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Economic Analysis of a Conceptual Industrial Route for Printed Circuit Boards Processing Based on Mass and Energy Balances

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Abstract: With a generation of more than 2 million metric tons per year, Brazil is the largest producer of waste electrical and electronic equipment in Latin America. However, Brazil does not have its own way for treating printed circuit boards, a key component present in this type of waste. In this context, the processing of these components would allow the extraction of metals with high added value, mainly copper, silver, gold, and palladium. The purpose of this research is to design a conceptual treatment route, based on the integration of technologies described in the literature. After creating the route design, a mass and energy balances were performed, considering two printed circuit board source as raw material: (Case A) Wasted equipment in general; (Case B) Using only cell phones. For both cases, the treatment of 2 $t \cdot h^{-1}$ was considered. In addition, cost estimates and plant sensitivity analysis were carried out. For 15 years of plant production, the calculated Capex was USD 2,002,682, where an internal return rate of 140.1% and 3933.0% was obtained for Case A and B, respectively, and a net present value of USD 44,403,373 and USD 3,210,393,496 for Case A and B, respectively. Additionally, it was observed that Case A has a great sensitivity to the variation of the processing volume. Based on the present findings, this theoretical research has the potential to be a nucleation point in the design of a future industrial plant dedicated to the recycling of printed circuit boards, as well as to understand the key variables for the processing these components, based on Brazilian circumstances. Additionally, the project presents the hypothetical investment required for the creation of such conceptual plant, which is a crucial piece of information for potential investors.

Keywords: solid waste; waste management; material flow analyses; sensitivity analysis; recycling; e-waste

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1. Introduction

The amount of Waste Electrical and Electronic Equipment (WEEE) generated worldwide has an annual growth of 3–5% [1–3] and an estimated annual quantity of more than 53 million metric tons [4]. Brazil is the second largest WEEE generator in the Americas, with an annual production exceeding 2 million metric tons [4] and less than 10% of all this waste is properly treated [5,6].

There is a need to deal with generated WEEE, which has a large amount of material resources that can be recovered and reused. Based on this necessity, new concepts and ideas for managing and treating this waste were developed, in which the circular economy and urban mining can be mentioned [3,7]. Together, these two concepts can be applied in the treatment of electronic waste, with circular economy increasing its visibility, encouraging the use of secondary sources of raw material to produce consumer goods [3], and urban mining targeting the extraction of materials and components from urban waste [7].

Due to the wide variety of components present in electronic waste, a comprehensive range of elements is present in its composition (e.g., precious metals, base metals, ferrous metals) [8], thus making it a potential source of material extraction. The composition of metals present in this type of waste may be as high as up to 50 times higher than the concentration in natural deposits [9,10]. The metallic elements found in electronic scrap can be divided into five groups: precious metals, platinum group metals (PGM), base metals, and elements that pose a risk to the environment, as well as scarce metals [1,11]. Among all the components present in WEEE, Printed Circuit Boards (PCB) can be mentioned as one of the most complex components and with the greatest potential to be a source of materials with high added value [5,12]. Annually, worldwide PCB manufacturing grows by 17 to 25% [13], where on average it represents about 3 to 6% of all mass present in electronic waste [14,15].

In this context, the WEEE component with the greatest economic interest to be recycled is PCB [16], since this component has higher fractions of gold, silver, copper, and palladium [17]. The average composition present in a PCB, where approximately 40% of the mass is composed of metals, 30% ceramics, and 30% plastics [18,19]. However, it is noteworthy that compositions can vary drastically depending on the type of equipment [20], where, for example, cell phone boards tend to have a metal mass fraction above 60%, having even higher concentrations of gold and silver when compared to other equipment [21,22]. Regarding mobile phones, in terms of devices composition, some significant amounts of gold (~347 $g \cdot t^{-1}$) and silver (~3.63 $kg \cdot t^{-1}$) [20,21] can be observed. Additionally, the concentration of palladium can be up to 100 $mg \cdot kg^{-1}$, thus making them a possible secondary source of these elements [23,24]. Thus, it is interesting to consider this type of device as a potential urban resource for extracting precious metals.

In 2018, there were 134 scrap recycling centers in Brazil as well as 13 export centers, in which the highest concentration of these companies lies in the south and southeast regions of the country [25]. Moreover, practically all recycling centers can only operate the first stages of this process, which would be the equipment separation and dismantling, with the subsequent stages of process being conducted abroad, mostly without any metallic or component recovery being carried out in Brazilian soil. Therefore, complex components with high added value (e.g., PCBs) are normally exported [5,25,26]. Additionally, in Brazil there are a large number of cell phones and other small electronic equipment that are stored, which produces a hibernation stockpile with substantial recycling potential [6].

One reason why complex components are exported is that Brazil does not have an operating industrial plant with technology to process these components, thus requiring incentives to carry out studies aimed to develop solutions for their treatment and recycling [5,25,26]. Additionally, in the literature associated with the Brazilian situation, most scientific publications are in the field of WEEE treatment and are mostly focused on its management or related to the use of some specific unit operation/processes, alone or in a small sequence [27]. It seems that there is a paucity of information regarding potential flowcharts and the economical requirements, considering Brazilian circumstances, that would allow the treatment of this residue and the consequent recovery of components without the need to export such values to other countries [27]. Our previous research estimated the value of the Brazilian stockpile in hibernation to be at least USD 797.50 million, based on the assessment of higher-education community behavior analysis and economic potential of stored devices [5,6]. Based on this impressive number, the premise of the present manuscript is related to the investigation of requirements and hindrances for the installation of a hypothetical electronic waste recycling plant in Brazil, as well as the economic potential assessment, which we consider a major information for potential investors. For this study, we consider an industrial plant dedicated to metal recovery under this perspective.

