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Resource and Greenhouse Gas Reduction Effects through Recycling of Platinum-Containing Waste

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Abstract: When disposing of waste metal resources in landfills, environmental issues such as soil contamination may arise. Recycling these resources not only recovers valuable metals but also mitigates environmental pollution. Platinum (Pt), a valuable metal used in fuel cells for its high water production activity, will see increased future demand as a fossil fuel alternative. This study analyzes the environmental and resource reduction effects of recycled Pt, considering the growing emphasis on its recycling for stable supply and demand of Pt. The environmental impact and resource consumption of recycled Pt with primary Pt (from natural mines) were compared and analyzed using the Life Cycle Assessment technique. The results revealed that resource consumption for primary Pt was 8.25×10^1 kg Sb-eq./kg, significantly more than the 5.45×10^0 kg Sb-eq./kg for recycled Pt. This represents an environmental reduction effect of approximately 93%. In the case of greenhouse gas emissions, primary Pt emitted 1.35×10^4 kg CO_2-eq./kg, while recycled Pt emitted 6.94×10^2 kg CO_2-eq./kg, resulting in an environmental reduction effect of approximately 95%. In conclusion, recycling Pt, compared to primary extraction, offers substantial environmental and resource reduction benefits. This study underscores the significance of recycling and highlights the potential environmental improvements achievable through sustainable practices.

Keywords: circular economy; platinum recycling; greenhouse gas emission reduction; resource saving; life cycle assessment

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1. Introduction

Globally, countries are adopting the circular economy model to address climate change, maximize resource utilization, and reduce greenhouse gas (GHG) emissions. Domestically, efforts are underway to promote "circular economy activation" in pursuit of the broader "2050 carbon neutrality" goal of GHG reduction. The circular economy, in stark contrast to the previous linear economic model of mass production, distribution, consumption, and disposal, represents a sustainable concept in which resource use and waste generation are fundamentally reduced throughout the process of production–distribution–consumption–reuse and recycling, allowing for repeated utilization of resources within the economic system [1,2].

This transition to a circular economy involves the reusing and recycling of waste that was traditionally disposed of in landfills or incinerated. This practice substantially reduces the burden of waste disposal and raw material extraction, contributing to carbon emissions reduction and the achievement of carbon neutrality objectives. Reduced resource input in the production process not only decreases environmental pollutant emissions but also reduces the ecological disruption caused by resource extraction, thereby contributing

to the conservation of biodiversity. From a circular economy perspective, this approach represents a new, limitless recycling technology that is capable of maximizing the efficiency of the resource value chain while addressing the fundamental issues of resource depletion, environmental pollution, and CO_2 emissions (carbon neutrality) and overcoming the limits of available resources for the establishment of a circular economy [3].

The expanded use of fuel cells is being advocated to enhance resource recycling and energy efficiency and aligns with the core principles of the circular economy. Fuel cells, typically reliant on hydrogen, are versatile energy conversion devices usable in various weather conditions and are favored as zero-carbon emission energy sources in various fields, as they are devoid of carbon within their fuel composition [4–6]. The cumulative distribution of fuel cells in South Korea, for example, has increased 69-fold in 2020 compared to 2008, with an annual average growth rate of 42.3% [7].

A proton exchange membrane fuel cell (PEMFC) is a device that electrochemically produces electricity from the oxidation of hydrogen at a fuel electrode and the reduction of oxygen at an air electrode, as illustrated in Figure 1. The fuel cell stack is designed with a membrane electrode assembly structure that features a minimal distance between the catalyst layer and the electrolyte to maximize the oxidation–reduction reactions. It consists of the following components: a gas diffusion layer, catalyst layer, polymer electrolyte membrane, gas gaskets, and separators.

