

# NEODYMIUM AND THE GLOBAL HEADPHONE MARKET

An analysis of the flow of neodymium magnets through headphones worldwide

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## List of Abbreviations and Symbols

CO<sub>2</sub> – Carbon Dioxide

CFC-11 – Trichlorofluoromethane

DALY – Disability-Adjusted Life Years

Eq – Equivalent

EU – European Union

MJ – Megajoules

Nd – Neodymium (elemental)

NO<sub>x</sub> – Nitros Oxide

NdFeB Magnet – Neodymium magnet: Magnet composed of an alloy of neodymium, iron, and boron

PCB – Polychlorinated Biphenyl

REE – Rare Earth Element

REO – Rare Earth Oxide

SO<sub>2</sub> – Sulfur Dioxide

US – United States

USD – United States Dollars

WEEE – Wastes from Electric and Electronic Equipment

1,4-DCB – Para-dichlorobenzene or 1,4-Dichlorobenzene

## Abstract

Wastes from electric and electronic equipment are a new kind of waste stream that requires focused attention from economic, social, and environmental perspectives. They represent a significant flow of both hazardous and valuable materials that has so far been mostly one directional. Neodymium is a rare earth element commonly used to produce neodymium magnets which are critical to the operation of many of our electronics today. The mining of this element is also responsible for a number of environmental, economic, and health related concerns. Speakers and headphones contain these neodymium magnets and represent a sizable portion of this flow of neodymium which hasn't seen much recovery through recycling. Headphones specifically are interesting to analyze due to their commonplace, cheap, and disposable nature. They thus represent a dissipative flow of neodymium into various traditional waste streams and are a source of environmental, social, and economic impacts. Here, literature review and laboratory work are used to help quantify the mass of neodymium magnets along with the environmental and health impacts represented by this flow of neodymium magnets through headphones. This research also identifies some ways to potentially reduce this impact through material substitution and recycling.

# 1. Introduction

Electronics have become a ubiquitous and critical component of the modern world. Though it is only a century or so that separates our lives today from a world without such devices, it is difficult to imagine our homes, workplaces, media, etc. existing in any familiar form without electronics. Indeed, even this report could not have been possible in its present form without the presence of a complex network of thousands of such electronics to aid the information collection, communications, calculations, composition, editing, printing, etc. necessary to perform tasks with ease, speed, and accuracy. This world of electronics though, being so young, has not fully developed and found its place in the larger system of human existence and natural systems. Electronics have not yet needed to be socially, economically, or environmentally sustainable, and have been exploiting existing systems to become as cheap, numerous, and useful as they are now. The introduction of new electronics introduces countless changes to established societal systems, and much attention has been directed to identifying these changes and focusing them toward the benefit of society. Unfortunately, the negative changes and impacts introduced by the disposal of electronic waste and sourcing of materials for new electronics have been largely ignored until now. These two actions represent flows of potentially harmful and valuable materials and, if interlinked through reclamation and recycling, can produce sustainable material flows.

## 1.1.WEEE and Material Flows

One specific but inevitable problem, the consequences of wastes from electric and electronic equipment, has only just become a part of scientific, public, and political dialogue. Critically, as digital devices become smaller, increasingly useful, and more affordable they become accessible to a growing proportion of the world's ever increasing population. Televisions, mobile phones, computers, and lamps are just some of the myriad of different devices promising to increase productivity, automate tasks, aid communication, save lives, and entertain with a seemingly infinite range of unique functions and applications. These electronics drive many markets not just through their use but through their manufacture and inevitable disposal. As technological advances are made or devices begin to age, these electronic tools are replaced with newer models which are often more capable, energy efficient, and visually appealing than their predecessors. These once useful instruments are then rendered obsolete or unusable and quickly labeled 'waste.' This electronic waste is evidence of a complex system of numerous material flows, each with their own impacts on the world.

These discarded electronic devices are specifically referred to as 'electronic waste,' 'e-waste,' or 'end-of-life electronics.' While differentiations can be made between some of these terms, the defining lines between them are becoming less distinct due to the variety of new devices being introduced to markets every year (Robinson, 2009). All devices that utilize electricity fall under at least one of these terms, and for the purposes of this review the term WEEE, short for “wastes

from electric and electronic equipment,” will be used to describe all electronic waste as it is defined in the 2012 EU WEEE Directive (The European Parliament and the Council of the European Union, 2012). While all WEEE devices are of special concern for disposal, focus tends to be directed toward devices that are: simple to recycle, have a large overall weight that can help meet recycling quotas, contain a concentrated amount of one or more economically valuable materials that are easily recovered, contain specific hazardous materials, or are subject to specific recycling regulations and laws. While this focus is understandable from social, economic, and even environmental perspectives, and gives clearly defined direction to such disposal and recovery efforts, it does not address a large proportion of WEEE. Some devices that are small, difficult to collect, contain no concentrated amounts of valuable or hazardous materials, do not contain a standard set of materials, or are simply difficult to process due to the small amounts of materials or complex components they contain. Such devices are difficult to separate and process economically and are inappropriately directed toward traditional waste processing streams. The importance of simpler, smaller, or more uncommon WEEE must not be understated as they are introduced to waste systems around the world.

WEEE in general are a relatively new addition to often well established waste streams. Systems developed specifically for their disposal were nonexistent for many decades. These established waste streams are built around the historical content of the waste they handle which has largely consisted of a combination of

papers, plastics, glass, metals, and organic matter. Technologies to treat and/or dispose of these materials in a way that is economically viable have been adopted, and are generally considered acceptable by social and environmental standards. Landfilling and incineration are among such common disposal technologies, and are sometimes coupled with sorting and recycling systems that aim to recover a few critical or valuable resources. Specialized waste streams have also appeared to handle sensitive wastes such as medical and chemical wastes. Electronics are a recent and constantly changing phenomenon however. As the amount of WEEE increased and the economic, social, and ecological impacts associated with it became clear, both private and regulatory entities took note. As a result, a budding recycling industry has emerged to reclaim materials from WEEE and responsibly disposing of still unrecoverable waste under new and sometimes changing regulations.

In tackling this growing problem however, balance between social, environmental, and economic practicality must be struck. The incredible diversity of electronics and the materials contained within them has made material recovery difficult and inefficient. This has forced industry players to critically analyze their feedstock WEEE and conduct cost-benefit analysis for the recovery of various categories of devices and types of material to ensure that their businesses are economically sound. Governments on the other hand have attempted to address various social and environmental concerns with new waste regulations, forcing the recycling industry to balance the reclamation of sometimes low value materials

with other, more profitable operations. The result has been a recycling industry not actively engaged in the markets and devices they are responsible for treating. Instead they must respond to uncontrollable forces of legislation, changes in material market prices, and availability of high yield, easily recoverable materials. Materials with low market value, small recovery potential, technologically complex recovery methods, or high manual labor needs are therefore deemed economically unattractive in the interest of business.

Still, some of these neglected materials have unseen economic, social, or environmental impacts, necessitating closer analysis to understand their true costs and benefits. While much attention has been given to the recovery of substances such as gold, silver, palladium, and lead due to their economic value or immediate environmental impact, and higher yield materials such as aluminum, steel, plastic, and glass, lower quantity materials like rare earth elements are ignored. It took a market crisis, an increased control of exports on the behalf of China beginning in 2007, to draw attention to elements such as neodymium and dysprosium (Kara, Chapman, Crichton, Willis, & Morley, 2010). Predictably though, as markets have begun to settle again research into the recovery of these materials has lost momentum. Indeed, neodymium is a metal with significant economic, social, and environmental impacts that is used in a large proportion of electronics in the form of small, yet powerful magnets. These magnets have played a critical role in miniaturizing electronics over the last few decades and are difficult to substitute with any other material. It is critical that the material flows of neodymium be

understood and potentials assessed to ensure this material is used in an efficient and sustainable manner.

## 1.2. Outline and Objectives

This research will address the issues surrounding material flows in WEEE and material sourcing by highlighting the dynamics of one material flow through one product. The material neodymium has been selected as the focus due to its importance as a critical metal from a technological, environmental, and geopolitical perspective. It is the core material to the most powerful permanent magnetic material known today, making it ideal for use in a wide variety of electronic devices. Neodymium is also a rare earth element that has numerous environmental and health impacts when mined. Furthermore, recent political and market pressures have made neodymium a critical element whose secure supply has become a topic of discussion for both market entities and governments reliant on the material. Consumer headphones have been selected as the product of focus due to their use of these neodymium magnets, global availability, and relatively common nature. Specifically, this research will attempt to quantify the flow of neodymium through the consumer headphone industry, identify and quantify its impacts, and identify potential actions to reduce this impact. To do this, a thorough analysis of relevant literature will be presented and combined with personal findings from lab work. It is hoped that such research will offer perspective for the importance of material flows through consumer electronics

while encouraging future efforts to quantify these flows and find ways to bring them full circle.

