Recycling of printed circuit boards

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***Abstract*—In this report we are going to examine the recycling process of printed circuit boards or (PCB). PCB's are used in a variety of products in today's society and some may contain hazardous materials. This report is going to delve into the different ways we can reduce environmental harm by recycling electronic devices with different methods. Some different methods and technologies of recycling that the report will bring up includes pyrolysis, hydrometallurgy, and bioremediation. Lastly the report will examine how the recycling industry is affect by the increasing amount of e-waste.**

***Index Terms*—printed circuit boards, pyrolysis, hydrometallurgy, bioremediation, recycling**

I. Introduction

Printed circuit boards (PCBs) are prominent in almost every electronic product in today's society. With everything from smartphones to calculators and now even *smart home* devices like light bulbs. PCBs are not going anywhere; with the increase in electronic products and the rise of global warming awareness, recycling is more important than ever. Even tough progress is made regarding hazardous materials in PCBs, older devices still often contains materials such as lead within the surface finish. Mercury and cadmium are other materials found within PCBs that are harmful for the environment and human health if not handled correctly. With the increase in electronic devices we also see an increase in wastes from electric and electronic equipments (WEEE). In a study made by UNs Sustainable Cycles Programme we generated a total of 53.6 Mt of e-waste, which calculates to a an average of 7.3 kg per capita [1]. Considering this, recycling is an effective way to mange the increasing waste stream, as it can recover valuable materials and prevent environmental pollution. This report will therefore bring up different ways and technologies, the regulation framework and also the challenges and opportunities within the industry.

II. Health and Environmental Risks of PCBs

A. Impact on human health caused by PCBs

Printed circuit boards (PCBs) are like previously mentioned in most of todays electronics. With an increase in smarter devices, the waste is also increased. According to The Global E-waste Monitor the formal documented collection and recycling of e-waste in 2019 was only 17.4% [1]. Considering this, the majority of e-waste is handled improperly, these practices include e.g. incineration and illegal dumping. Because of the complexity of PCBs they often contain a variety of different materials. This is one of many reasons why the disposal and recycling of PCBs must be taken with utmost seriousness. One common way PCB recycling is handled poorly is illegal dumping into landfills. These landfills are often located in low-income or developing countries with workers from informal sectors often women and children. This could expose them to hazardous toxicants from the e-waste. Some of the prominent hazardous substances in PCBs are Lead, Cadmium, and Mercury. They all can have negative consequences on the renal, and both lead and mercury can have neurodevelopmental effects in the human body. [2]. The neurodevelopmental consequences can especially in children have severe effects as it can hinder their intellectual learning process at a young age. Other health effects could include DNA damage, adverse birth outcomes when older, and changes in lung and respiratory functions. The health risk may also go down in generation, women working and living within close proximity to these landfills could get complications with their unborn baby e.g. stillbirth, premature births, as well as low birth weight and length [2].

B. Environmental risks and dangers

Other risks which can be caused by poor handling of printed circuit board recycling are environmental dangers. E-waste poses a toxic threat, as it cannot be naturally broken down and has a tendency to accumulate in various environmental components, including soil, air, water, and living organisms. When landfills are located close to or on top of agriculture or farmlands, toxic substances such as heavy metals and other pollutants can seep into the ground where food is produced and later consumed by both humans and other species. The heavy metals and other pollutants can remain within the soil for an extended period of time and therefor harm the natural flora and fauna of that region [3]. Pollution and dangerous substanses can also make its way into the air. One common method used by workers in the landfills are open-pit burning, this method i used in order to extract metals and other comonents that could be of value. When practicing this method it could cause the discharge of hazardous chemicals like polycyclic aromatic hydrocarbons (PAHs) and halogenated PAHs into the air and the nearby environment [3].

III. PCB Recycling Technologies

In this segment the report is going to focus on 3 main methods that are/or could be used in order to correctly recycle PCBs and reduce the risks of environmental and human health risks. The first method that we are going to examine is pyrolysis, or rather vacuum pyrolysis.

A. the use of vacuum pyrolysis for PCB recycling

In 2009, an experiment conduced by the 2 Chinese universities, Guangdong University of Technology and Haoguan University regarding the use of vacuum pyrolysis as a recyling method. The experiment used a fixed bed reactor, the reacor was heated by an electric furnace. The schematic of the procedure can me seen in the following diagram [4].