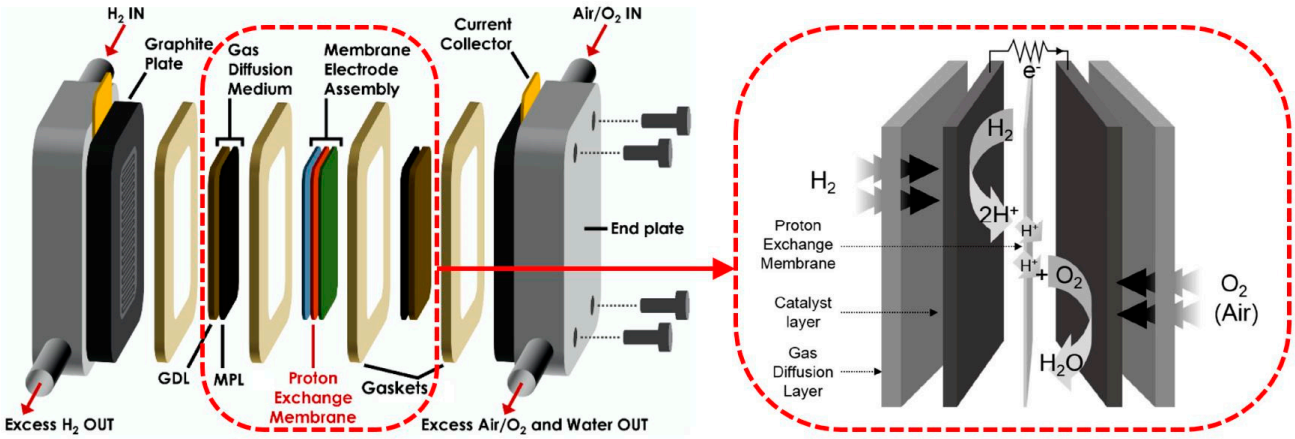


Figure 1. Main components and roles of a proton exchange membrane fuel cell. Modified [8,9].

Hydrogen supplied to the fuel electrode passes through the gas diffusion layer and undergoes oxidation, splitting into hydrogen ions and electrons owing to the platinum (Pt) catalyst in the catalyst layer. These electrons flow externally, generating power by reacting with oxygen that has passed through the air electrode, ultimately producing water. The hydrogen ions subsequently react with oxygen in the air to produce only water as a by-product [9,10].

In PEMFC systems, the cost of the stack constitutes approximately 49% of the total cost, with Pt as the most significant cost component within it. From a physicochemical perspective, Pt is highly stable and exhibits exceptional catalytic activity in water production, rendering it the most widely used material in fuel cells. However, Pt is classified as a rare metal with limited reserves, rendering it highly susceptible to supply and demand dynamics [11,12]. Pt is sourced and produced in countries such as South Africa, Russia, Canada, the United States, Zimbabwe, and Colombia, among others. However, the majority of global production—specifically over 70%—is contributed by South Africa [13]. Presently, South Korea produces approximately 0.6 tons of Pt annually from by-products generated in the copper production process. To meet the domestic market demand, however, the country relies primarily on imports. Considering the projected increase in demand, especially in resource-scarce countries such as South Korea, there is a growing need to recycle Pt.

The Pt-containing waste generated in South Korea is either entirely collected for domestic recycling by local companies or exported to overseas processing companies for Pt recovery. Recycling technology for Pt-group metals can be divided into dry and wet methods. Dry methods involve processes such as grinding and reduction, which tend to be complex and carry a risk of explosion when high temperatures are used for metal separation. Moreover, it can be challenging to achieve high-purity recovery using dry methods. In contrast, wet methods have an advantage over dry methods as they produce much less waste and are less energy-consuming. In addition, wet methods enable the recovery of components from very dilute solutions and facilitate the separation of both main products and certain by-products. Therefore, from the standpoint of environmental protection, wet methods are considered a more ecological approach [14]. These include ion exchange, reverse osmosis, cementation, and electrowinning. In wet methods, after a pretreatment process, valuable metals are leached with acid or alkali, followed by solvent extraction, chemical precipitation, ion exchange, filtration, and distillation to recover the target metals. Among the wet methods, the electrowinning method, which involves electrochemical reduction to recover soluble precious metals, is known for its highest recovery rate and purity, typically reaching 99.99% [15].

Furthermore, in 2017, South Korea implemented an integrated environmental management system that established an environmental management framework for businesses that promoted a symbiotic relationship between the environment and the economy [16]. This system comprehensively analyzes the environmental impact of pollutants and establishes an optimal environmental management strategy framework for businesses, aiming to minimize pollutants throughout their facilities using economically feasible "Best Available Techniques" (BAT) [17]. Standards for Korean BAT reference documents have been disseminated across various business sectors to facilitate the application of BAT. BAT standards for the nonferrous metal manufacturing industry include techniques related to waste recovery and treatment aimed at resource recycling and energy efficiency improvement [18]. This highlights the significance of the circular economy as an essential environmental management approach, emphasizing the need to conserve resources and energy throughout the production process, from raw material inputs to product manufacturing, while concurrently reducing pollutant generation and emissions.

