, the impact results obtained when using different allocation methods vary significantly, especially for gold and palladium compared to copper. This is due to the differences in the mass and the market value of these products.

If the prices of the products were not so different or if the environmental impact would scale proportionally to the mass of the product outputs, mass allocation could be useful. Although this is not the case in the present study, the results are shown in the second bar from the bottom.

When allocation is carried out according to SKARN (the bar at the top of Figure 2), copper has the highest impact. This is because the process of copper converting (see Figure 1) has the greatest impact and is only allocated to copper. Only the low-impact process steps of refining the precious metals in the anode slime are economically allocated.

3.3. Scenario Analysis

The scenario analysis results are shown in Figure 3. The graph shows the CO_2eq per kg of gold (economic allocation) for the four scenarios.

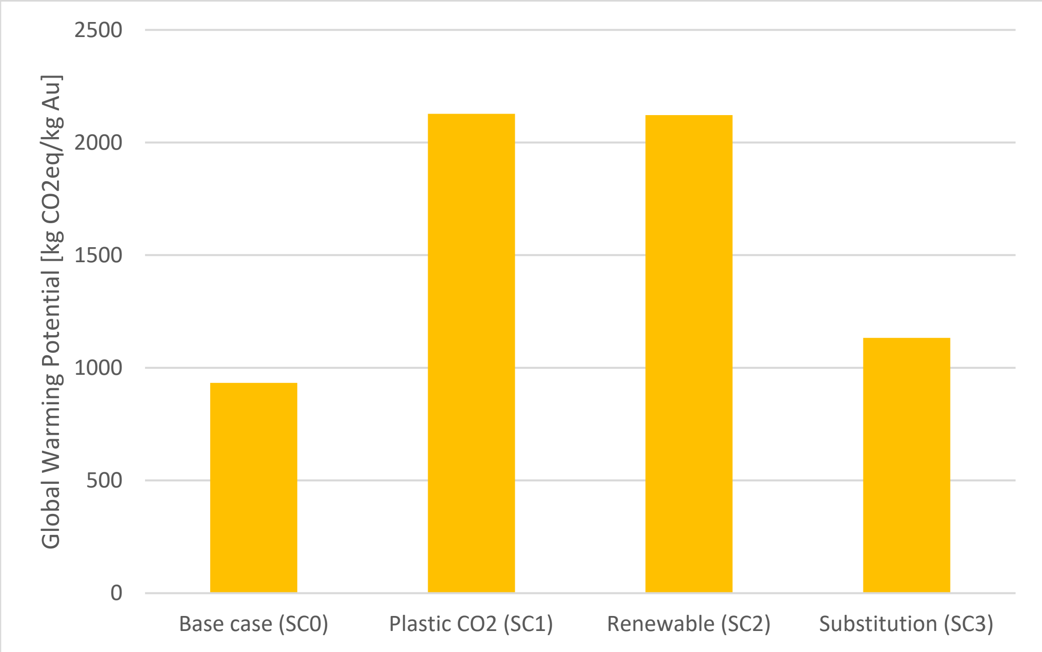

Figure 3. Scenario analysis for the carbon footprint of gold from WEEE in economic allocation.

One interesting finding is the significant impact that omitting the CO_2 emissions has on the results due to the plastic fractions that occur in the WEEE during smelting. This can be seen in the difference between SC0 and SC1, which has more than double the impact on climate change, despite the use of carbon-intensive quicklime being reduced in SC1. In SC1, the contribution of quicklime to the total CO_2eq decreases to around 4%, while the CO_2 emissions generated by plastic combustion have the highest overall impact, at around 95%.

The most striking finding was the marginal difference observed when switching to electricity from run-of-river hydroelectricity (ROR) instead of the Swedish grid mix (see Supplement Table S1), and when using hydrogen instead of natural gas (SC1 vs. SC2). Note that the converter is only fed with the energy from the plastics of the WEEE.

What stands out in Figure 3 is how substituting natural gas heating with the heat of the plastic fraction can significantly lower the carbon footprint (around 50%).

3.4. Transportation Impacts

In all the scenarios considered so far, scrap and gold transportation has been omitted. In the following analysis, an attempt is made to estimate the significance of this process phase (for the method used, see Section 2.4). Table 7 illustrates the contribution of the processes to the total climate impact of producing the whole product basket (SC1) and extending the LCA model by including the results of the transport analysis (see Section 2.4).