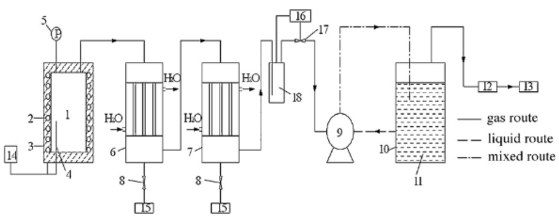

Fig. 1. Caption

The experiment conducted formost cut the recycleble PCBs into 5x5cm pieces to be able to fit in the reactor. The wasted circuit boards was than vacuum sealed and heated to a temperature of 550 degrees Celsius for 120 minutes. After the 120 minutes the circuit board was cooled until room temperature, still within a vacuum. After this step the following stage is to divide any gases and oils that may have been created by the pyrolysis, this is done in 2 steps to insure all the recede is collected.

The main materials left from the vacuum pyrolysis was then proceeded into a crushing step. This step is crucial to separate the different materials to be able to correctly recycle to PCB. The high-speed crusher used was able to crush the material into small particles. The particles was then categorized into different sizes, and any particles still bigger than 4.0 millimeter was once again fed back into the crusher. For scientific purposes the copper amount was measured in each container of different sizes.

The last and final step is gravity separation, this is used in order to separate the materials with different densities. The method used the for the separation involved airflow inside a zigzag formed apparatus. Depending on the different sizes on the particles categorized in the previous step the airflow was regulated. Using this technique the separation could divide the matter into "light fractions" containing mostly non metallic materials and, "heavy fractions" mostly copper. [4]

1) Conclution: Using this method to retrieve the different materials within a PCB the method can without a any environmental disadvantages recycle the PCB to a sublime level. From the report by Laishou Long et al. the extracted levels where; 74.7 wt.% residues, 15.0 wt.% oils, and 10.3 wt.% gases. The main component residues included mostly copper at 50.6 wt.% subsequently glass fiber at 36.9 wt.% and lastly carbon at 12.5 wt.%. A total of 99.86% of all copper was received. The oils contained mainly phentol and 4-(1-Methylethyl)phenol whilst the gases primarily consisted of carbon-monoxide and carbon-dioxide. The copper from the residue could be used for new electronic devices or other copper uses and the oils and gasses for fuel or other chemical resources. [4].

B. hydrometallurgy recycling of PCBs

The next method that we are going to examine is hydrometallurgical treatment. A review about the subject was written by Hao Cui and Corby G Anderson for the *Kroll Institute for Extractive Metallurgy* [5]. The study is a review of the recycling of printed circuit boards with a focus on hydrometallurgical treatment. Efficient recycling of PCBs is important for economic and environmental reasons and do to its lower capital cost, higher selectivity, and lower environmental impact, this could be a promising method [5].

Hydrometallurgy is a process that involves extracting a metals by creating an aqueous solution of a metal salt and then recovering the metal from the solution [6]. The process have been used and well-established within the mining industry, extracting copper from copper ore but there is currently no industrial-scale process that can efficiently recycle copper from PCBs [5].