## 2. Literature Review

A material flow in an industrial society traditionally consists of a material sourced from Earth's natural systems, used for a specific purpose, and eventually returned to the Earth's natural systems. As far as humanity is concerned, this is traditionally a one-directional flow with an effectively infinite source and sink. While this was once effectively true, so long as the material is one processed by nature and flows in amounts sufficiently small in comparison with the natural system, we have come to realize that this is increasingly not the case in our modern world. Many materials we use are no longer a part of Earth's natural metabolism and the volumes we need are approaching limits. Electronics and the material flows they represent are one of the latest additions to this phenomenon. While there are many material flows present in the electronics industry, a sizable portion of these electronics are audio devices which contain the rare earth element neodymium. Analyzing this specific material flow reveals how large these electronic-related flows are, what impacts they are responsible for, and what types of opportunities for positive change they represent.

### 2.1. Waste Electronics

An incredibly large and growing volume of electronics containing many hazardous materials are in need of safe disposal worldwide. In 2011 alone, a world population maintaining about 6 billion mobile phone subscriptions

purchased more than 1.55 billion mobile phones and smartphones (Chancerel, 2012, p. 46; The World Bank Group, 2012). That same year, according to Gartner Inc., sales of PCs and laptops reached 350 million units (Gartner, Inc., 2012). The countless electronic toys, tools, equipment, and personal devices perpetually designed and created have become a staple of modern life. They evolve rapidly and constantly render their aged counterparts obsolete. These broken and obsolete electronics currently fall into the category of WEEE, or 'wastes from electric and electronic equipment' in the European Union, according to the WEEE-Directive 2012/19/EU (The European Parliament and the Council of the European Union, 2012). The United Nations Environment Programme estimated that somewhere between 20 million and 50 million tonnes of WEEE is generated per year in a 2005 publication, while Robinson estimates that the range is around 20 to 25 million tonnes in his 2009 research (Robinson, 2009; United Nations Environment Programme, 2005). It is further suggested that more numerous electronics with shorter usable lifespans make this is an increasing trend (Robinson, 2009).

These waste electronics are both too dangerous and too valuable to be landfilled or incinerated though, especially in such large numbers. Many of the metals and other materials contained within WEEE are a hazard to environmental and human health if not disposed of correctly. Even recycling, while usually considered a solution to these issues, can be detrimental if implemented improperly. The destructive human and environmental health effects of this practice are evident in many developing regions. Furthermore, the inherent

current and future value, and relative scarcity of materials contained within many electronics makes material recovery economically smart. The need for a regulated disposal stream for these devices is apparent, and recycling and material recovery are the key to turning costly and potentially hazardous disposal in landfills and incinerators into profits through material sales or, at the very least, low impact material cycles.

### 2.1.1. Impacts

The impacts of these waste electronics can be broken into three categories: economic, social, and environmental. The economic impacts of electronic waste are mostly related to the materials these products contain and how their flows affect material markets. This includes the stability of the market for virgin materials, the increasing scarcity of these virgin materials, the flow of these materials into costly disposal systems, and the economic potential of recycling operations. Social impacts are concerned with how waste electronics benefit or harm human life and well-being. This covers the social effects of irresponsible disposal or recycling along with the health and small-scale economic impacts this has on communities handling this waste. The social impacts of not manufacturing specific electronic devices, positive or negative, can also be considered. Finally, the environmental impacts of electronic waste are numerous as well. Mining and different disposal methods can negatively affect the environment through noise, air, water, and land pollution or destruction. To understand the importance of these issues, a detailed look is necessary.

While negative environmental and social impacts of electronic waste are often the major focus of discussion in media, ignoring the reclamation value of such waste can be just as harmful economically. Recycling WEEE has the potential to not only generate revenue from the sale of recovered materials, but provide an avenue for all involved entities to display their corporate social responsibility. As stated before, various materials contained within electronic devices can be recovered and resold. The material content of various types of electronics and the market price for each material, presented by Cucchiella et al., illustrates this fact and its complexity beautifully (Cucchiella, Adamo, Lenny Koh, & Rosa, 2015). Materials like gold, palladium, and platinum command high market prices and, though not found in large quantities within devices, are economically interesting to reclaim (Cucchiella et al., 2015). Other materials, like plastic and steel, sell for far lower prices but are present in bulk in WEEE (Cucchiella et al., 2015). They thus generate economic interest for reclamation and drive the search for, or creation of a suitable market. Of course, not all materials represent the same economic opportunity due to their differing market values or lower quality after first use. Some, lead for example, do not have the quantities or market to generate the economic intensive for recovery or proper disposal (Cucchiella et al., 2015). In this case, re regulations citing concerns for health and the environment can serve to generate interest. Furthermore, this presents an opportunity for companies to report their corporate social responsibility to a consumer base that is increasingly aware of such issues. Further economic benefits arise in the avoidance of future

expenditures. Take for example the electronics manufacturer General Electric. This company contaminated long stretches of New York's Hudson River with PCBs before 1970. They are now responsible for cleaning up this contamination and, as of 2010, had spent 830 million USD on this effort (General Electric, 2010). The consequences of improper electronic production or waste handling, whether known or unknown, can become major expenses which responsible entities, governments, and the public must eventually bear.

Of course, the discussion of environmental and social impacts of mishandled WEEE is more impassioned. Many of the materials found in waste electronics are harmful to the environment and human health if they are allowed to disperse uncontrolled into the environment. This leads to contaminated air, water, food, and places of work and residence. In this regard, the simple landfilling of WEEE and its associated pollutants are often the best case scenario for developing regions, as incineration or even crude material recovery practices can have far more damaging consequences. Places like Guiyu, China have been shown to have elevated levels of heavy metals in the local dust of workshops, schoolyards, food markets, and roadsides, thus exposing residents to various associated health risks (Leung, Duzgoren-Aydin, Cheung, & Wong, 2008). The urgent need to properly manage WEEE from not just an economic perspective, but environmental and social perspectives as well, is evident.

## 2.2. Neodymium as a Rare Earth Element

There are no simple solutions to the issues WEEE presents however.

Electronic devices usually contain many complex components, which are themselves composed of multiple materials. Understanding the larger flows of materials through their creation, use, and disposal becomes a rather daunting task. A true understanding of a device's impact on economics, society, and the environment does not simply amount to a complete map of these material flows, but an all encompassing analysis of the device through all parts of its life. One way to change a device's impacts then is to look specifically at the materials it is composed of. While some materials are absolutely necessary for the device to function, others are substitutable or interchangeable if needed. Such changes may not be without consequences however.

### 2.2.1. Introduction to Neodymium and Rare Earth Elements

Neodymium is one such element that raises questions about its necessity. Its place as element 60 in the periodic table is shown in Figure 2.1, highlighting its abundance in Earth's crust as well as its other elemental properties (Dayah, 1997). While it has rapidly made its way into all sorts of electronics, it is not the only material available for the tasks it is currently charged with. This element, used primarily in neodymium iron boron magnets, is one of the driving elements for the increased mining of rare earth elements, or REEs. This group of elements is always found and mined together. In fact, in 2010 neodymium made up 18.7% of global REE production and 69% of this neodymium was used for magnets alone

(Otto, 2011). This makes NdFeB magnets, or neodymium magnets, a significant driver for REE mining and production.

With neodymium supply closely intertwined with REE supply in general, it makes sense to discuss REEs when trying to understand its impacts. There are multiple interpretations of what elements are defined as REEs and how they should be organized, but the group generally consists of 15 to 17 elements broken into smaller groups of light and heavy REEs. A list of these elements and their oxide forms, along with a few of their important applications is presented in Table 2.1 (Koltun & Tharumarajah, 2014; United States Environmental Protection Agency, 2012). REEs are, despite their name, not rare in the sense that they are limited in quantity on the Earth. They are in fact relatively common. For example, in an analysis of the makeup of the continental crust done by Wedepohl, neodymium was found to have concentrations similar to that of copper and cobalt with 27, 25, and 24 parts per million respectively (Hans Wedepohl, 1995). Nearly all REEs are significantly more plentiful than silver and gold by such measurements (Hans Wedepohl, 1995). Bountiful supply of these elements in the market is however, constricted by several factors.