Table 7. Analysis estimating the contribution of transport processes to the total carbon footprint (SC1) of producing the metals in the product basket.

Process Step	Amount (SC1) [kg CO_2eq]	Relative [%]
Transport scrap	6.5×10^2	9.63%
Conversion	6.1×10^3	89.8%
Electrowinning	2.5×10^1	0.37%
Pressure leaching	4.1×10^0	0.06%
Moebius electrolysis	2.8×10^0	0.04%
Wohlwill electrolysis	4.5×10^0	0.07%
Transport gold	1.7×10^0	0.02%

Conversion has by far the greatest total impact, while the transport of scrap (and the transport of gold) has only a minimal contribution. The overall impact of the transport processes remains low (around 10%) compared to energy-intensive metallurgical processes.

4. Discussion

This study explores ways to reduce the climate impact of recycling gold from WEEE. We found that recycling gold from WEEE by the most common process route, i.e., the pyro-metallurgical route, has an impact on climate change of around 2000 kg CO_2eq/kg Au. This result depends strongly on the allocation method used.

The recycling of gold from WEEE in a primary copper smelter is a good example of the effect of subjective allocation choices on the results. If the purpose of the integrated copper smelter is to obtain a new raw material input with high metal grades to produce more metals and have a higher revenue, then the environmental impact should probably be allocated on an economic basis. In this case study, the revenue contributed by palladium to the product basket is the highest, followed by gold, silver and then copper. Although the plant is a copper smelter and copper is the material produced in the greatest quantities, a big part of the revenue is generated by the more expensive metals; therefore, the allocation should also follow this economic logic.

In the present case, the CO_2eq is mainly influenced by the fossil carbon bound in the plastic fraction of the WEEE and the energy carrier used. The latter could be improved by switching to renewable energies such as run-of-river electricity and green hydrogen. Meanwhile, for the CO_2eq of plastic combustion, more complex and tedious solutions are needed. To minimize emissions from the plastic fraction of the WEEE, the plastic could be removed prior to smelting in a mechanical or a hydrometallurgical process. However, it would then have to be ensured that the fossil carbon content in these plastic fractions does not end up as CO_2 emissions downstream (unless, e.g., a co-product such as heat production results from waste treatment).

The fact that switching to a renewable scenario does not substantially reduce the impact on the climate (since CO_2 emissions stem from the burning of the fossil carbon in the plastic) has broader implications for the industry. If copper smelters seek to become part of the circular economy (CE) by increasing their WEEE recycling, they will paradoxically increase their carbon footprint. This suggests that limiting WEEE recycling and instead producing copper from primary material using non-fossil energy might be a more promising path to achieving carbon-neutral copper. However, this leads to a conflict of objectives between CE and CO_2 emissions.

In countries where the landfilling of WEEE is not permitted (as in Germany), the WEEE that is not recycled most likely ends up in waste incinerators and releases the same amount of CO_2 emissions as in the pyrometallurgical method, losing large quantities of metal in the process. This would be a fruitful area for further work. A study could compare the system described in this study with an alternative system of disposing the WEEE in household scrap using the existing infrastructure for collecting, sorting and incinerating scrap and then extracting the metals from the fly ash as, for example, Umicore in Hoboken, Belgium does.

The present study has found that district heating is generally an effective means of reducing the carbon footprint of gold from WEEE. When system boundaries are extended to include the provision of waste heat from a WEEE recycling copper smelter to surrounding households using natural gas heating, the carbon footprint of the plant and thus of its products can be reduced by around 50%. The company Aurubis, which supplies heat for around 8000 households in HafenCity East in Germany and plans to significantly expand this by 2025, provides an illustration of what can be accomplished [41].

A final potential means of reducing the CO_2 emissions generated by burning the plastic in WEEE would involve using carbon capture and storage, as exemplified at Amager Bakke in Copenhagen [42,43]. Its success depends on the stored carbon not being released at a later point in time.

All these solutions shift or postpone fossil CO_2 emissions instead of eliminating them. A focus on the producer would open up a more radical solution: namely, not using fossil carbons in EEE in the first place, and instead using plastics derived from biogenic sources. This, of course, comes with its own set of problems (such as the "tank vs. plate debate"), which are outside the scope of this study.