In this context, the present work aims to propose and analyze a conceptual route for the treatment of PCB. For the construction of the theoretical processing flowchart, we assessed several materials published in scientific, technical, and commercial literature. Through several potential technologies reviewed, an integrated route to extract high value-added PCB materials was designed. Block diagrams of the conceptual route were then constructed to illustrate the material flow. To assess the feasibility of the hypothetical process, we calculated the mass and energy balances in ideal conditions.

2. Materials and Methods

2.1. Process Statements

To form an integrated route for PCB treatment, the main steps necessary for electronic waste recovery were reviewed in the literature. The main steps for recycling are [8,12,26]:

(a) Device Dismantling: Disassembly of electronic equipment, where the internal components are liberated and separated.
(b) Unit Operations of Mineral Processing: Reduction of the volume of PCBs and physical separation of the materials/components in them (e.g., plastics, ferrous metals, non-ferrous metals, fiberglass, among others).
(c) Extractive Metallurgy Unitary Processes: recovery of high value-added metals (mainly gold, silver, palladium, and copper). At this stage, mainly pyrometallurgical or hydrometallurgical processes are applied.

Within these main identified steps, all the inputs necessary to build the conceptual route and to generate a mass and energy balance that allows estimating the costs of the process were obtained. Two cases for PCB recycling were analyzed: (Case A) Use of any type of e-waste; and (Case B) Use of mobile phones. The latter was selected as a case of interest in our previous study, since it was identified that such devices have a higher fraction of PCBs and a higher grade of precious metals [6]. The data used as input for the mass balance are presented in Table 1. To visualize the integrated route, two block diagrams with the main processes were produced. To design the diagrams, we used the open software diagrams.net version 13.9.9 [28].

Table 1. Mass fraction values obtained in the literature for the treatment of PCBs.

Fraction	Mass Fraction for Electronic Waste in General (Base Case A)	Reference	Mass Fraction for Cell Phones (Base Case B)	Reference
PCB	0.045	[14]	0.25	[29,30]
Polymer decomposed in pyrolysis	0.238	[31]	0.13	[22]
Condensable gases in pyrolysis	0.76	[31]	0.76	[31]
Non-magnetic	0.9	[21,27]	0.9	[21,27]
Au	0.00025	[11,16,32]	0.000347	[20,21]
Ag	0.0003	[16]	0.00363	[20,21]
Cu	0.25	[18,33]	0.128	[20,21]
Pd	0.00014	[1]	0.00015	[20,21]
Fiberglass	0.3	[18]	0.24	[22]

As already shown, Brazil generates more than 2 million metric tons of WEEE per year [4], however, only about 2% is collected (about 40,000 metric tons) [26,34]. Thus, the Brazilian government has the goal of raising this value to 17% (about 340,000 metric tons) [35]. In this context, a WEEE flow of 2 ton·h^{-1} was proposed, which represents 5% of the annual target proposed by the Government [36]. Additionally, in Brazil there are more than 16.96 million mobile phones in hibernation, being stored by their users [6], making Case B even more valid to allow the recovery of materials present in these. An ideal recovery rate of 100% was considered as process hypothesis and to simplify the variables at the first stage. Naturally, for concrete future developments, the recovery rates in laboratory and pilot conditions are necessary information to be used to provide adequate data for investment decisions.

2.2. Economic Analysis of the Conceptual Route

For the economic analysis, the Capital Expenditure (Capex) and Operational Expenditure (Opex) of the hypothetical plant were estimated using the process route of the conceptual design. For plant installation, Capex was calculated for the main process, considering main and auxiliary equipment, where the total value was estimated by the standard method described in Plant Design and Economics for Chemical Engineers by Peter and Timmerhaus 1991 [37,38]. Opex was estimated considering fixed and variable costs as well as operational labor expenses. An ideal continuous operation of 24 h per day without any daily stop was considered in this part of the study.

The costs of the main equipment were estimated by quotations on the websites of international suppliers, where the average price of the equipment was considered. Since the quotations were obtained at current values, it was not necessary to apply any present value method to correct the costs. Additionally, the quoted prices have been adjusted to include import taxes and shipping. To calculate the plant's revenue, only the values of gold (Au), silver (Ag), copper (Cu), and palladium (Pd) were considered, in which the auction price for each metal was 57,590 USD·kg^{-1} for Au, 819.88 USD·kg^{-1} for Ag, 9.75 USD·kg^{-1} for Cu, and 84,488 USD·kg^{-1} for Pd. All prices considered were removed from the market quotation by the end of July 2021 [39]. To be conservative, only 90% of the quoted metals price was considered, as the market values of these can have significant variations since they are commodities [40,41].

Additionally, it was considered an 18% tax for the trade of metals [34], together with the income tax of 25% on the gross profit, with a value of depreciation per year of 10% of the calculated Capex was fixed [42], at the same time as a maintenance fund of 3% of the Capex, as well as an annual correction due to inflation of 7% (as an approximation of Brazilian inflation [43]). The use of 100% of equity capital was considered in the entire economic feasibility analysis, without considering third-party financing. Them was generated the income statement for the year and the free cash flow. Additionally, a sensitivity analysis of the main variables of the project was performed to determine their influence on the net present value (NPV). Finally, the internal return rate (IRR) was determined, considering the minimum attractiveness rate (MAR) for the viability of the plant at 12%, since it is usual to consider the MAR in this range for industrial investments in Brazil [44,45].