The supply of REEs is limited by the low concentrations they are found in, the complicated extraction and purification methods used, and the environmental and social concerns raised by these operations. REEs are found in over 200 different minerals in the Earth's crust, but few of these have concentrations considered suitable for mining (Jordens, Cheng, & Waters, 2013; United States



**Table 2.1: The Rare Earth Elements and their Applications**

Elements 57 through 63 are generally considered to be the 'light REEs' while elements 64 through 71 are 'heavy REEs.' When included, scandium is a 'light REE' and yttrium is a 'heavy REE.'				
Atomic Number	Abbreviation	Name	Oxide Form <sup>[1]</sup>	Applications <sup>[2]</sup>
57	La	Lanthanum	La <sub>2</sub> O <sub>3</sub>	Batteries, catalysts, lasers, digital cameras
58	Ce	Cerium	CeO <sub>2</sub>	Catalysts, polishing (esp. for electronics parts), metal alloys
59	Pr	Praseodymium	Pr <sub>6</sub> O <sub>11</sub>	Magnets (to resist corrosion), pigments, searchlights, lenses
60	Nd	Neodymium	Nd <sub>2</sub> O <sub>3</sub>	High-power magnets, lasers, catalysts
61	Pm	Promethium	Pm <sub>2</sub> O <sub>3</sub>	Catalysts, source of beta radiation
62	Sm	Samarium	Sm <sub>2</sub> O <sub>3</sub>	High-temperature magnets, reactor control rods
63	Eu	Europium	Eu <sub>2</sub> O <sub>3</sub>	Liquid crystal displays, fluorescent lighting, glass additive
64	Gd	Gadolinium	Gd <sub>2</sub> O <sub>3</sub>	MRI contrast agent, glass additive
65	Tb	Terbium	Tb <sub>4</sub> O <sub>7</sub>	Lighting and display phosphors
66	Dy	Dysprosium	Dy <sub>2</sub> O <sub>3</sub>	High-power magnets, lasers
67	Ho	Holmium	Ho <sub>2</sub> O <sub>3</sub>	Highest-power magnets
68	Er	Erbium	Er <sub>2</sub> O <sub>3</sub>	Lasers, glass colorant
69	Tm	Thulium	Tm <sub>2</sub> O <sub>3</sub>	High-power magnets
70	Yb	Ytterbium	Yb <sub>2</sub> O <sub>3</sub>	Fiber-optics, photovoltaic cells, metal alloys, lasers, X-ray radiation source
71	Lu	Lutetium	Lu <sub>2</sub> O <sub>3</sub>	X-ray phosphors
Sometimes included due to chemical similarity <sup>[2]</sup> and because they are commonly found in the same ore deposits <sup>[1]</sup> :				
21	Sc	Scandium	Sc <sub>2</sub> O <sub>3</sub>	Aerospace metal alloys
39	Y	Yttrium	Y <sub>2</sub> O <sub>3</sub>	Ceramics, metal alloys, lasers, satellite microwave communication, electronic color displays, temperature sensors

Table 2.1: List of REEs, their oxide forms, and some of their applications.

Adapted from:

[1] Koltun, P., & Tharumarajah, A. (2014). *Life Cycle Impact of Rare Earth Elements*. *ISRN Metallurgy*, 2014, 1–10. <http://doi.org/10.1155/2014/907536>

[2] United States Environmental Protection Agency. (2012, December). *Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues*. United States Environmental Protection Agency. Retrieved from <http://nepis.epa.gov/Adobe/PDF/P100EUBC.pdf>

Environmental Protection Agency, 2012). Bastnasite, xenotime, and monazite are considered to be effective mineral sources of REEs (United States Environmental Protection Agency, 2012). While these minerals can have very high concentrations of useful REEs and are present in at least 34 countries around the world, inclusive of each continent, only two locations have thus far successfully mined REEs on a large scale (Chen, 2011; Jordens et al., 2013). Adding difficulties to securing REE supplies is the fact that the process for mining and purifying REEs is much more involved than it is for many other metals. Multiple REEs are found mixed together in these mineral deposits not as pure elements, but as oxides, necessitating complicated separation methods to produce pure and useful elements for the market (United States Environmental Protection Agency, 2012). Furthermore, these REE containing minerals frequently contain uranium and thorium, both radioactive elements that must be separated and either refined or safely stored (Jordens et al., 2013; Juetten, 2011; United States Environmental Protection Agency, 2012). This complicated extraction process can include steps like leaching, washing, filtering, drying, and calcining, with the use of acids, solvents, and water (United States Environmental Protection Agency, 2012). These processes and substances will invariably use large amounts of energy and create copious amounts of waste. Though some economic and social questions can be posed, this specifically raises a number of environmental concerns.

### 2.2.2. Impacts of REE Production

Environmental impacts of REE mining operations are numerous and often have economic and social consequences. Mining operations are energy intense, requiring many processes, the use of large machinery, and the transportation of materials, including wastes (Schüler, Buchert, Liu, Dittrich, & Merz, 2011). Critically though, these REE mining impacts revolve around the production, storage, and treatment of particularly hazardous wastes. They can include waste solvents, lead filter cake, and tailings which are the waste fractions of the processed ore (United States Environmental Protection Agency, 2012). These tailings are particularly concerning because they contain concentrated residual wastes from the ore processing steps as well as unused ore components including heavy metals, sulfates, organics, and even radioactive substances (Campbell, 2012; United States Environmental Protection Agency, 2012). If not stored properly, these tailings can contaminate air, soil, and water through runoff and weathering. It is not just waste that impacts a REE mine's local natural and human environments however. Operations in general can have numerous negative impacts on air, soil, and water if unchecked, affecting natural resources and human health (Campbell, 2012). These environmental and social impacts furthermore have the potential to be very costly for responsible entities, the government, or even the public in the near and long term. Both of the two largest REE mines in the world, Mountain Pass and Bayan Obo, are unfortunately good examples.

The Mountain Pass mine in the US, located near Mountain Pass, California and operated by Molycorp Inc., was once the largest REE mine in the world. An aerial view of the mine is shown in Figure 2.2 and shows that the mining operations span approximately 2.5 kilometers from north to south and from east to west (Google Inc., 2014). It began operations in 1952, and between 1965 and 1995 the mine provided the world with more REEs than any other mine in the world (Molycorp Inc., 2013a). Though the mine was closed for nearly a decade between 2002 and 2010, plans to restart and modernize mining operations pulled



*Figure 2.2: Satellite image of Mountain Pass, CA rare earth mine - March 2013.*

*Note: The visible site spans approximately 2.7 kilometers from east to west and 2.3 kilometers from north to south.*

*Image source: Google Inc. (2013). [Google Earth interactive satellite imagery application]. Google Earth. Retrieved from Google Earth PC desktop application*

through (Molycorp Inc., 2013a). The mine was able to produce 3000 tonnes of rare earth oxide in 2010, anticipated increased production capacity to over 19,000 tonnes by mid-2013, and planned to increase production capacity further to 40,000 tonnes by possibly 2016 (Jordens et al., 2013; Juetten, 2011; Molycorp Inc., 2013b). Quarterly reports by Molycorp Inc. however do not indicate that such high production volumes are being met (Molycorp Inc., 2015). The ore at this site is mostly bastnasite which contains 8% to 12% rare earth oxides (Molycorp Inc., 2013a). Mining operations have left notably negative mark on the area however.

The United States Environmental Protection Agency, in their 2012 report on rare earth elements, provides an overview of historical problems at Mountain Pass. Impacts revolve around the mishandling of wastewater and tailings. First, local groundwater quality was impacted until 1980 due to the percolation based wastewater disposal and conventional dam impediments used for tailings. Contaminated groundwater is being treated. To better handle wastewater, evaporation ponds were constructed, but these suffered from mechanical failures that allowed the 13 mile, or 21 kilometer, pipeline between the mine and the evaporation ponds to spill tailings and leak water onto the ground, contaminating it. Two spills in particular, in 1989 and 1990, together discharged over 48,000 gallons, or 182,000 liters, of this wastewater onto surface soil, though the spills were contained. It is claimed however that between 1984 and 1998 up to 600,000 gallons, or 2.27 million litres, of wastewater, possibly containing uranium, arsenic, lead, and other harmful elements, were spilled (Juetten, 2011). These

facts, combined with the reopening of the mine, has raised concerns amongst NGOs and the public, and as a result the operating company, Molycorp Inc., has highlighted its updated more efficient and impact conscientious operation plans (Juetten, 2011; Molycorp Inc., 2013a; Schöler et al., 2011).