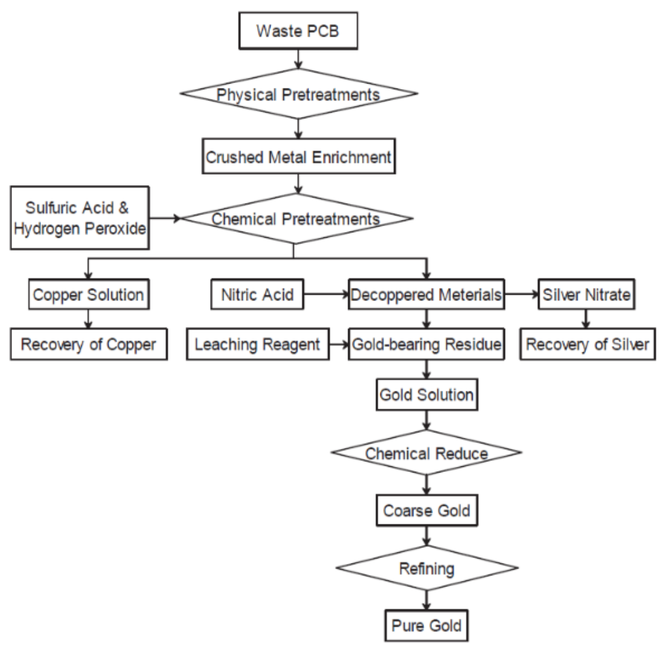

Fig. 2. hydrometallurgic schematic

The hydrometallurgy process itself can only extract metals, however PCBs contain more than just metals. Hence another method has to be used consecutively with other methods in order to retrieve all the materials. The non-metallic part of PCBs can be separated from the metallic part using physical methods like magnetic separation, flotation, electrostatic separation, and gravity separation. However, achieving a clean separation between the two parts still poses challenges for physical recycling. Chemical recycling of the non-metallic part can be done using four methods: pyrolysis, gasification, supercritical fluid depolymerization, and hydrogenolytic degradation [5].

One upper hand that the hydrometallurgy method have is its ability to very well extract precious metals. Electric and electronic industries have utilized precious metals due to their exceptional electrical conductivity, low contact electrical resistance, and resistance to corrosion. Although rare earths have started replacing precious metals in some electronic applications, a considerable amount of e-waste still contains significant quantities of precious metals, including gold, silver, and palladium. It is essential to recycle these precious metals from e-waste. For example, PCBs contain 35-50 times more gold than gold ore, highlighting the importance of recycling precious metals from e-waste [5]. The key aspect practicing this approach is what leaching reagents to use to maximize output gains.

One of the alternatives that is on the uprise is Thiourea (NH_2CSNH_2) due to its fast leaching rate and non-toxic properties. However, it has high cost and consumption due to poor stability. Thiosulfate leaching is also highlighted as an option, but it only extracts around 15% of gold, and copper ions are found to promote gold extraction in the sodium thiosulfate system. A recovery rate of 98% gold could be achieved using a solution containing 20 mM copper, 0.12M thiosulfate, and 0.2M ammonia.

Iodine leaching of gold from PCBs without pretreatment is the most effective method as it resulted in 93.5% gold being leached out directly. However, it is important to note that thiourea leaching has also been proven to be highly efficient, with 69% of gold being extracted under certain conditions. Ultimately, the choice of leaching material would depend on several factors such as cost, toxicity, stability, and the specific conditions of the extraction process [5].

1) Conclusion: Printed Circuit boards contain a great load of valuable materials such as copper, gold, and silver, making their recycling economically attractive. With the increasing amount of PCB waste and negative impact on the environment, recycling methods have become more crucial than ever. The hydrometallurgical process has been studied due to its advantages, such as low capital cost and minimal environmental impact. Recent studies indicate a promising future for PCB recycling, with ionic liquid and chlorine-based media showing potential for extracting both precious metals like gold, silver and palladium and also base matals like copper. However, proposed flowsheets are currently limited to lab-scale, and larger-scale studies are necessary to achieve commercialization.

C. bioremediation

This last rapport about recycling methods isn't solely based on a method of recycling, rather a method of handling contamination in the soil caused by unfavorable handling of e-waste. The paper published by Xiao Li, Yufeng Wu and Zhe Tan for the *Beijing University of Technology* a study was conducted on how bioremediation technology can be used to sustain soil contaminated by heavy metals and other environmental hazardous substances [7].

The three most common ways for pollution to enter the soil is by open burning, irregular acid picking and random dumping with the most common pollutants being Cu, Pb, Cd, Zn, Ni, Cr, PAHs, PCBs, PBDEs are not limited to printed circuit boards rather e-waste in general. The method ofbioremediation can be seperated into two different categories of strategies. PAHs, PCBs, PBDEs use microbial degradation whilst the heavy metals Cu, Pb, Cd, Zn, Ni, Cr etc use phytoremediation [7].

For oragnaics such as PAHs, PCBs, PBDEs that uses microbial degradation, the article discusses various remediation methods. Polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) are oraganic compounds that can contaminate the soil and thus could use microorganisms to degrade the pollutants. This type of method has shown promise in both in-situ and ex-situ applications. Some examplesof ex-situ bioremedation technologies are composting and bioreactors. However the use of microorganisms in bioremedation is not flawless, under some conditions this method can actully enhance the toxicity of the pollutants. To address this, biostimulation, bioaugmentation, and plant-assisted degradation have been employed to improve microbial activity and efficiency. Soil enzymes also play a crucial role in the process [7].