In this study, a theoretical calculation was conducted to demonstrate that the transport of the gold produced from WEEE accounts for approximately 10% of CO_2eq. Additionally, it was shown that the impact of the transport of the final product gold to the market on climate change is insignificant compared to the total CO_2eq from recycling. This is in line with the market for gold in ecoinvent v.3.11 (cut-off), where the total impact of transport is 0.08 kg CO_2eq/kg Au. This initial approximation was rather rudimentary and was based exclusively on secondary data. Further research would be beneficial in this regard to record the flows and distances more accurately, thereby facilitating a more comprehensive understanding of the issue of illegal exports.

This also applies to the district heating scenario, which is based on a very simplistic and theoretical calculation of the net usable heat. This would be a fruitful area for further work that studies thermodynamic modelling and the technical efficiencies in greater depth.

This study, as well as all others to our knowledge, lacks primary industry data. Consequently, future studies should aim to conduct a detailed analysis of on-site data in a copper smelter in a combined LCA model of the primary and secondary routes; this is in order to find further improvements that can reduce the total CO_2 equivalent emissions of copper smelters.

5. Conclusions

WEEE poses significant environmental and health risks if not properly managed. At the same time, it contains economically valuable metals such as gold. Given the environmental and social challenges associated with gold mining, recovering gold from WEEE presents a clear win–win opportunity. However, the industry faces a unique challenge when applying common sustainability strategies.

A major contributor to the carbon footprint of WEEE recycling via the most common route is the combustion of embedded plastics, leading to the emission of approximately 2000 kg CO_2-eq per kg of recovered gold. This is about forty times higher than the carbon footprint of high-value recycling (≈53 kg CO_2eq/kg Au), which supplies nine times the market volume (1350 t Au/a). Since the plastics in WEEE are burned, transitioning to lower-carbon energy sources—one of the standard decarbonization strategies in the smelting industry—has a limited impact. This creates a dilemma: increasing circular economy (CE) efforts while simultaneously reducing CO_2 emissions is counter-productive. A promising strategy to mitigate the climate impact of gold recycling from WEEE is utilizing waste heat from smelters to replace carbon-intensive heating systems in nearby facilities or communities. Further measures include reducing the plastic fraction in input materials, promoting biogenic plastics, or implementing CCS.

Nevertheless, it is important to recognize that the carbon footprint of gold from mining, at approximately 30,000 kg CO_2-eq/kg Au, is more than ten times higher that of current WEEE recycling [12]. Additionally, WEEE presents broader environmental and health risks beyond CO_2 emissions from pyrometallurgical processing. If smelters do not recycle

WEEE, the waste will likely end up in incinerators or landfills, generating similar emissions elsewhere, or be exported to the Global South, where it poses even greater hazards [9,10].

Future policies and pathways must take an integrated approach rather than focusing solely on increasing recycling rates. Sustainable solutions require the coordinated involvement of EEE producers, municipal waste management, smelting infrastructure, global socioeconomic interactions, and consumer behavior regarding usage, repair, and disposal. Only by considering these factors together instead of simply demanding specific recycling rates can a truly sustainable system for WEEE management be achieved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17052086/s1, Table S1. List of ecoinvent processes used in this study; Table S2. List of coordinates of smelters recycling gold from WEEE used for the transportation model; Table S3. List of closest airports to smelters recycling gold from WEEE including distances used for the transportation model; Table S4. Literature values for comparing secondary with primary (mining) production; Table S5. Energy to bring copper to melting point; Table S6. Energy to bring silica to melting point of copper; Table S7. Energy to melt copper; Table S8. Available net energy for district heating.

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Abbreviations

The following abbreviations are used in this manuscript:

CCS	Carbon Capture and Storage
CE	Circular Economy
CO_2eq	CO_2 equivalent
GLO	Global
GWP	Global Warming Potential
EoL	End of Life
LCA	Lifecycle Assessment
LCI	Lifecycle Inventory
PCB	Printed Circuit Board
ROR	Run-of-river hydroelectricity
RoW	Rest of world
SC	Scenario
TKM	Ton-kilometers
WEEE	Waste Electrical and Electronic Equipment

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