The Bayan Obo mine presents another perspective on the impacts of REE mining. Located in Bayan Obo, Inner Mongolia, China, the Bayan Obo mine is the world's largest REE mine (Jones, 2010; Jordens et al., 2013 citing Gupta and Krishnamurthy, 2005). It has been in operation for more than 40 years (United States Environmental Protection Agency, 2012). An aerial view of the mine is pictured in Figure 2.3 and shows that the mine's operations span more than 10.5 kilometers from east to west (Google Inc., 2013). It relies on the large deposits of



*Figure 2.3: Satellite image of Bayan Obo, China rare earth mine - August 2014.*

*Note: Mining operations appear within the area of this image, and to the east. This image spans about 10.5 kilometers from east to west.*

*Image source: Google Inc. (2014). [Google Earth interactive satellite imagery application]. Google Earth. Retrieved from Google Earth PC desktop application*

bastnasite in the Bayan Obo mining region and alone produced 45% of the world's REEs in 2005 while also producing iron as a co-product (Jordens et al., 2013 citing Gupta and Krishnamurthy, 2005). In 2007 it produced 69,000 tonnes of rare earth oxides (Du & Graedel, 2011). To help to achieve this, the mine has a tailings impoundment covering 11 square kilometers and has produced 150 tonnes of tailings containing radioactive thorium (Schüler et al., 2011).

Along with other mines in China, the Bayan Obo mining region has come under increased scrutiny in recent years. The water, land, and air in the region have all been negatively affected by its operation and local people are beginning to feel the effects. In 2014, Wang, Liang, Zhang, and Li reported that rare earth atmospheric particulates were present in the atmosphere around the mine and were indeed caused by the enrichment operations taking place there (Wang, Liang, Zhang, & Li, 2014). The 11 square kilometer tailings impoundment has contaminated the groundwater, soil, and vegetation in the area with radioactive substances (Schüler et al., 2011). A report by the Chinese Society of Rare Earths claims that around ten million tons of wastewater is discharged, untreated, by this mine each year (Hurst, 2010). Indeed, the same source reports that “every ton of rare earth produced, generates approximately: 8.5 kilograms of fluorine, 13 kilograms of dust, 9,600 to 12,000 cubic meters of “waste gas containing dust concentrate, hydrofluoric acid, sulfur dioxide, and sulfuric acid,” 75 cubic meters of acidic wastewater, and one ton of radioactive waste residue (Hurst, 2010). The land and food around a different mine in Hetian Town in Fujian Province, China

was also the subject of a study. It found that REEs from mining operations here concentrated in soil, water, and food, and ultimately the blood of residents, though here the levels of intake were considered to be still safe (Li, Chen, Chen, & Zhang, 2013). Concerns have been expressed about the health impacts from rare earth elements in the land, water, and air could have on humans. Sources indicate pneumoconiosis, chronic poisoning, reduced IQ, and slower nerve conduction as possible effects (Hirano & Suzuki, 1996). It has been reported that these conditions have caused the relocation of several villages near tailing lake of the Bayan Obo mine (Jones, 2010). 5,387 residents of the region suffer from black lung and make up 50% of such cases in the Inner Mongolia autonomous region (Jiabao & Jie, 2009). Furthermore, “lead, mercury, benzene and phosphorous poisoning” are common occupational hazards here (Jiabao & Jie, 2009).

Neodymium, is a significant product of these REE mining operations, and shares responsibility for the environmental issues surrounding the actual or potential contamination of soil, water, and air. Furthermore, social consequences related critically to human health are intertwined with these environmental concerns.

### 2.2.3.Reducing the Impacts of Neodymium

A number of actions can help reduce these environmental impacts however, and can potentially help consequently reduce social and economic impacts as well. There exist other magnet types that may have lower impacts than those neodymium creates, meaning that material substitution is an option. Though these

magnets may not have the same desirable qualities as neodymium magnets, not all applications necessarily require the use of neodymium magnets specifically.

Other actions like recycling, though yet to be implemented on a large scale, show some promise for reducing impacts as well. Assessing the impacts of alternative magnets and their potential or lack of potential in each neodymium magnet application, along with the feasibility for recycling would help to ensure negative impacts due to neodymium sourcing are minimized.

Neodymium magnets only first became available in the 1980s and are the strongest magnets known today. Other magnet types however, such as alnico and ferrite magnets, had met the demands of electronics before the discovery of these new, stronger magnets and continue to be used in various applications. While the total impact of these magnets depends on each application, since the size and form of the magnet depend on the application, it is possible that they would have lower environmental, social, and possibly economic impacts due to their composition of more common materials. Though they may not be suitable for all applications that neodymium magnets currently are used in, such as where magnet weight and strength play a critical role, not every application necessarily needs neodymium magnets.

In fact, recent economic pressure in the global REE supply have caused some companies to consider neodymium magnet alternatives, or the complete removal of permanent magnets in their products all-together. For example, a single Toyota Prius hybrid car contains about 1.3 kilogram of neodymium magnets to operate its

electric motor (Takeda & Okabe, 2014). In 2011 Toyota announced that it was well on its way to producing an induction motor that would use electricity to create the magnetic field needed for it to operate, removing the need for large permanent magnets (Ohnsman, 2011). Hitachi, in a similar move, announced in 2012 that it had designed a sizable 11kW motor that replaced neodymium based magnets with a REE-free, iron-based permanent magnet (Hitachi Ltd., 2012). An industry-wide reduction in neodymium use would reduce total mass flows.

The recycling of neodymium magnets has also become a topic of discussion recently. Market pressures forced neodymium-dependent industries to seriously consider urban mining. Since these magnets are found in many products, including consumer electronics, they could be collected and recycled with an appropriately designed technology (Binnemans et al., 2013; Takeda & Okabe, 2014). While some magnets can already easily be recovered and directly reused, like large ones used in wind turbines, further collection and reuse of magnets from smaller and more diverse applications may need to be remanufactured or reprocessed before reuse. This would still help make a significant portion of the neodymium material stream in existence today circular. An imagined flow of neodymium mined specifically for use in neodymium magnets is shown at the top of Figure 2.4. Adding the collection, reclamation, and reprocessing of a significant amount of neodymium magnets to this flow increases the amount of material available for reuse while decreasing the need for virgin material. This change in the cycle is seen at the bottom of Figure 2.4.