D. microbial degradation for PAHs

PAHs (Polycyclic Aromatic Hydrocarbons) are a class of organic compounds that consist of aromatic rings concisting of hydrogen and carbon. In room tempature the PHAs are solids with low volatility and are hard to dissolve in water. The paper bring up different biodegradation strategies to better improve the process of bioremediation. One of these strategies are the use of microorganisms to treat PAHs, this includes fungi and soil bacteria such as Bacillus, Pseudomonas, Mycobacterium, Acremonium, Pleurotus ostreatus, and Fusarium. These microbes and fungi can decompose and phase out the toxicity of PAHs. Li et.al also states that the more effective method is to use a mix of culture rather than a single one within the bioremediation method.

E. phytoremediation for heavy metals

The other method of bioremidation is phytoremedation, this biogeochemical process plays a crucial role in controlling the availablity and mobility of heavy metals in soil. The method consist of extraction, volatilization or immobilization to counteract and eliminate the metals. Both extraction and volatilization are effective techniques for removing heavy metals from contaminated soil. Phytoextraction and phytovolatilization involve the uptake and transfer of heavy metals from the soil to the above ground parts of plants, effectively reducing metal levels in the soil. Compared to other methods for heavy metal removal, phytoremediation stands out as a cleaner and more cost-effective approach, particularly suitable for agricultural land with low pollution levels and shallow metal distribution [7].

IV. Framework and regulations governing the recycling of PCBs and other e-waste

1) WEEE-directive: Because of the increasing levels of e-waste the European Union decided on a new directive called the WEEE or Waste from Electrical and Electronic Equipment. The objective of the regulation is to promote sustainable manufacturing and consumption by tackling environmental and other concerns arising from the mounting quantity of electronic devices being disposed of in the EU. To do this the main objectives of the regulations are [8]

- Prioritizing the prevention of WEEE's creation as the primary goal.
- Encouraging resource efficiency and the recovery of secondary raw materials via reusing, recycling, and other forms of recovery.
- Enhancing the environmental performance of all stakeholders involved in the life cycle of EEE.

To achieve these goals the directive requires proper treatment and well function collection of waste. The directive sets tagets for the collection, recover and recycling of electronic devices labled with the WEEE directive. In addition, it aims to reduce illegal exporting of electronic waste by making it more difficult for exporters to disguise illegal shipments of WEEE. The directive also calls for the harmonization of national EEE registers and reporting formats, thereby reducing administrative burdens [8].

The directive and their label are mandatory for most electronic equipment this includes everything between fridges, computer screens, solar panels and smaller IT devices such as smartphones. Because of their mixture of complex and hazardous materials they could disrupt the enivornment if not recycled properly. The directive states that products marked with this label must me handed in to authorized recycling facilities or electronic stores where the product was bought [9].

Overall, the WEEE Directive plays a significant role in promoting sustainability, reducing waste, and encouraging the responsible use and disposal of electrical and electronic equipment in Europe.

2) Basel convention: This is an international treaty designed to reduce the movement of hazardous waste between nations, including electronic waste such as printed circuit boards. The treaty prohibits the export of hazardous waste from developed countries to developing countries, unless there is an agreement between the two parties, this ensures that the exploitation of developing countries and their cheap workforce can be reduced.

Since the conventions adoption there has been a number of changes and significant progress. In 1995 the convention adopted the "BAN Amendment", this was the amendment that would stop countries from the EU and OECD to export dangerous and hazardous electronic waste to other countries not included the the above mentioned organization/union [10]. Even though this was decided almost 30 years ago it took until 2019 to take effect [11]. The challenge to protect vulnerable countries from unwanted dangerous waste importation. At the same time the imported waste can be seen a source of valuable materials such as gold, copper and silver. Because of how the amendment is written this could also lead to countries that are well suited to recycle e-waste in a safe and environmental friendly way could be prevented from doing so. At the COP 9 in 2008 a discussion on how to handle this issue was initiated [10].