3. Results

3.1. Conceptual Process Design

Herein, we present the integration of reviewed technologies for PCB to design a hypothetical processing flowchart which will be used as a conceptual object in this study. The proposed process route is presented in Figure 1, where it starts with the separation of the WEEE components. The only desired component in this initial step is PCB. Since the practice of collecting and separating WEEE is already present in Brazil [25], there is the possibility of the PCB being collected from collection centers, not necessarily requiring this first step. To reduce the size and promote some degree of liberation of constituent in PCBs, they must be shredded [8], in which similar processes require around 137 MJ per metric ton of material to be processed [21].

The shredded PCBs are then sent to a pyrolizer, where the metallic and inorganic non-metallic fractions will be concentrated [16,29], while the organic fraction will be volatilized, and it is expected that the condensable gases will be recovered as oil. To optimize the process, low-temperature pyrolysis should be applied, which allows for a better separation of metals and fiberglass, when compared to high temperatures [27,46,47]. The oil obtained at this stage has the potential to be used as fuel in the process [27,46,48], or be used as a source of phenols or raw material to produce resins [31]. The energy required for the PCB endothermic pyrolysis reaction is 19692 MJ per metric ton of PCB [46]. The solid product of pyrolysis is then milled in a ball mill, where the objective is to reduce the solids size to liberate the metallic parts from the non-metallic parts [49,50]. Due to the heterogeneity of the PCB, it does not have a specific liberation size, where the non-metallic part tends to concentrate in fine powder fractions [50]. Using a mill with a power of 90 kW, the consumption of this operation will be 324 MJ·h^{-1} [51]. The released product, which has a particle size of 5 mm [27], is then submitted to magnetic and electrostatic separation [12,50,52]. The magnetic separation is applied first, separating metallic components, i.e., mainly iron and nickel [52]. For the magnetic separation, the consumptions described in the literature for mineral-metallurgical operations were considered, which is 504 MJ per hour of operation [53]. Additionally, electrostatic separation has the potential to separate non-ferrous metals from other inorganic compounds, where considering a separator with a consumption of 5 kW, the consumption of this operation will be 18 MJ per hour.

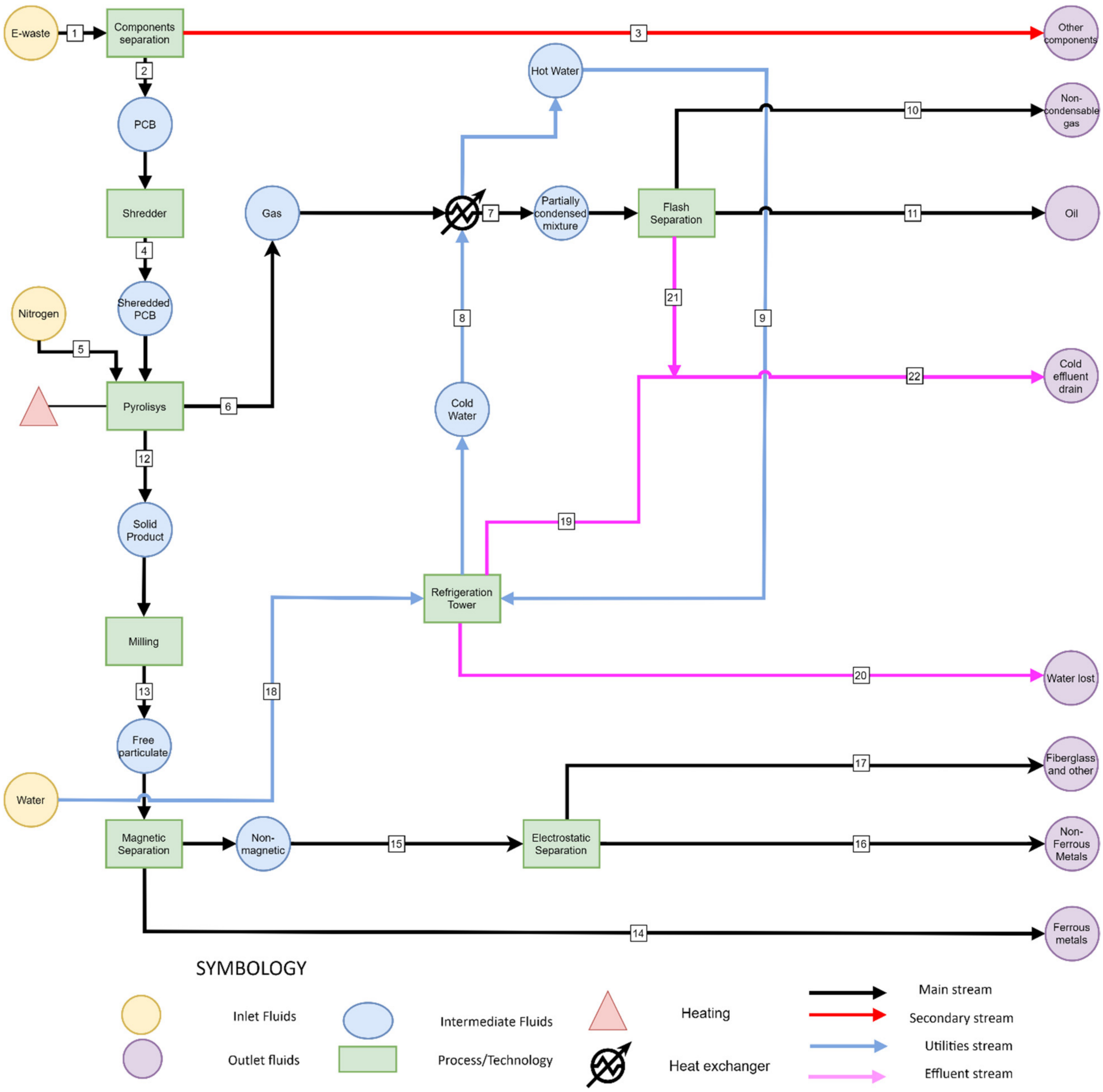

Figure 1. Block diagram of the first part of the proposed process route.