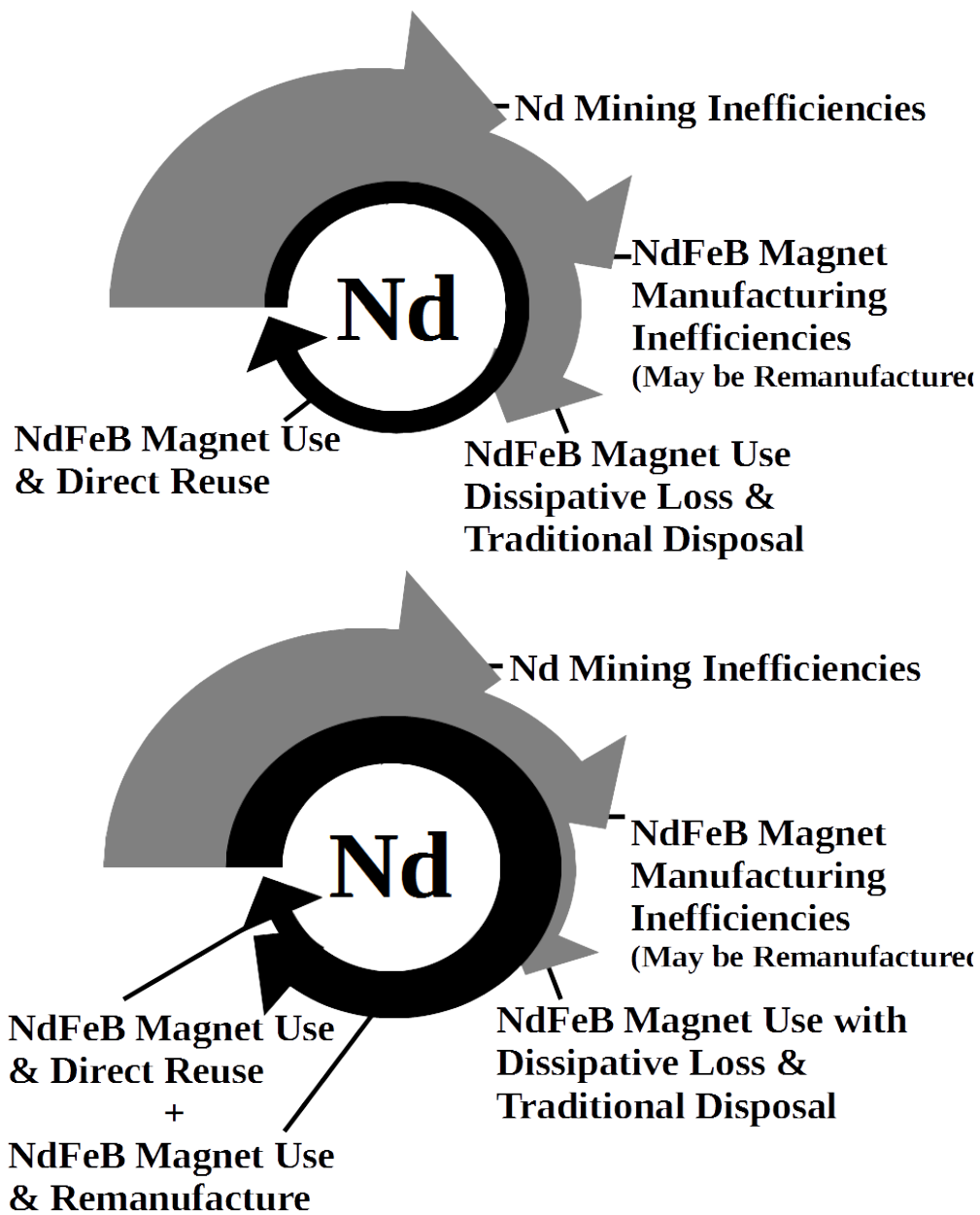


Figure 2.4: Flows and potential circular flows of Nd for use in magnets. Top: Representation of current Nd flows. Bottom: Representation of Nd flows with significant Nd magnet recovery and remanufacture.

*Note:* Arrow widths, while meant to represent Nd mass flows, do not correspond to actual Nd mass flows.

*Note:* Other uses for Nd exist. Shown here is a representation of the flow of Nd directly related to Nd magnet manufacture.

Several hurdles must be overcome to bring these flows full-circle in this way however. The small fraction of collected material that is neodymium magnets, the separation of this material, the diversity of magnet compositions, and the reprocessing steps are all issues that have hindered the realization of this idea. Separation is specifically troublesome since recycled material it must be sufficiently free of pollutants to be usable in any way similar to virgin material (Dragland, 2014). Electronics generally have small amounts of large numbers of materials, making this a difficult task to automate. Nevertheless, trials have started. Hitachi, for instance, has targeted hard disk drives and air conditioning compressors for neodymium magnet collection and, as of 2010, had planned to supply about 10% of their REE needs through this source (Binnemans et al., 2013).

Obviously alternatives to, and recycling opportunities for, neodymium magnets exist. Reducing these environmental, social, and economic impacts is a matter of identifying applications and opportunities where a change is technically and economically feasible, and implementing that change. Since these magnets are used in such a large variety of applications, it is difficult to do this in a generalized way. Each application is in need of a detailed analysis of its environmental, social, and economic impacts and potential for change. The audio industry as one such application and opportunity for positive change.

## 2.3. Audio Equipment

The audio industry is one of the many technological sectors that have made recent advancements in consumer electronics possible. While the audio industry is generally not defined or discussed as its own entity, being frequently joined with the video or media industry when mentioned, its products and technology are critical for the success of many electronic devices. A vast number of electronics, such as computers, mobile phones, audio players, televisions, and stereos, heavily depend on audio equipment to fulfill their many functions. Recently however, an increasing number of other electronics have begun adopting the ability to communicate with their users audibly as well, in ways more complicated and personal than a simple beep, buzz, or chirp. Workout machines, cameras, clocks, and ovens have all been rapidly developing the ability to convey information through music and voice, and thus require more complex audio equipment in their manufacture. As sound is one of the five ways humans connect with the world around us, audio equipment in our electronic devices will likely become a necessity for even more electronics in the future.

The audio industry is made up of many different entities and includes companies that design and manufacture devices and technologies that deliver sound as their ultimate product. Companies manufacturing speakers, headphones, microphones, amplifiers, etc. fall into this industry as well as ones that develop advanced software or hardware to process and deliver sound. Some well-known examples include Bose, Sony, Koss, Apple, and JVC Kenwood, as well as lesser

known companies working behind the scenes. Cirrus Logic and Audience, for example, have manufactured audio chips for Apple iPhones in the past, enabling the devices to deliver quality sound and noise cancellation for the user's enjoyment and convenience (Edible Apple, 2011; iFixit, 2013). While there are many companies delivering numerous unique audio services, the speaker manufacturing industry, itself a subset of the audio industry and dependent on magnets, has its own complexities.

Speakers are ultimately the technology required to deliver sound to the user, and industry players can be defined as companies designing or manufacturing speakers either as their primary product or as a part of products they manufacture and sell. For example, the company Bose clearly sells speakers as their primary product, while Apple designs speakers for use in many of the products they sell. Headphones, being a type of speaker, also fall into this industry. Speaker manufacturers, like companies in a number of other industries, find themselves with two main choices when marketing their products. First, they can sell their speakers as their own unique, easily identifiable, branded products. This allows them to develop a brand image and market to certain consumers like audiophiles and people interested in building home entertainment systems. Their second option is to become a hidden player, manufacturing products for use in the products of other companies, or for the purpose of being re-branded.

Headphones are a rather large and diverse category of speaker products, and public demand for them has created a similarly large and diverse industry. They

can be sold in different types, sizes, colors, and designs, can be sold in varying qualities for different markets, and can feature a variety of unique functions like noise cancellation. They are useful and often necessary accessories to many devices, especially mobile devices like the Sony Walkman introduced in 1979 and Apple's iPod introduced in 2001. Headphones have been around for over a century and were first used for telephone and radio communications and military applications (Berriman, 1998; Heffernan, 2011; Stamp, 2013). However, headphones as we know them today were designed by Nathaniel Baldwin around 1910 for sale to the US Navy and have been updated many times over the years with advancing technologies and emerging markets (Howeth, 1963; Stamp, 2013). Koss Corporation introduced the first stereo headphones in the 1950s and in 1979 the introduction of the small, portable, Walkman cassette player created demand for new lighter, more portable headphones (Berriman, 1998; Heffernan, 2011; Stamp, 2013). The iPod innovation and the rise in the use of mobile devices over the last decade has ensured a pair of headphones is close at hand for a large portion of the world population, right next to their portable media players and mobile phones.

Headphone design closely follows that of traditional speakers, in that they are essentially miniature speakers meant to produce small amounts of sound directed toward a user's ears. They convert electricity provided by a computer, iPod, or other device into mechanical energy that is distributed as sound waves. For basic speakers, a permanent magnet is placed in a housing to provide a static magnetic

field (“loudspeaker,” 2013). A diaphragm or cone made of a flexible, sheet-like material is placed to one side of the magnet and is attached to a coil of wire or voice coil. This coil sits between the diaphragm and the magnet, within the static magnetic field. A current, provided by the electronic device the headphones are connected to, is applied to the coil of wire making it an electromagnet with controllable strength and polarity. By rapidly adjusting the current at specific frequencies, the electromagnetic coil, or voice coil, is made to move within the static magnetic field and causes the diaphragm to move back and forth with it. This movement of the diaphragm causes vibrations in the air in front of it, producing sound waves. There are a multitude of designs and materials that can be used to create this speaker, but the size and weight constraints of headphones create limitations.

As a result of these limitations, the application of neodymium magnets in headphones is obvious. They provide the strongest magnetic fields for their size and weight (Kara et al., 2010). They thus allow headphone speakers to be made smaller and more lightweight than was possible with ferrite, ceramic, or Alnico magnets, while producing the same amount of sound. Furthermore, they are relatively cheap to manufacture and use less overall material which means that headphones can still be competitively priced or even distributed as included accessories. Apple has done just this with all of their iPod and iPhone products (Apple Live Chat Support, 2014).

### 3. Theoretical Framework

This research follows the framework of a limited material flow and impact analysis. It is descriptive in nature and draws conclusions inductively. It attempts to qualify and quantify a material flow, while also highlighting the relevant environmental impacts of the material in question. Being focused on these aspects however, it does not provide comprehensive mass balance calculations, nor does it map entire material flows as a full material flow and impact analysis would. The extent of this study is limited by available information and resources.

Despite these limitations the sources of material and data for this research are as comprehensive as possible. Existing scientific literature is used as a source of qualitative and quantitative data when available, and other more informal primary and secondary sources of information are used when such scientifically reviewed data is not available. This knowledge, combined with specific case studies conducted firsthand in the laboratory, is used to draw conclusions.