During the 1980s when the environmental requirements in the west tightened the overall cost of correct handling of dangerous waste such as toxicities, environmentally dangerous and pathogenic substances was also increased. Waste dealers quickly realised that offering to send this hazardous waste to developing countries at a low cost and where the the resources and knowledge to handle the waste in an environmentally and health-friendly way were inadequate. The convention is based on the following principles [11]:

- Lower the exporting of hazardous waste
- Make sure the waste is handled correctly
- Mange the waste close to the source
- Lower the hazardous waste in general

V. Challenges and opportunities for the e-waste recycling market

When it comes to the market for recycling printed circuit boards there are a lot of both challenges and opportunities, a lot of the challenges regarding this topic has already been been addressed in the paper. However some of the challenges that are associated with the market itself are:

- Circular market
  It can be hard to create a circular market when it comes to electronics this can be the case due to the fact that most electronics are very complex with its material. This makes it difficult to and expensive to recycle electronics Another factor is that in today's context it can be hard in some cases to find a new use case for from e-waste materials. In some cases recycled carbon fiber from the aerospace industry is used in laptops. This is a method called *Industrial symbiosis*.
  Another reason is how the global supply chain usually functions, this can be hard the trend to break. The current global supply chain is designed to facilitate the movement of materials through the manufacturing process and distribute electronic products to the costumers world wide, this is what is called a linear model. Consequently, incorporating recycled content into this system proves to be a difficult task. To enable circular practices such as repair, reuse, recycling, and manufacturing, there is a pressing need to reconfigure global supply chains, allowing for the seamless flow of products and materials within a circular economy framework [12].

Opportunities:

- Circular Economy

As mentioned previously in the text only about 17.4% of all e-waste is formally recycled in 2019 [1]. Therefore their is a huge market for a more circular economy when it comes to recycling of e-waste. When the ever so increasing levels of electronics and their waste, we have no other option than to implement a more circular economy to drive the recycling market forward.

- More advanced technologies
A more digital society leads to more waste, but also more innovation, the methods of recycling gets better and better, and with better sorting, chemical extraction and better methods of separation. The future of recycling will hopefully be able to keep up with the growing e-waste volumes.
- Consumer Awareness
Consumers become more and more environmental consciousness with the growing threat of global warming. This results in consumers putting more and more emphasize on greener and sustainable products and methods [13]. This creates a positive feedback loop where companies need to be more be more environmentally conscious while costumers get better and greener products and the at the same time save the planet.

VI. Case study of real world e-waste recycling facility

A. New Boliden

I have been in contact with a company specializing in ”mining metals”, they are a big company with many different facilities. Searching for natural raw materials, mining, smelting and recycling. The company ”New Boliden” is a Swedish company with its roots in northern Sweden.

The part of the company that interested me and the subject of this paper, was their smelting facility outside of Skellefteå called Rönnskär. Rönnskär focuses on the melting of copper and therefore also recycling of E-waste such as PCBs. In figure ”?” we can see an overview of the recycling process. Following the electronic arrows we can see how the waste first enters ”e-kaldoverk” which is the furnace where everything melts. The mater than goes through converters and lastly the different materials are separated using a electrolysis plant to retrieve the copper and processed in another plant to retrieve the precious metals such as gold, silver palladium etc. After the electrolysis they can achieve a copper rate of 99.9% copper

The recycling facility can process up to 70 000 tons of electronic waste each year, where most of the waste is imported from abroad. This shows just how big of a market recycling e-waste really can be if handled correctly.

When asked what challenges they pose, they told me that one of the biggest problems that they want to solve is the carbon emission that they let out from the burning facility. This is a case of plastic burning as it’s very difficult to separate prior to melting the e-waste.

Another challenge or rather risk are hazardous substances such as beryllium and mercury which are 2 banned compounds in the facility. One of the reason for this is work environment issues

Other factors that may enable the company to ban certain substances are substances that worsen the quality of the copper or other metals.

VII. Conclusion

In conclusion, the recycling of printed circuit boards is a huge market with a lot of different methods and regulations. The industry is only growing as more and more *Internet of Things* devices appear which results in more e-waste e.g circuit boards.

The different methods can be used and are good for different reasons. Using Pyrolysis is a more stable and well researched method build on methods widely used, whilst hydrometallurgy is a more experimental method. Hydrometallurgy is also better for the environment and also a method used in other industries, therefore showing its a serious method that could be implemented on a bigger scale.

I believe that a mix of different methods is a good thing where we can have bigger more efficient but less greener methods to keep up with the growing amount of waste, but as time goes on more and more exchange the methods with greener alternatives.

Using a bioremedion method to help and clear up areas affeted by the poor treatment of electronic waste could also be way to a greener recyling market.

I believe that more regulations and to take them more seriosly is one way forward in this debate, richer countries will alway have the upper hand when it comes to making deals wih countries with a lower economical stance. And without regulaions they will always do whats best for them and not the planet as a whole.

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