The global market is increasingly seeking metals with a high recycled content as sustainable raw materials to mitigate the carbon footprint of the final products [5]. Recycling metal, which involves reprocessing waste into new metal products, can lower GHG emissions, preserve natural resources, and efficiently manage energy consumption [19]. Effective waste management stands out as a crucial component in the pursuit of sustainable development and the establishment of a circular economy [20]. As highlighted by Inman et al. [21], leaching emerges as the most prevalent method for recovering metals from electronic waste in various concentrations.

The disposal of Pt-containing waste in landfills can lead to environmental issues, including soil contamination. Conversely, recycling such waste not only allows for the recovery of valuable metals but also aids in the reduction of various forms of environmental pollution [3]. This study aims to compare and analyze the environmental effects of recovered Pt (hereafter referred to as "recycled Pt") sourced from urban mines in contrast to Pt extracted from natural mines (hereafter referred to as "primary Pt") using a Life Cycle Assessment (LCA) methodology. No research results on the environmental effects of recycled Pt have been found so far. This study addresses an existing gap in environmental assessments related to Pt recycling, thus providing valuable foundational data for research, development, and commercialization within this field.

2. Materials and Methods

This study was conducted using the LCA method, following the procedure outlined in ISO 14040 [22] and ISO 14044 [23]. LCA comprises four main stages, which are goal and

scope definition, inventory analysis, impact assessment, and interpretation. These stages are interrelated and mutually reinforcing [22].

In the initial goal and scope definition stage, research objectives were selected, and the functional unit, reference flow, system boundaries, allocation rules, assumptions, and limitations of the product or service under study were defined. During the inventory analysis stage, both qualitative and quantitative data on the inputs and outputs within the system that were necessary to perform the functions of the study subject were compiled. The compiled input and output data were linked to a comprehensive database of elementary flow data. A final inventory analysis was conducted in accordance with the principles outlined in ISO 14048 [24]. In the impact assessment stage, the environmental impact was quantified by multiplying the factors characterized by the environmental burdens identified during the inventory analysis and categorizing them by impact categories to provide a comprehensive view of their effects. During the interpretation stage, the results obtained from both the inventory analysis and impact assessment were evaluated in line with the initial research objectives and scope. This interaction phase facilitated a deeper understanding of the environmental implications and allowed for drawing meaningful conclusions from the data.

2.1. Recycling Process for Platinum-Containing Waste (Waste Solution and Waste Catalyst)

The Pt recycling process assessed in this study combined the cementation and electrowinning methods to recycle Pt, as illustrated in Figure 2. The combination of these two methods provides the advantage of achieving high-purity refinement while simultaneously reducing reaction times. This approach minimizes the use of chemicals and energy in chemical processes, presenting a more efficient and environmentally friendly method for Pt recycling. Waste solutions and waste catalysts discarded in the field were collected and subjected to varying processes such as incineration, dissolution, concentration, precipitation, reduction, and drying to produce Pt with a purity of 99.95 wt%.

Pt-containing waste, comprising defective products and waste liquid generated from a Pt catalyst manufacturing facility, underwent a comprehensive recycling process. To begin with, the liquid waste was filtered to eliminate impurities. The filtered solution, together with solid waste from spent catalysts, was subsequently incinerated at high temperatures. Post-incineration, the resulting sludge underwent dissolution in water, after which hydrochloric acid was introduced to the solution during heating to concentrate it.

Following concentration, impurities were removed through a filtration process, and the solution underwent precipitation via the addition of ammonium chloride to reduce Pt compounds. The resulting mixture was filtered once more, and water separation was carried out. After filtration, the compound underwent reintroduction into water through a series of dissolution, concentration, and filtration processes. The pH of the resulting solution was carefully adjusted to fall within the range of 7 to 8 using sodium hydroxide, and any remaining impurities were filtered out.

To further refine the solution, a reducing agent was added to initiate the reduction process. The resultant sponge formed during reduction was filtered and separated. Finally, the resulting products underwent a drying process, completing the intricate series of steps in the recycling procedure.

2.2. Goal and Scope Definition

The objective of this LCA study was to assess the environmental impact of primary and recycled Pt and quantify the environmental reduction effects achieved by recycled products compared to primary products. The subject products were defined as primary Pt produced from natural mines and recycled Pt from Pt-containing waste. The system boundary was set as "Cradle to Gate" (CtG), encompassing raw material acquisition and production up to product manufacturing, as illustrated in Figure 3. The functional unit was defined as 1 kg of the Pt product. Accordingly, the reference flow for data collection and calculation was "1 kg of Pt".