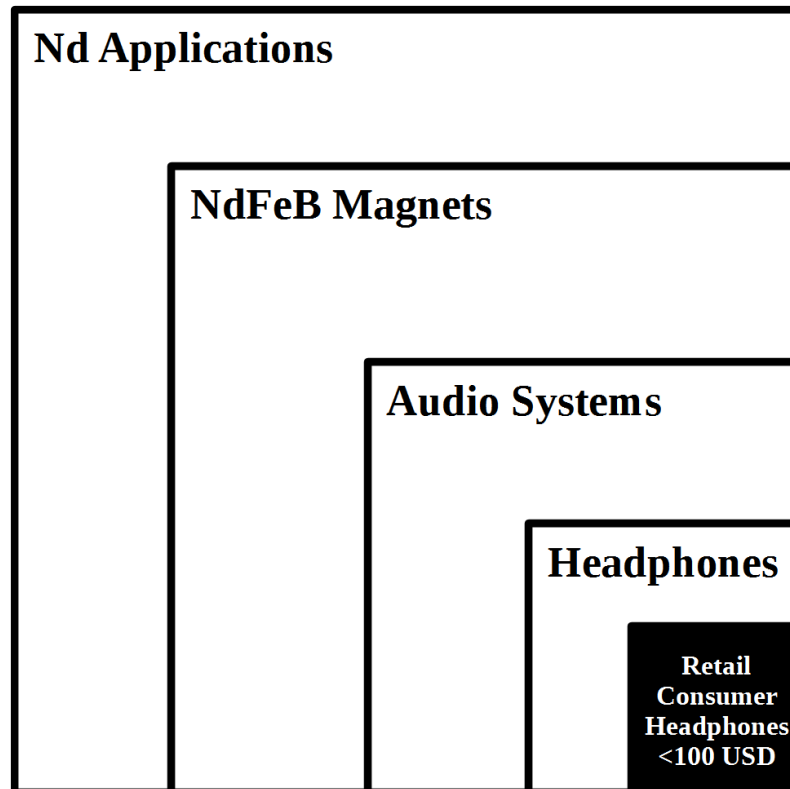
#### 3.1. Scope

The scope of this research is broken into the material of analysis, one specific application for the material, the market for this application, and the region of market covered. The element neodymium is the material of interest. While it has many applications, of concern here is NdFeB magnets in consumer headphones sold in the global market.

While there are several kinds of magnets that exist and could be found in consumer headphones, NdFeB magnets are the focus of this research. The mass flows and impacts, or associated estimations and conclusions, of both these magnets and the neodymium they contain will be the central outcome. Complementing this is a discussion about related findings from lab work, such as the use of alternative magnets, and recycling research and potentials of the NdFeB magnets.

The product of focus, consumer headphones, must be further defined as well. This research focuses on mid-priced to low-end headphones, not higher-end headphones generally marketed to audiophiles, music industry, and professionals. The headphone market covered here sells devices priced below 100 USD at retail. This distinction is made for two reasons. First, this market sells to a more general and casual consumer base. This is assumed to represent a flow of more devices, and thus more dispersion of the magnets they contain. It is not known however, if this focus on lower-end headphones represents a larger or smaller overall flow of NdFeB magnets. Second, headphones in this market are more likely to adhere to a simpler, more uniform internal design. High-end headphones can make use of more expensive and specialized mechanical parts that are not necessarily common in the industry. As such, making generalizations about this high-end headphone market becomes much more difficult. This scope is summarized in Figure 3.1.

As far as region is concerned, efforts are made to come to conclusions about the global flow of neodymium through these products. While the analysis



*Figure 3.1:* Research scope in respect to general neodymium applications

attempts to draw conclusions globally, the data available limits what conclusions can be made. Regions quantitatively covered are identified in the text, as are any qualitative generalizations that are made about the amount of neodymium headphones represent globally and the magnitude of related impacts.

### 3.2. Specific Questions

In this research, specific questions are addressed to paint a qualitative and quantitative picture of the flow of neodymium and its impacts. These are:

- What is the size of the headphone market in units per year?
- What proportion of headphones use neodymium magnets?

- What is the mass of the magnets found in these headphones?
- Is there a correlation between headphone type and the type or size of magnet used?
- What is the mass of neodymium used in these headphones each year?
- What mass flow of neodymium does the production, use, and disposal of consumer headphones represent?
- Are any trends evident in this flow?
- What are the ecological impacts of this resource flow?
- Are there any neodymium magnet recovery technologies available or being researched that could be applied to this material flow?

While there may not be a quantitative solution available for each of these questions, a qualitative look at their answers will illustrate the dynamics of this material flow and its impacts.

### 3.3. Definitions

A few terms must be defined at the outset. First, the use of the term 'headphone' and its different types must be understood. Second, the term 'neodymium magnet' must also be explicated.

The word 'headphones' is interpreted to be a set of speakers worn on the ears to hear audio from an audio device such as a computer, radio, or portable media player, without other people hearing. This definition derives from the Oxford Dictionary's definition for 'earphone' and not 'headphone,' as the latter is interpreted there to consist of only earphones that usually have a connecting head

band (Oxford University Press, 2015a, 2015b). Many categories of earphones do not include this head band, yet are commonly referred to as headphones.

Headphones, as used here, are further broken into categories defined by and widely used by industry and the public. There are generally four main types of headphone design, three of which will be discussed in this research. While there are many other ways to categorize headphones such as whether or not they are wireless, contain a microphone, etc., only the divisions explained below are considered in this research.

The four categories considered here are 'circumaural,' 'supra-aural,' 'earbud,' and 'in-ear.' The first two types, circumaural and supra-aural, consist of a speaker housing that sits over the outer ear. They also may or may not include a head band. Circumaural headphones sit around the outer ear, generally with a shaped cushion or pad, while supra-aural sit on the ear. The other two headphone types are earbuds and in-ear headphones. These are headphones where the speaker housings, which are much smaller than those found in circumaural and supra-aural headphones, sit in the ear. Earbuds sit loosely in the outer ear and direct sound into the ear without using a tight fitting. In-ear headphones use shaped fitting, usually made of silicone, to direct sound directly into the ear canal. A visual illustration of these different headphone types is presented in Figure 3.2 with two examples given for supra-aural headphones to illustrate the diversity of design but similarity of speaker housing. Similar design variations can be made with each type of headphone by its manufacturer. It should be noted however that there is

no industry wide standardization of terms. Therefore these terms are defined by the author here for use in this study. Other terms such as 'over-ear' and 'on-ear' can be used to describe circumaural and supra-aural headphones or both, while a term such as 'in-ear' can sometimes describe both earbud and in-ear designs together.

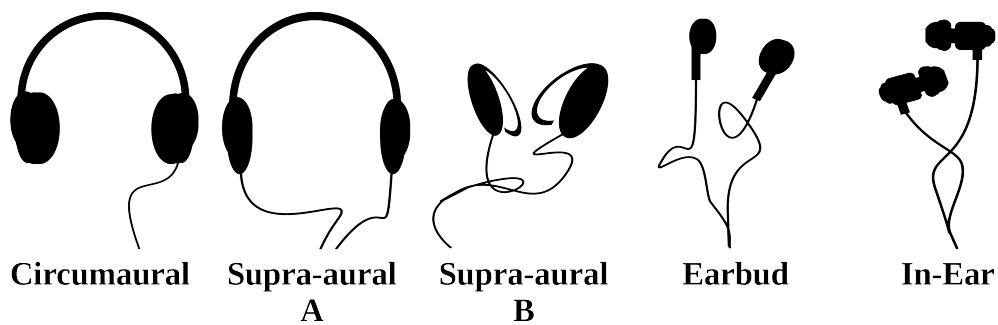


Figure 3.2: Types of headphones

Finally, the term 'neodymium magnet' is defined here as a NdFeB magnet, or magnetic metal alloy of the three metals neodymium, iron, and boron. These magnets are further classified as sintered and bonded magnets, referring to their differing production methods. While neodymium magnets are also sometimes called 'rare earth magnets,' this term is not specific to NdFeB magnets; it also includes samarium-cobalt magnets, which are not covered here.

The terms mentioned above are central to this research and their definitions are sufficiently specific inasmuch as this research is concerned. While other definitions or terms may be used elsewhere, and may differ slightly, these have been created to best conduct and illustrate the research and concepts here. Other, lesser used terms will be defined in-text as they are introduced.

### 3.4. Hypothesis

Considering the framework presented above, the working hypothesis for this research is as follows:

While the flow of neodymium magnets in headphones is expected to be a relatively small flow when compared to the larger neodymium magnet market, it represents a dispersion and loss of a valuable and harmful material through a common consumer product. It is expected that neodymium magnets are found in the majority of mid to low-end consumer headphones and that impact reduction measures, such as material switching and recovery technologies exist. It is also expected that this flow of neodymium magnets has a measurable negative environmental impact and that recovery can improve this impact.