The non-metallics consist mostly of flame retardant dust (generated in pyrolysis) and fiberglass [27]. The present work does not cover the treatment or destination of these products, but there are published material reporting the possibility of flame retardants incorporation along with fiberglass into plastics and composites [18,54]. On the other hand, the metallic products obtained from electrostatic separation are subjected to hydrometallurgical based sulfuric leaching, as shown in Figure 2 for obtaining metals with high added value. The main objective is the recovery of copper, silver, gold, and palladium, as the metals can be considered as the main value-added elements to be recovered, representing approximately 60% [20] to 80% [21,55] of the entire value proportion.

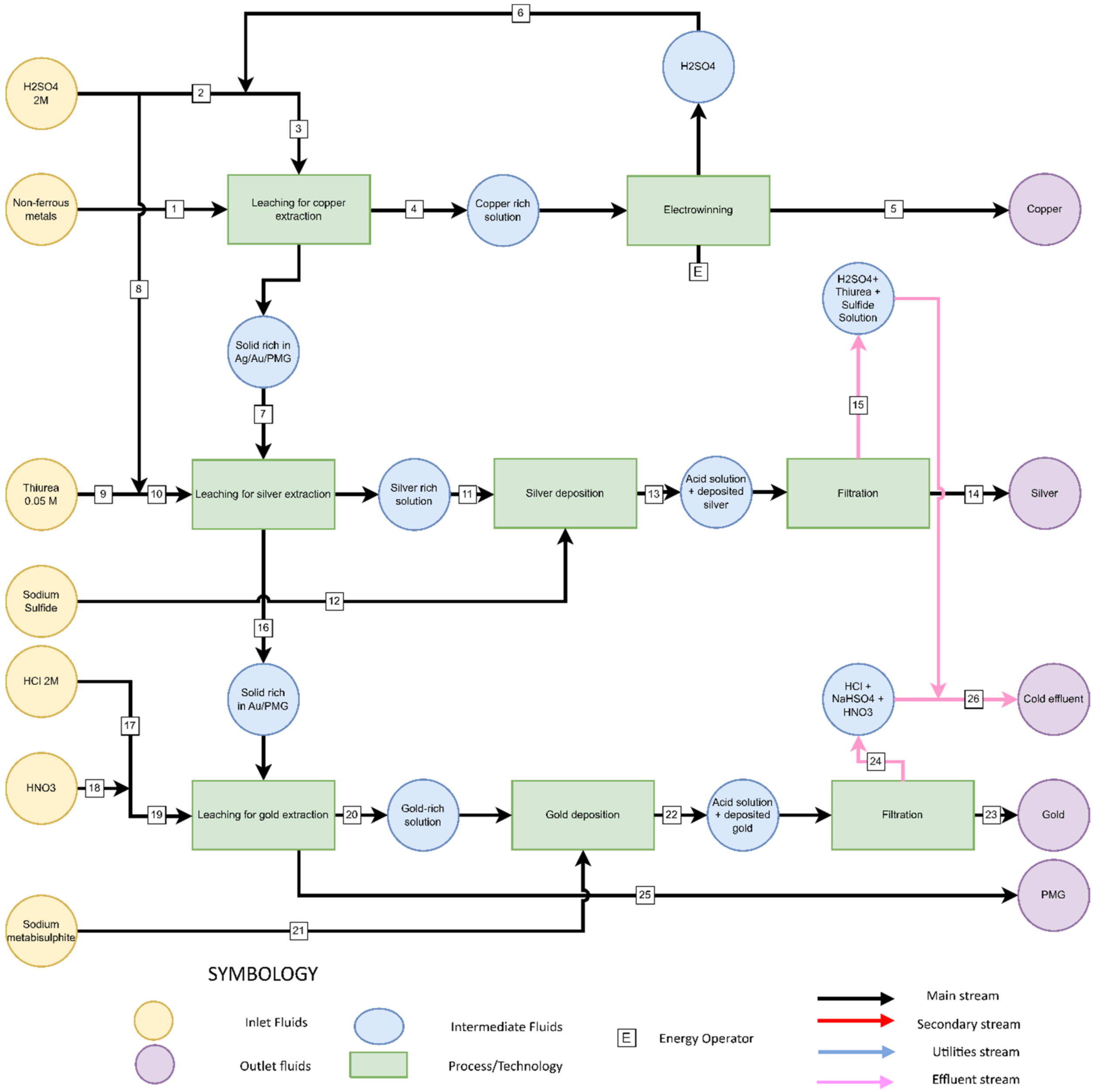

Figure 2. Block diagram of the second part of the proposed process route.

The nonferrous metals stream is first treated with a 2 M solution of H_2SO_4, where the copper is leached into copper sulfate ($CuSO_4$) [21,56]. To avoid potential obstacles caused by corrosion due to H_2SO_4, other copper leaching processes are described in the literature, such as the use of Fe^{3+} [15,33,55], or the complexation of copper by chelation–dechelation processes [57]. However, to design the present process route by means of the most traditional manner, these other options were not considered. Copper is then recovered by electrowinning, where a voltage of 3 V is used with energy expenditure close to 10,000 MJ per metric ton of recovered copper [21,58].