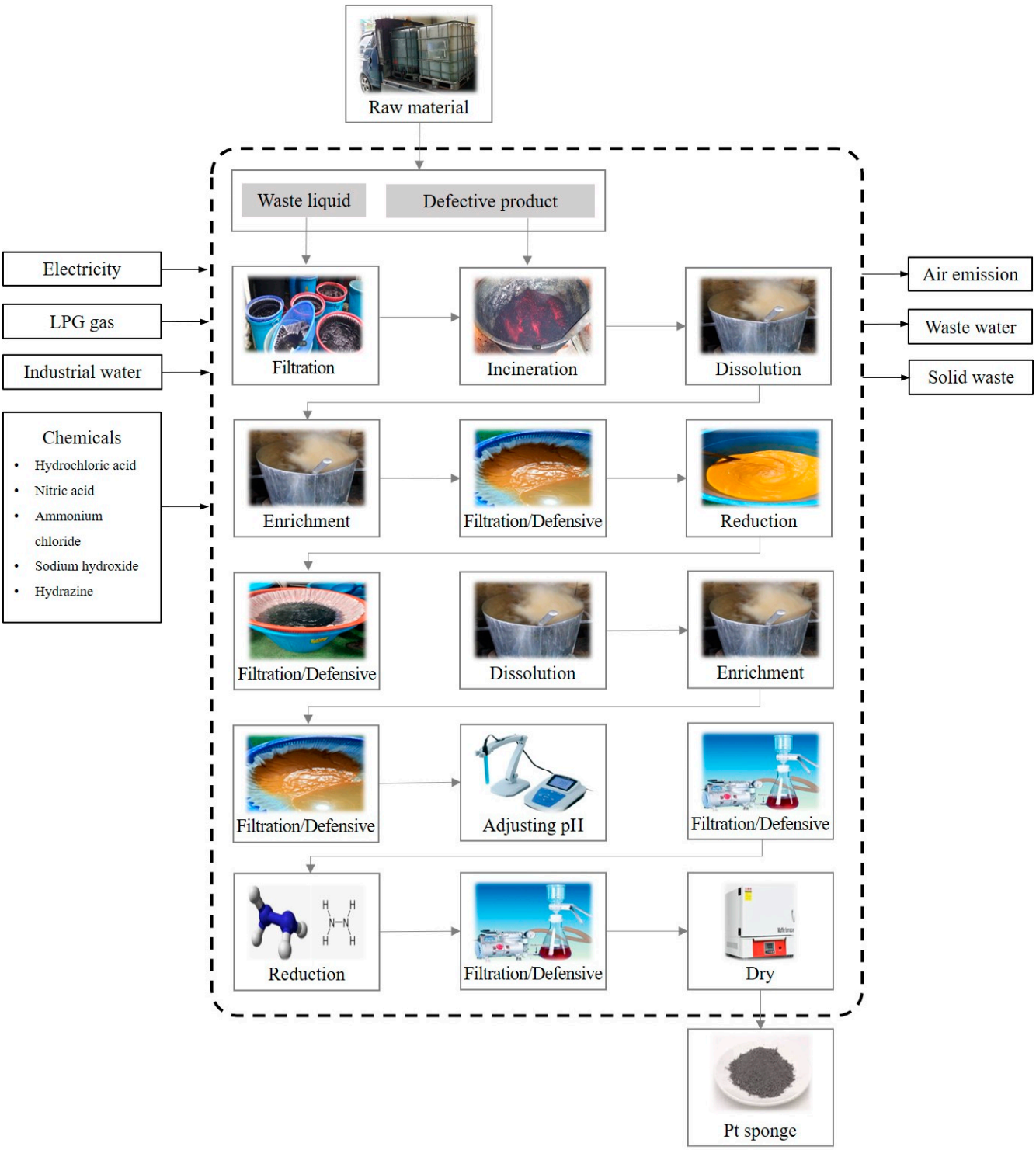


Figure 2. Platinum recycling of electrolytic recovery methods.

Primary Pt was divided into the raw material extraction and transportation stages. Given that South Korea relies predominantly on imports to meet the demand for Pt, it is assumed that all Pt is imported, and the transportation stage is thus also included. Recycled Pt was divided into the raw material extraction and recycling stages. Recycled Pt was obtained from the recycling of Pt-containing waste and defective products at "Company A" in the metropolitan area. It was compared with primary Pt produced from raw materials to analyze the environmental performance of recycled Pt.