## 4. Methods of Data Collection

Two methods of data collection are used for this research. This research is largely based on review of existing literature and available data, and so these materials are extensively used. Lab work is also used however to provide more quantitative analysis in the form of case studies.

Data collected for this research are largely from academic articles and other primary and secondary sources of information. Academic articles will be preferred when available but as this research is specific to a section of the neodymium magnet market that has not been extensively reviewed before in the academic realm, non-reviewed and non-academic sources will be necessary to

provide some information. Confidence in the accuracy of source material is discussed in-text.

Lab work used here consists of the manual disassembly of six different sets of headphones to remove, analyze, and weigh the magnets they contain. Disassembly consists of one speaker housing being removed and taken apart to extract the magnet, with pictures being taken during each step. Once the magnet is removed, it is visually identified as either ferrous or neodymium and is weighed on a laboratory scale five times. The mass each time is recorded and the results are averaged to provide a mass for each magnet. Next, the volume of the magnets is calculated by using a micrometer or vernier caliper to find its diameter, width, and any other measurements necessary to calculate this. Since both speakers are identical in structure, it is assumed that they contain the same magnets and thus the resulting mass from the lab are multiplied by two for each set of headphones analyzed.

This lab work was conducted in two separate locations, resulting in two separate laboratory scales being used, as well as both a vernier caliper and a micrometer being used for measurements. A Mettler Toledo PL83-S balance was used for finding the mass of the magnets found in the Apple and JVC headphones, while a Sartorius BP 210 S was used for the other four headphone magnets. The scales were accurate to 0.001 and 0.0001 grams respectively. The masses of the Apple and JVC magnet measurements made on the Mettler scale were confirmed to be within 0.01 grams of later measurements taken on the Sartorius scale. A

digital Mitutoyo vernier caliper was used to measure the diameter and width of the Apple and JVC headphones, which was accurate to 0.1 mm. The other magnets' dimensions were measured with an E-Top micrometer which was accurate to 0.01 mm. To cope with these differences in accuracy, mass measurements for these magnets were rounded to 0.001 grams and lengths were rounded to the nearest 0.1 mm.

## 5. Presentation of Materials

The flow of neodymium use in headphones worldwide is part of a larger flow of neodymium in the audio industry. This industry today is one of the primary consumers of neodymium but existed long before neodymium magnets were discovered, relying on other magnet types. Still today, the industry does not only use neodymium magnets, and the magnets found in headphones are evidence of this. Disassembly of a few headphones reveals the use of neodymium and other magnets in this industry. This information provides a foundation for discussion on the flows of neodymium magnets through this industry worldwide and on the potential for reducing their impacts.

### 5.1. Neodymium and Audio Equipment

According to a study done by Du and Graedel in 2011, audio equipment around the world was estimated to hold over 31 gigagrams, or 31,000 tons of neodymium in 2007 (Du & Graedel, 2011). The study included stocks of estimated in-use neodymium and excluded the stock held within discarded devices. This made

audio equipment the second largest in-use stock of neodymium, behind computers which the study estimated held 40 gigagrams, and surprisingly above wind turbines which contained an estimated 18 gigagrams. Comparisons from this study are shown in Figure 5.1. Shin-Etsu, a Japanese company estimates the percentage of neodymium magnet demand directed toward 'optical and acoustic applications,' not including stocks, is around 10% (Schüler et al., 2011 citing Shin-Etsu). Another study suggests that acoustic applications for rare earth magnets is specifically around 6% of total rare earth applications (Bristøl, 2012). This apparent discrepancy may indicate some disagreement about how much of the neodymium magnet market is dedicated to audio devices, or it could indicate a buildup in the stock of audio devices over time, perhaps due to a longer life of

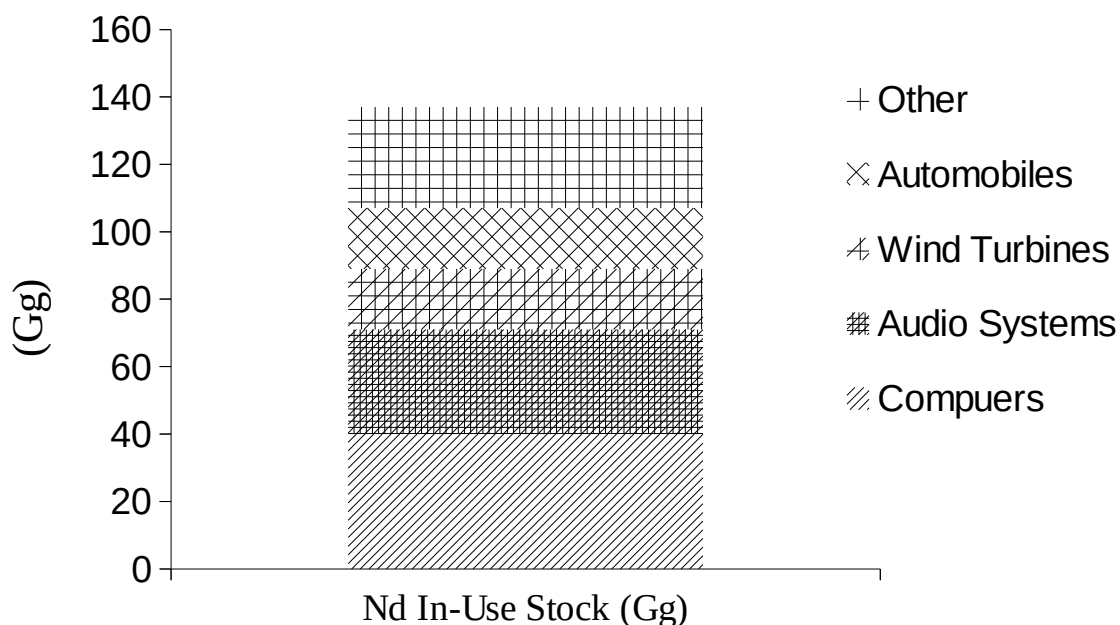


Figure 5.1: In-Use Stock of Neodymium in Various Applications in 2007

Adapted from: Du, X., & Graedel, T. E. (2011). *Global In-Use Stocks of the Rare Earth Elements: A First Estimate*. *Environmental Science & Technology*, 45(9), 4096–4101. <http://doi.org/10.1021/es102836s>

these audio devices when compared to hard drives or motors. In other words, a lower mass stream of neodymium that builds up to larger in-use stocks may exist. Still, this stock of neodymium in audio devices is likely to have increased since this time as such devices become even more integrated into society and older equipment is continually replaced.

When looking toward the future, there are likely to be a few significant changes to these stocks due to changing technologies and markets. The use of neodymium magnets in wind turbines is likely to have risen, and will continue to rise significantly, as more turbines are constructed worldwide. The use of neodymium magnets in motors, especially within the growing electric car market, is also likely to become even more significant in the near future. Though new designs and alternative magnets have been suggested in some applications, they have yet to become a sizable market trend and are mostly limited to research and development (Hitachi Ltd., 2012; Ohnsman, 2011). With the prevalence of audio devices within and as necessary accessories to electronic devices, and with the lack of a suitable substitute for neodymium on the horizon, the stocks of this metal are likely to increase significantly in the coming years.

## **5.2. A Closer Look at the Headphone Market**

The headphone market is a sizable segment of the audio market and has enjoyed much attention in recent years due to the popularity of portable music devices like the Sony Walkman and Apple iPod. It is incredibly large and diverse,

spanning the entire world and including a wide variety of device shapes, sizes, qualities, features, etc. Research by Futuresource Consulting provides information about the size and makeup of this market in research for 2013 (CEATEC JAPAN, 2013 quoting Futuresource Consulting). The worldwide market was expected to sell around 284 million units during 2013 and exceed \$8.2 billion USD in revenues (CEATEC JAPAN, 2013 quoting Futuresource Consulting). This is a solid increase from 2012, during which around 260 million units were shipped and 2011 when about 225 million units were shipped (CEATEC JAPAN, 2013 quoting Futuresource Consulting). Futuresource also predicted an increase in sales through 2017.