It is recognized in the copper industry that in copper electrowinning anode slimes, there is a high concentration of Ag, Au, and Pd [21,59]. Therefore, three steps are performed: silver extraction, gold extraction, and palladium refining. In this context, for the extraction of silver, the use of a solution of 0.05 M H_2SO_4 and 0.05 M thiourea was chosen, which has the potential to extract more than 99% of the silver present [30,60]. This leach solution forms a complex with silver ($[Ag(CS(NH_2)_2]^{3+}$), in which pure silver is recovered through precipitation using a 50 mM sodium sulfide ($Na_2S{\cdot}9H_2O$) solution, with almost full recovery of silver [30,60].

The unleached solid is then taken to another step, in which gold is extracted by adding a solution of 2 M HCl and HNO_3 in a 3:1 ratio [56]. Afterwards, sodium metabisulfite is added to the leached solution, which promotes the precipitation of gold [56], as presented in Equations (1) and (2). Due to the corrosive characteristics of this method, it is also possible to apply other solutions (e.g., thiourea in an alkaline medium) [61]. Still, in the present conceptual route design, we opted for the first option. The remaining solid, which was not leached, consists of elements of the platinum group, mainly palladium, which can be obtained through fractional precipitation process, where there is an energy consumption of 64,120 MJ per kg of product produced [21].

$$Na_2S_2O_5 + H_2O \rightarrow 2NaHSO_3 \tag{1}$$

$$2AuCl_3 + 3NaHSO_3 + 3H_2O \rightarrow 2Au \downarrow + 6HCl + 3NaHSO_4 \tag{2}$$

3.2. Mass and Energy Balance of the Conceptual Process

As already mentioned, for the two base cases, a WEEE input of 2 $t{\cdot}h^{-1}$ was fixed. Thus, to obtain the mass balance, the information presented in the Table 1 was used as a reference. Analyzing the first part of the process (Figure 1), the inlet and outlet streams are shown in Table 2. In a corresponded approach, in Table 3, the inlet and outlet of the second part of the process are presented (Figure 2).

Table 2. Calculated flow rates and compositions of the inlet and outlet streams of the first part of the process.

Inlet Fluid	Case A Flow ($kg{\cdot}h^{-1}$)	Case B Flow ($kg{\cdot}h^{-1}$)
WEEE	2000	2000
Water	18.51	56.16
Nitrogen	(only used for initial inertization, not accounted for)	(only used for initial inertization, not accounted for)
Outlet Fluid	**Case A Flow ($kg{\cdot}h^{-1}$)**	**Case B Flow ($kg{\cdot}h^{-1}$)**
Other components	1910	1500
Non-Condensable Gases	5.1	15.6
Oil	16.3	49.4
Water lost	18.5	56.16
Fiberglass and Others	39.2	127.3
Non-ferrous metals	22.6	264.3
Ferrous metals	6.9	43.5

Table 3. Calculated flow rates and compositions of the inlet and outlet streams of the second part of the process.

Inlet Fluid	Case A Flow ($kg{\cdot}h^{-1}$)	Case B Flow ($kg{\cdot}h^{-1}$)
H_2SO_4	0.13	33.85
Non-ferrous metals	22.6	264.3
Thiourea	0.13	33.85
Sodium Sulfide	0.1	3.75
HCl	0.0675	2.082
HNO_3	0.02	0.69
Sodium Metabisulphite	0.17	5.28
Outlet Fluid	**Case A Flow ($kg{\cdot}h^{-1}$)**	**Case B Flow ($kg{\cdot}h^{-1}$)**
Copper	22.5	256
Silver	0.27	7.26
Gold	0.0225	0.694
Palladium	0.0126	0.30

Subsequently, considering the entire process, for Case A, it is possible to obtain 22.5 g·h^{-1} of Au, 27.0 g·h^{-1} of Ag, 22.5 kg·h^{-1} of Cu, and 12.6 g·h^{-1} of Pd. When analyzing the process for the Case B, it is possible to obtain 694 g·h^{-1} of Au, 7.26 kg·h^{-1} of Ag, 256 kg·h^{-1} of Cu, and 300 g·h^{-1} of Pd.

The power consumption for the Case A required in the process is presented in Table 4, where the calculated energy consumption is 3663.5 MJ·h^{-1}. Additionally, as can be seen in Table 4, the total energy spent in the Case B is 32,556.5 MJ·h^{-1}.

Table 4. Power consumption to process PCB for Case A and Case B.

Process	Energy Consumption for Case A [MJ·h^{-1}]	Energy Consumption for Case B [MJ·h^{-1}]	Reference
Shredding	12.3	68.5	[21]
Pyrolysis	1772.3	9846	[46]
Milling	324	324	[51]
Magnetic separation	504	504	[53]
Electrostatic separation	18	18	[62]
Electrowinning	225	2560	[58]
Palladium recovery	807.9	19,236	[21]
Total	3663.5	32,556.5	

3.3. Cost and Investment Estimation Associated with the Conceptual Route

The costs of the main equipment for the designed conceptual route are presented in the Table 5, additionally, a quantity of 10% of the main value for auxiliary equipment was considered [37]. Thus, the estimated total price for equipment was USD 456,192.00.

Table 5. Main process equipment costs for the base case, quoted on the website of international suppliers, with import and shipping fees included.