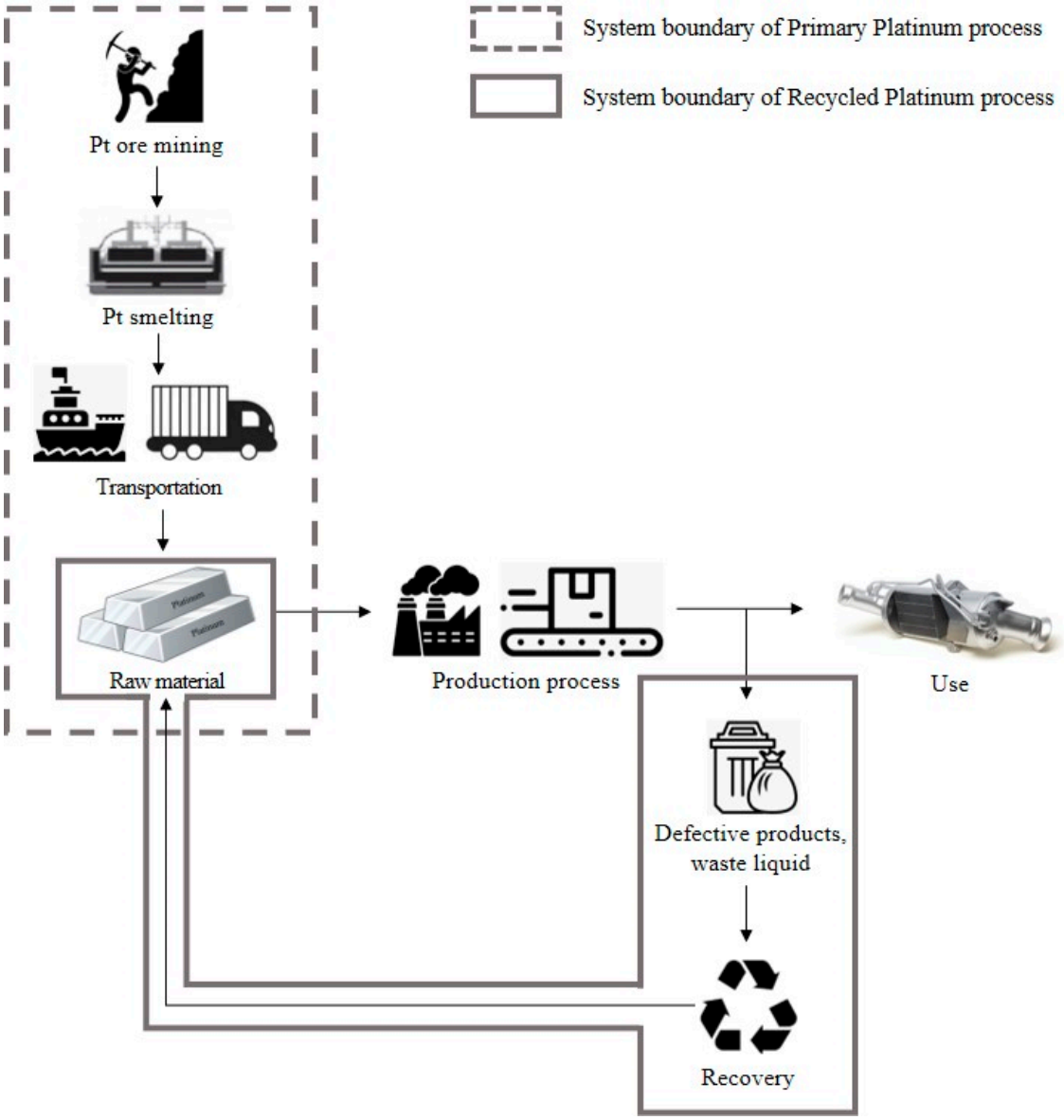


Figure 3. The Life Cycle Assessment (LCA) system boundary for primary platinum and recycled platinum of electrolytic recovery method.

2.3. Life Cycle Inventory Analysis

Data Sources and Calculation

The inventory analysis stage involved data collection, organization, and quantification of input and output materials for unit processes associated with the product system, which is in accordance with the functional unit. Data sources for primary Pt relied on literature values, given its reliance on imports. In contrast, data for recycled Pt were collected from "Company A" in the metropolitan area from January to December 2021. The collection of recycled Pt data primarily focused on general information and annual input-output performance items, ensuring reliability through verification with actual field data, as shown in Table 1.