	Main Process Equipment	Quantity	Total Cost [USD]	Reference
1	Shredder	1	56,700	[63]
2	Pyrolizer	1	108,000	[64]
3	Ball Mill	1	56,700	[65]
4	Plate filter press	2	58,320	[66]
5	Electrostatic separator	1	40,500	[67]
6	Magnetic separator	1	13,500	[68]
7	Electrowinning Cells	3	81,000	[69]
	Total main equipment cost		414,720	
	Total main + Auxiliary Equipment (10% of the Total main)		**456,192**	

With the total estimated value for equipment, it was used as 100% of the value for applying the Peter and Timmerhaus method [37,38]. Subsequently, the total fixed investment capital of USD 2,002,682 was obtained, as shown in Table 6. For both cases, the purchase price of WEEE was set at 455.82 USD·t^{-1} (Considering the updated value obtained by the study by Azevedo, 2019 [34]), the energy cost considered was 105.00 USD·MWh^{-1}, the reagent costs varied in a range of 7.00–12.00 USD·kg^{-1} and the cost of water was fixed at 2.00 USD·t^{-1}. The annual operational labor cost was estimated at USD 781,056.

For the processing of 2 t·h^{-1} of WEEE, the annual operating cost is described in Table 7, and the value obtained was USD 10,000,761 and USD 37,585,455 for Cases A and B, respectively. The working capital value was considered as the operating costs for 2 months of operation, which are equivalent to USD 1,666,793 and USD 6,264,260 for Cases A and B, respectively. Thus, the total capital investment for Cases A and B was USD 3,669,476 and USD 8,266,943.

Table 6. Total Capex for the Cases A and B, calculated using the Peter and Timmerhaus method.

	Item		[USD]
A		**Direct Costs**	
1	Main Equipment	100%	456,192.00
2	Purchased-equipment installation	38%	173,352.96
3	Instrumentation and controls (installed)	13%	59,304.96
4	Piping (installed)	29%	132,295.68
5	Electrical (installed)	18%	82,114.56
6	Buildings (including services)	35%	159,667.20
7	Yard improvements	10%	45,619.20
8	Service facilities (installed)	56%	255,467.52
9	Land (purchase is required)	5%	22,809.60
B		**Indirect Costs**	
10	Engineering and supervision	40%	182,476.80
11	Construction expenses	45%	205,286.40
12	Contractor's fee	9%	41,057.28
13	Contingency	41%	187,038.72
	Total (A + B)		**2,002,682.88**

Table 7. Total Annual Opex for the Cases A and B.

	Item		Case A	Case B
		Variable Costs [USD]		
1	WEEE		7,876,569.60	
2	Water		319.80	970.44
3	H_2SO_4		21,755.03	5,849,684.85
4	Thiourea		13,053.02	3,509,810.91
5	Sodium Sulfide		1204.39	323,847.44
6	HCL		5248.80	161,896.32
7	HNO_3		1360.80	41,973.12
8	Sodium metabisulphite		14,802.03	456,560.41
9	Energy		866,507.54	8,204,237.98
C	Total		8,800,821.00	26,425,551.06
		Fixed Costs [USD]		
10	Telephone/Internet Service		4800.00	4800.00
11	R&D [a]		303,470.23	8,603,532.12
12	General costs		24,000.00	24,000.00
13	Maintenance Service		12,000.00	12,000.00
14	Accounting Service		4800.00	4800.00
15	Contingencies		54,919.88	1,375,203.50
D	Total		418,884.27	10,378,958.55
		Labor Cost [b] [USD]		
	Function	**Quantity**	**Value**	
16	Plant Manager	1	51,840.00	
17	Engineer	4	167,616.00	
18	Operator	10	172,800.00	
19	Assistants	15	162,000.00	
20	Administrative	5	86,400.00	
21	General Services	5	32,400.00	
22	Security	10	108,000.00	
E	Total		781,056.00	
	Total (C + D + E)		**10,000,761**	**37,585,455**

[a] Cost with R&D considering 1.5% of gross revenue. [b] Considering the taxes provided in Brazilian legislation.

4. Discussion

4.1. Economic Evaluation

For both Cases A and B, a scenario of 15 years of plant operation was considered, where the income statement for the year, already with a 25% discount of the Brazilian income tax, can be observed in Figures 3 and 4. To calculate the income statement for the year, the revenue from the metals trade was considered, from these values of taxes, Opex, depreciation, and maintenance fund were subtracted.

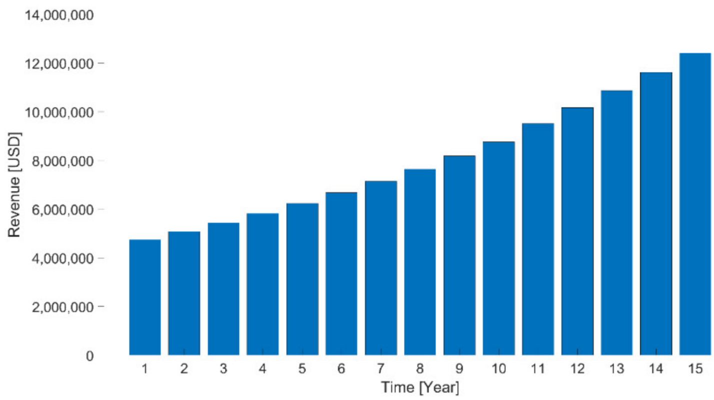

Figure 3. Income statement for the year of Case A.