Table 1. Input and output database for platinum recycling process of electrolytic recovery method.

Input				Output			
Group	**Material**	**Unit**	**Quantity**	**Group**	**Material**	**Unit**	**Quantity**
Raw material	Process waste	kg	145.14	Product	Pt	kg	1
Energy	Electricity	kWh	1305.78	Air emission	TSP	kg	0.73
	LPG	kg	43.88		NOx	kg	0.09
Utility	Tap Water	kg	36.74		HCl	kg	0.09
Chemicals	HCl	kg	32.45		NH_3	kg	0.01
	HNO_3	kg	9.1		N_2H_4	kg	0.07
	NH4Cl	kg	1	Water emission	Wastewater	kg	36.74
	NaOH	kg	10.65				
	N_2H_4	kg	1.021				

The inventory analysis for recycled Pt utilized the production information of the subject product to investigate the materials entering the product and quantified them to match the functional unit. In the Pt recycling process, the primary raw material was process waste, and secondary raw materials include hydrochloric acid, nitric acid, hydrazine, and utilities such as water, electricity, and liquified petroleum gas (LPG). The outputs include Pt, air, and water emissions. Subsequently, inventory analysis was performed for the inputs and outputs of each process to calculate the environmental impact.

For the raw material acquisition stage of recycled Pt, annual averages were used as the primary raw material, which consisted of process waste (defective products and waste liquid). For the quantity of chemical substances, actual measurement data recorded by the company for the functional units were used to determine the quantity of chemical substances. Emissions were calculated by considering the ratio of emission facility installation permits to the quantity of chemicals used. The emission quantities of air and water pollutants were calculated using the process information.

Electrical power and LPG were used as energy sources in the product-manufacturing stage of recycled Pt. Since the energy consumption of each product is not managed separately, allocation was required to distribute energy usage among the different products. Therefore, in this study, the factory's total electricity consumption data were calculated based on the production quantity of the subject product using Equation (1), based on the energy consumption data collected in 2021. LPG usage was calculated following Intergovernmental Panel on Climate Change guidelines and applied [25].

$$EC_{pi}(\mathrm{KWh/kg}) = \frac{EC_{total}}{P_{total}} \times \frac{P_i}{P_{total}}, \quad (1)$$

where EC_{pi} is the energy consumption per 1 kg of target product's (KWh/kg), EC_{total} is the annual total electricity consumption (KWh/yr), P_{total} is the annual total product quantity (kg/yr), P_i is the annual production quantity of product (EA/yr), and i is the target product (primary product, recycled product; EA).

The data related to raw materials, utility production, and wastewater treatment for both primary and recycled Pt are presented in Table 2. Ecoinvent, an overseas Life Cycle Inventory Database (LCI DB), was used for primary Pt and hydrazine, whereas a domestic LCI DB was used for other substances. After data collection and selection of the appropriate LCI DBs, the entire Life Cycle Assessment was conducted using TOTAL software (version 6.5.5).

Table 2. Life Cycle Inventory Database (LCI DB) and sources for platinum recycling process of electrolytic recovery method.

Type	Material	LCI DB	Source
Raw material and energy production	Pt	Platinum	Ecoinvent 3.8.1
	Electricity	Electricity	Korea National LCI DB
	HCl	Hydrogen chloride	Korea National LCI DB
	HNO_3	Nitric acid	Korea National LCI DB
	NH_4Cl	NH_4Cl	Korea National LCI DB
	NaOH	Caustic soda	Korea National LCI DB
	N_2H_4	Hydrazine production	Ecoinvent 3.8.1
Waste treatment	Wastewater	Wastewater	Korea National LCI DB
	TSP	TSP	Korea National LCI DB
	NOx	Nitrogen dioxide	Korea National LCI DB
	HCl	Hydrogen chloride	Korea National LCI DB
	NH_3	Ammonia	Korea National LCI DB
	N_2H_4	Hydrazine	Korea National LCI DB