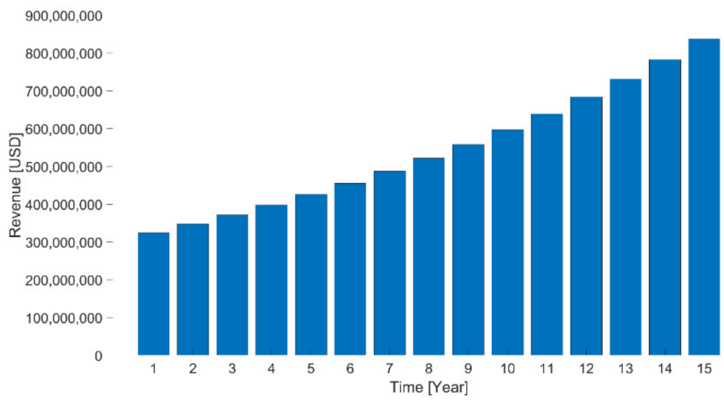

Figure 4. Income statement for the year of Case B.

Additionally, the accumulated Free Cash Flow for the two cases are presented in Figures 5 and 6. Therefore, it can be observed that for Case A, the discounted payback period was estimated in less than one year of operation, giving a NPV of USD 44.4 million, and IRR was estimated at 140.1%. In this context, with an IRR greater than zero, Case A can be considered viable. On the other hand, for Case B, under the operating conditions considered, it has also a discounted payback period of less than one year, a fact that could be connected to the large fraction of PCBs in cell phones [30] and by the high concentrations of Au, Ag, and Pd [6,21]. In this case, the NPV was over USD 3.2 billion. Since our previous study has estimated that for higher-education communities of Brazil only, the number of metals that can be recovered from mobile phones and other small electronic equipment is worth almost USD 800 million [6], the calculated NPV is not surprising. The IRR was estimated at 3933.0%, which makes this case greatly viable, in theory.

It is noteworthy that in the proposed conceptual process route, the trade value of oil produced by pyrolysis, ferrous metals and fiberglass was not considered, therefore, the profit calculated in this work may be underestimated and, considering the possibility of marketing these secondary products, it may be possible to have an increase in such value. However, it is important to mention that the expected value of precious metals can reach more than 80–90% of the total value present in WEEE [6,55].

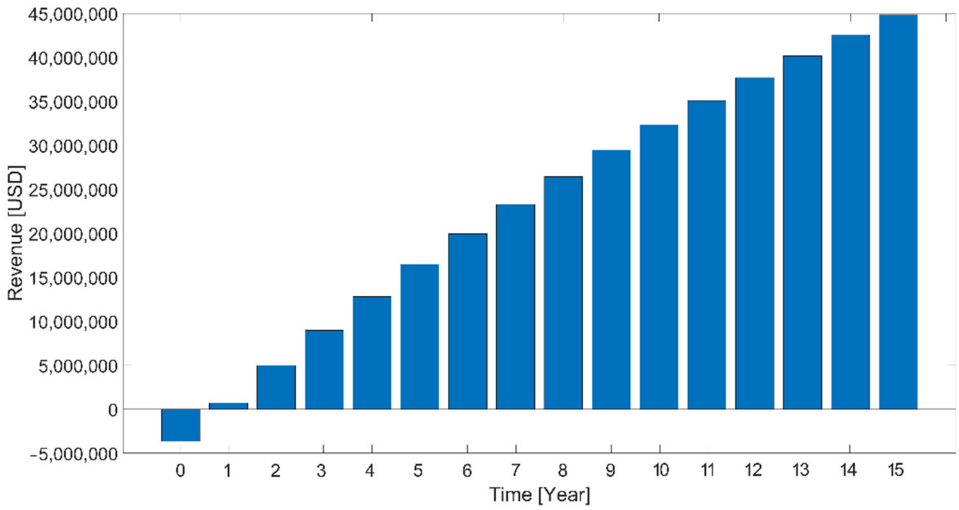

Figure 5. Free Cash Flow for Base Case A.

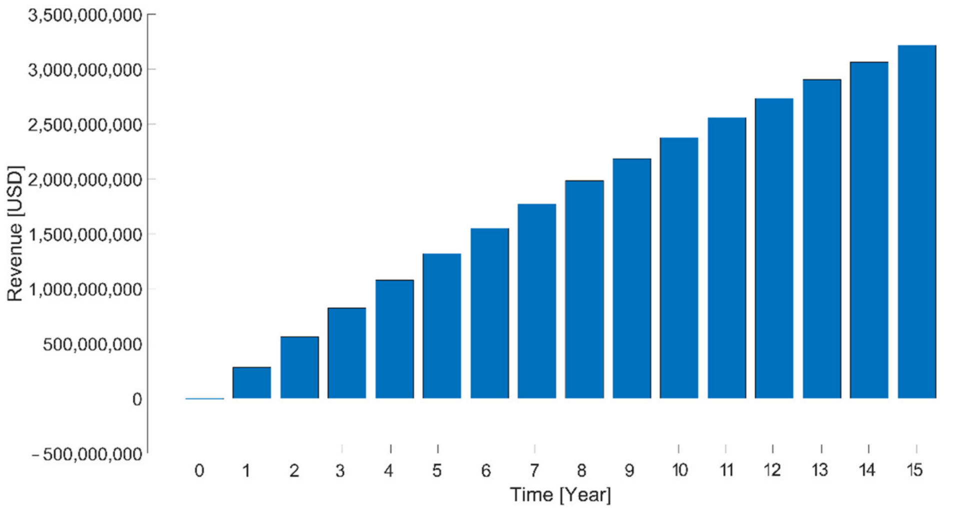

Figure 6. Free Cash Flow for Base Case B.