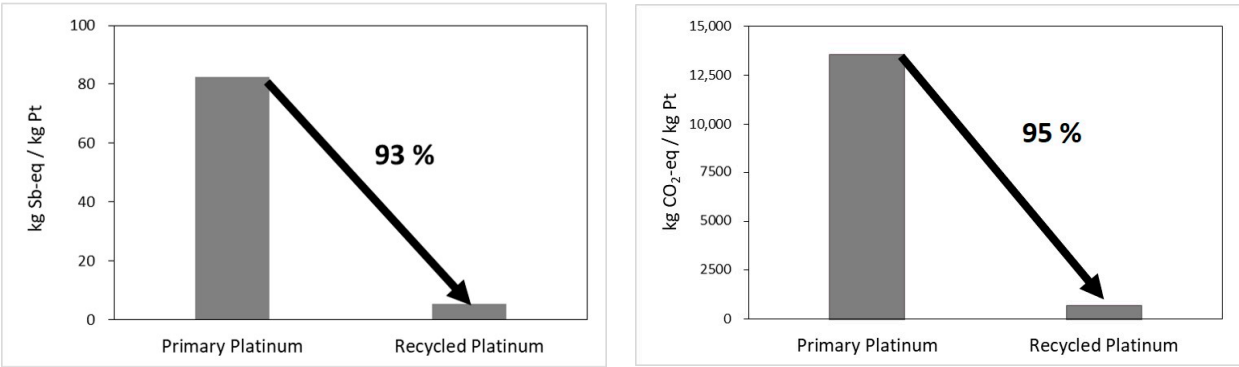
Given that over 70% of primary Pt produced originates from South Africa, this study assumes that primary Pt is imported from South Africa [26]. The transportation stage for primary Pt thus considers transportation from South Africa to the domestic market. The transportation route from South Africa to domestic locations was calculated, and a scenario was created using the Ministry of Environment's shipping transportation LCI DB (overseas container ship (average)). The average transportation distance from South Africa to Incheon Port was calculated to be 13,000 km and was used in the calculation. Additionally, the transportation route from Incheon Port to the recycling company was calculated, and a scenario was established using the Ministry of Environment's road transportation LCI DB (road transportation: less than 1 ton). The transportation distance from Incheon Port to the Pt catalyst company was calculated to be 14 km and was used in the calculation.

2.4. Life Cycle Assessment Results

This study used the TOTAL (version 6.5.5) LCA program developed by the Ministry of Environment. The environmental impacts were quantified in six categories, including abiotic resource depletion (ADP), acidification (AP), eutrophication (EP), global warming potential (GWP), ozone depletion (ODP), and photochemical oxidant creation (POCP). However, this study primarily focused on the impact assessment for major environmental categories, namely, resource depletion and global warming, due to Pt's finite availability and its energy-intensive extraction and refining processes. Moreover, energy generation for these processes typically relies on fossil fuels such as coal and oil, leading to significant GHG emissions, such as carbon dioxide, into the atmosphere.

3. Results and Discussion

The results for the environmental impact assessment in the resource depletion and global warming categories for 1 kg of Pt, comparing primary and recycled products, are presented in Figure 4. In the resource depletion category, primary Pt was calculated as 8.25×10^1 kg Sb-eq./kg, and recycled Pt was calculated as being 5.45×10^0 kg Sb-eq./kg. The use of recycled Pt resulted in an environmental impact reduction of approximately 93%. In the global warming category, primary Pt was calculated as being 1.35×10^4 kg CO_2-eq./kg, and recycled Pt was calculated as being 6.94×10^2 kg CO_2-eq./kg. The use of recycled Pt thus resulted in a remarkable reduction in environmental impact of approximately 95%. This is interpreted as a simultaneous improvement in environmental and economic performance owing to reduced GHG emissions and resource-saving achieved through Pt recycling.



(**a**) (**b**)

Figure 4. LCA results for (**a**) abiotic resource depletion and (**b**) global warming of primary platinum and recycled platinum using electrolytic recovery method.

Upon examining the substances that affect ADP and GWP for 1 kg of primary Pt and recycled Pt, it was found that fuel components such as Crude Oil and Hard Coal had a notable effect on resource depletion. Among GHG emissions, CO_2 and N_2O had the highest emission levels. This can be attributed to the fact that Pt extraction from ore occurs at temperatures of approximately 1500 °C, requiring substantial quantities of fuels like bituminous coal and electricity to attain such temperatures, resulting in elevated GHG emissions [27].