Thus, it is clear to us that the two considered cases are technologically viable, making it interesting to apply national technology for PCB recycling in Brazilian territory. The biggest obstacle to the plant's operation would be the logistics and the lack of public policies aimed at disposing of electronic waste in Brazil [6,70].

4.2. Sensitivity Analysis

To perform sensitivity analysis, some variables present in economic analysis were selected. The objective is to find the values of each of these variables that zero the NPV, maintaining the other constant variables. The selected variables were (a) processing volume of WEEE, (b) number of months of operation considered in the working capital value, (c) electronic scrap price, (d) Capex, (e) sales tax, and (f) metal trade price. As can be seen in Figure 7, for Case A, the process is highly sensitive to variations in processing volume and has a degree of sensitivity to the variation of gold price, WEEE buying price, and palladium price. The variation in the Capex value, sales tax, and working capital value is not so sensitive as to reset the NPV, and thus, these are not variables that influence the theoretical operation's viability for a 15-year scenario. The silver and copper prices were not considered, as these variables alone do not reset the NPV.

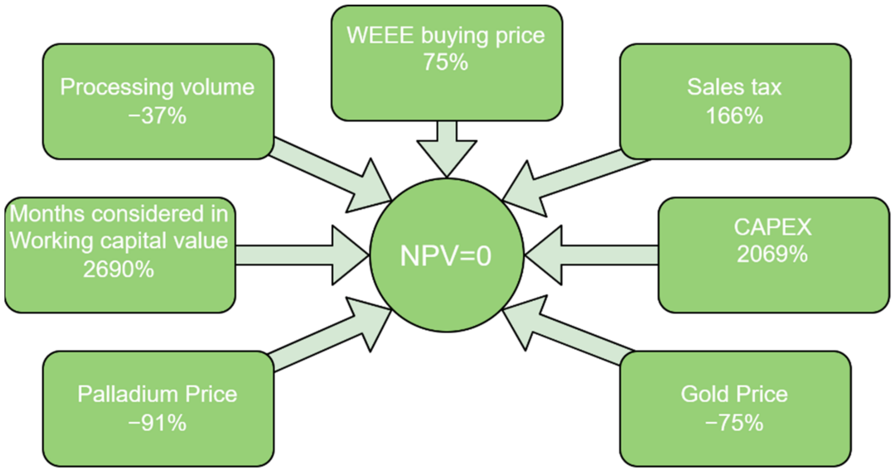

Figure 7. Sensitivity Analysis to reset the NPV of Case A.

In Figure 8, the sensitivity analysis for Case B is presented. As can be seen, no small variation of a variable makes the conceptual process unfeasible. In fact, an increase of 5367% in the WEEE purchase price would be necessary to make the process impractical, thus giving a large slack in the WEEE price estimative considered. Additionally, the variation in the isolated price of metals is not capable of resetting the NPV. Thus, it can be observed that Case B is highly profitable, and with the variables considered, the possibility of the plant becoming unviable is very low.

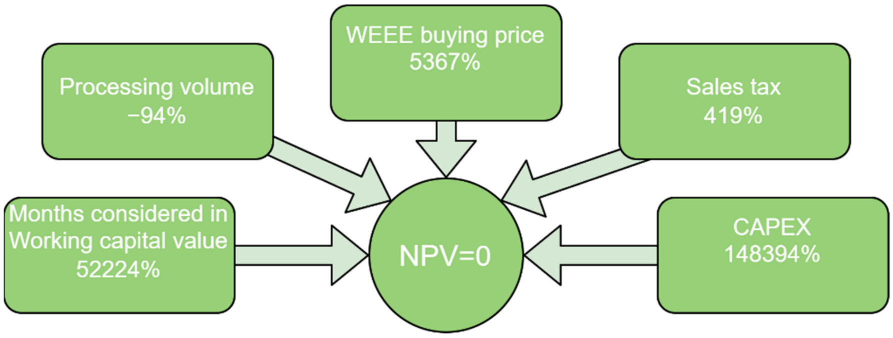

Figure 8. Sensitivity Analysis to reset the NPV of the Case B.

5. Conclusions

This research proposed an integrated route for industrial processing of PCB which is, until the moment of this study, something pioneering in Brazil. From the economic analysis carried out, the proposed process route is feasible, both for Case A and Case B. In theoretical 15 years of operation, it is possible to obtain an NPV greater than USD 44.4 million and USD 3.2 billion for Cases A and B, respectively. Additionally, the total estimated investment for both cases is USD 3.6 million and USD 8.2 million, considering Capex and working capital. Opex for Case A was estimated at around USD 10.0 million per year, while for Case B, it is around USD 37.5 million. Given the sensitivity analysis, for Case A, the variables related to the trade price of gold, the WEEE purchase price, and the processing value have a high degree of sensitivity, which may affect the overall feasibility of the conceptual process. The IRR for both cases was higher than zero, a fact that demonstrates viability and has the potential to attract investors.

All the analysis carried out in this research did not consider the trade value of other metals and process coproducts, e.g., iron, nickel, as well as pyrolysis oil. In this context, the estimates are possible to be lower than the real value that can be obtained in the process, using the considered variables. Additionally, in future work, it is necessary to consider the logistics of transporting WEEE from the recycling points to the industrial plant, as well as to determine better own collection points, to reduce the WEEE acquisition value. It is worth noting that because it is a theoretical conceptual route, the values of the mass and energy balances used in this work were all taken from the literature and there may be a variation in a real scenario, with a variation of the type of WEEE used. However, this work fulfills the objective of creating an innovative route, which can be applied in Brazil, in order to mitigate the growing generation of WEEE in the country, which currently does not receive the appropriate treatment.

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