Pt is present in trace amounts in ores containing copper, nickel, and other elements. Specifically, the natural Pt concentration in the Bushveld Complex in South Africa ranges from 3 to 10 g/ton according to ore standards [28]. Consequently, a substantial amount of ore (resources) is required for primary production. Moreover, the traditional process of mining and refining Pt involves high-temperature smelting and refining in furnaces that require large quantities of fossil fuels and electricity as inputs, resulting in significant GHG emissions. In contrast, the recycling process extracts Pt from scrap metals rather than from mining ores, resulting in relatively lower energy consumption. For instance, the concentration of Pt in automotive catalysts, one of the scrap metals, is 2700 g/t [29]. Additionally, the energy consumed for primary ore mining is 70–100 times greater than that consumed for recycling Pt [13]. Therefore, recovering Pt from waste sources is not only economically advantageous but also more ecologically sustainable. The reduced reliance on fuel for achieving high temperatures during the recycling process contributes to a lower environmental impact compared to that of primary Pt production.

Comparative Analysis of Similar Research Case

The results of this study were compared and analyzed with those of previous studies that evaluated the environmental performance of metal recycling processes using the LCA method. The findings were consistent with prior studies, confirming the environmental benefits of metal recycling. For instance, Shin [30] employed a CtG assessment method to calculate the resource consumption and GHG emissions associated with palladium (Pd) (one of the Pt-group metals) during its recycling and disposal. The analysis showed that recycling 1 kg of Pd resulted in a remarkable reduction of 8967.17 kg CO_2-eq. in GHG emissions and a decrease of 10.10 kg Sb-eq. in resource consumption. Furthermore, Pd recycling resulted in a substantial 50% reduction in natural resources (Pd).

Shin [31] applied the LCA methodology to quantify the environmental impacts of using or not using secondary resources (scrap) in the production of primary processed products for copper and aluminum. The results showed that, for copper, when producing 1 ton of secondary processed products, the environmental impact across all environmental categories was 6.09×10^1 person-yr/f.u. when using secondary resources, compared to 7.23×10^1 person-yr/f.u. without them, indicating an 18.8% lower environmental impact when using secondary resources. For aluminum, when producing 1 ton of primary

processed products, the environmental impact across all environmental categories was 2.34×10^2 person-yr/f.u. when using secondary resources and 3.01×10^2 person-yr/f.u. without them, demonstrating a 28.4% reduction in environmental impact when secondary resources were used.

Comprehensive findings from previous studies on metal recycling revealed a reduction in the environmental impact of metal recycling. Specifically, there was a 50% reduction in Pd, an approximately 49% reduction in GHG emissions, an approximately 20% reduction in the case of copper, and an approximately 30% reduction for aluminum. These results confirm the environmental benefits of metal recycling.

When comparing the environmental reduction effects of this study with those of previous studies, the higher efficacy in this study could be attributed to differences in the comparison subjects. In the case of Pd, the comparison was between the disposal and recycling processes [30]. In the instances of copper and aluminum, the comparison was between production from ore versus production from ore and secondary resources (scrap) [31]. In contrast, this study compares natural resources such as ores with Pt-containing waste materials. Consequently, the effects of resource saving and GHG reduction in this study appear to be substantially greater than those reported by Shin [28] and Shin [29]. Pt refining from ore requires a substantial amount of resources and energy, whereas the waste materials considered in this study required far less energy for Pt extraction than the ore. This indicates a relatively substantial environmental reduction effect compared to natural ore resources.

4. Conclusions

In this study, a quantitative analysis of the environmental performance of both primary and recycled Pt products was conducted using LCA. Based on this analysis, the following conclusions were drawn:

The significant environmental advantage observed in the LCA for Pt recycled from Pt-containing waste materials is attributed to the energy consumed for primary ore mining, which is 70–100 times greater than that consumed for recycling Pt compared to that in natural ore mines. This substantial difference in Pt content is the key factor behind the remarkable 93% reduction in resource consumption and equally noteworthy 95% reduction in GHG emissions against Pt derived from natural ore mines. The primary environmental impact factors also showed that the reduced input of new resources led to the most substantial decrease in the environmental impact from the perspective of resource scarcity. Additionally, during the product manufacturing phase, the environmental impact of primary Pt production exceeded that of recycled Pt, mainly due to the higher electricity consumption during primary product manufacturing.

Pt, being a rare metal with limited resource extraction capabilities, demands innovative solutions for resource conservation. Domestic recycling technologies are a significant avenue for overcoming these limitations and contributing to the efforts of energy-poor nations. If the findings of this study are integrated into national policies, the promotion of a circular economy is expected to be facilitated. Furthermore, with the anticipated surge in Pt demand driven by the burgeoning hydrogen economy and increased market needs, efforts to improve Pt recycling rates will be necessary in the future.

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