It is worth noting that there are significant differences in sales figures across regions. Of this \$8.2 billion of sales and 284 million units in 2013 approximately \$2.3 billion and 80 million units represents the US market while \$77 million and 3.8 million units the Southeast Asian market, which includes Singapore, Indonesia, Malaysia, and Thailand (CEATEC JAPAN, 2013 quoting Futuresource Consulting; Johnston, 2014 quoting NPD Group; Rappler, 2014). These two regions have similar population sizes, revealing significantly lower per-capita sales. This is probably the result of a significant difference in the use of portable electronic devices such as music players and smartphones between these regions. There is also a difference in the average price of headphones purchased. The average price of headphones sold in the US calculated with these figures comes out to about \$29 while for the Southeast Asian region specified it equates to about

\$20 per unit. The notable increased sales of higher end headphones in recent years is at least partly responsible. Such a general analysis may trivialize the headphone market though. The headphone market can be broken into two very different segments: a market for high-end headphones aimed at audiophiles and professionals, and market for lower-end headphones marketed more toward casual users. Furthermore, there are different design categories of headphones sold.

The high-end headphone market as attracted much media attention in recent years with the development of unique technologies and features, such as noise canceling, and marketing toward specific groups of users. High end, or premium, headphones are generally considered headphones that sell at or above \$100 USD each, and are priced as such because of their claims on sound quality, extra features, and style (Johnston, 2014 quoting NPD Group). Beats headphones, a popular brand of high-end headphones owned by Apple, alone claimed 23% of global headphone market sales in 2012 while the high-end headphone market as a whole grew by an incredible 21% in 2013 (CEATEC JAPAN, 2013 quoting Futuresource Consulting; Johnston, 2014 quoting NPD Group). As a result of their higher cost, these headphones can use different speaker technologies than basic headphones. Sony, for example, currently markets headphones using balanced armature drivers, a technology that uses the same fundamental physics of common coil speakers, but in a different way (Sony Electronics Asia Pacific, 2014). Because of the size of and space required for these different technologies as well as style choices, these headphones generally, but do not always, fall into

the category of over-ear headphones. This research will not focus on these high-end headphones however.

Headphones not placed in this high-end market are what are categorized here as mid to low-end headphones. These headphones would be sold at prices lower than \$100 USD each or sold alongside devices such as the Apple iPod. Such headphones might not deliver the same quality sound or provide the same advanced features as the high-end headphones but they do account for the vast majority of unit sales. This is evident when comparing monetary sales figures for a year like 2013 when \$8.2 billion was paid for 284 million headphones worldwide, amounting to approximately \$29 paid per pair of headphones on average (CEATEC JAPAN, 2013 quoting Futuresource Consulting).

Different categories of headphone forms also represent different parts of the market. A breakdown of sales in the UK from 2009 shows that of 7 million headphones sold that year 5.1 million, or over 70% are categorized as having an in-ear design (What Hi-Fi?, 2010 quoting GfK). This in-ear design mentioned probably includes what are categorized here as earbud and in-ear headphones in this paper. This shows a general preference toward earbud and in-ear models in the UK which, due to their portability and generally cheaper pricetag, can probably be roughly estimated to represent the general world market as well. This preference may be a result of the small and sometimes cheap nature of this type of headphone and/or them being perceived as more disposable in nature than over-ear models.

### 5.3. Magnet Use: Device Level

Each of these headphones sold requires magnets to operate. While some high-end headphones can have complex construction utilizing multiple magnets, the standard design for the vast majority of headphones places one magnet in each speaker, amounting to two magnets per unit. While there are various magnetic materials that can be used, three have generally been used for application in speakers: alnico, ferrite, and neodymium magnets (Owsinski, 2011). The first of these, the alnico magnet, is a strong type of magnet that has been in use for over 50 years and can be identified by its metallic appearance and homogenous nature. It has however since fallen out of favor and been largely replaced by the latter two magnets (Owsinski, 2011). The second of these represents the cheaper of the options in common use today, though it is not quite as strong as the latter which has enjoyed recent proliferation, especially in the electronics sector where small, strong magnets equate to size and weight reductions as well as precise movements. These two types of magnets found generally in speaker applications today have differing appearances, magnetic properties, and compositions.

Ferrous magnets are usually gray in color and have a dull appearance. They have a weaker magnetic field than neodymium magnets and are essentially a ceramic composed of around 90% of iron and 10% of either barium or strontium oxides, though the specific amounts and composition can vary (First4magnets,

n.d.-b; Navarro, Zhao, & Sutherland, 2014). They can often be seen in such applications as cheap refrigerator magnets and the like.

Neodymium magnets on the other hand are usually metallic in appearance due to the plating necessary to protect the magnetic material from corrosion. This plating is usually made of a thin layer of nickel or layers of nickel, copper, and nickel, though other materials to protect the magnetic material can be used depending on the application (First4magnets, n.d.-a; Magnaworks Technology Inc., n.d.; Sprecher et al., 2014). The actual magnet is composed of neodymium, iron, and boron, as well as small amounts of other additives if specific qualities are needed. By elemental mass fractions of these magnets can vary slightly, but generally fall around the same proportions. Neodymium makes up between 27% and 32% of the mass of the magnet, boron about 1%, and iron makes up the majority of the rest of the mass (e-Magnets UK, n.d.; Navarro et al., 2014; Oakdene Hollins, 2010). Additional elements that are added to change magnet properties account for only small portions of the total mass of the magnet. Dysprosium for example can be added to help the magnet operate at high temperatures, but may only replace a small portion of the neodymium in the magnet (e-Magnets UK, n.d.; Navarro et al., 2014; Oakdene Hollins, 2010; Sprecher et al., 2014). The magnets used in headphones likely do not need such additives due to their rather mundane operating conditions. The electroplated coating of the magnet also contributes to its mass. Hard drive magnets for example were found to have nickel plating contribute to 10% of their total mass

(Sprecher et al., 2014). This is a common type of protective coating for neodymium magnets and this figure will be used for later calculations.

#### 5.4. Quantitative Impacts of Neodymium Magnets

The neodymium for rare earth magnets must be obtained and disposed of somewhere at the beginning and end of its useful life. This will have impacts on the on society, the economy, and the environment. While many of these impacts are difficult to quantify, the environmental impacts have been quantitatively estimated for the production specific mass of neodymium.

As stated previously, the Chinese Society of Rare Earths places a specific material impact on rare earths in general. “8.5 kilograms of fluorine, 13 kilograms of dust, 9,600 to 12,000 cubic meters of “waste gas containing dust concentrate, hydrofluoric acid, sulfur dioxide, and sulfuric acid,” 75 cubic meters of acidic wastewater, and one ton of radioactive waste residue are the hidden burden of each ton of rare earths on the market (Hurst, 2010). This all, along with ten million tons of wastewater (Hurst, 2010). These numbers have been repeated by the United States Environmental Protection Agency in reports (Campbell, 2012; United States Environmental Protection Agency, 2012). While this may not be the exact impact of REE mines around the globe, over 95% of global supply came from China in 2012 (United States Environmental Protection Agency, 2012). These values would thus be an effective representation of some of the impacts of neodymium production.

A detailed life cycle inventory for the production of rare earths and neodymium magnets specifically has been published by Sprecher et al. in 2014. The goal of the publication was to determine the “environmental impact of the primary production process of 1 kg of NdFeB rare earth permanent magnet and [compare] this with two alternative recycling processes” (Sprecher et al., 2014). This particular analysis relies heavily on the assumption that the REOs in question were sourced from the Bayan Obo mine in China, but as this is a significant source of REE in the world today this seems a reasonable base assumption. The analysis reveals quantitative results for several life cycle assessment impact categories for three different scenarios of primary NdFeB magnet production, as well as for REOs themselves. The results from this paper are shown in Table 5.1 as three scenarios: “a baseline scenario that represents the current state of the industry, a high-tech scenario that assumes best available technology, and...a low tech scenario” (Sprecher et al., 2014; Takeda & Okabe, 2014). The table also provides the results of multiplying these impacts to the size of sintered NdFeB manufacturing production in 2010. The environmental impacts covered include the potential for such magnet production to eutrophy or acidify waterbodies, ozone, and present a toxicity hazard to freshwaterbodies and humans. Furthermore, energy demand and REO use are quantified. The environmental and human impact categories here highlight a few of the critical concerns for NdFeB magnet production including global warming potential, potential impact on human

<b>Table 5.1: LCA Scenarios for Production of 1 kg of Primary NdFeB Magnet Material with Total 2010 Production Estimate Comparisons</b>					
Impact Name	Units	High-tech <sup>[1]</sup>	Baseline <sup>[1]</sup>	Low-tech <sup>[1]</sup>	2010 Production of 45,000 tons <sup>[2]</sup> (Baseline Eq)
Eutrophication Potential	kg NO <sub>x</sub> -Eq	0.14	0.19	0.30	8.5 million
Acidification Potential	kg SO <sub>2</sub> -Eq	0.37	0.44	0.66	20 million
Photochemical Oxidation	kg ethylene-Eq	0.014	0.017	0.026	77 million
Climate Change	kg CO <sub>2</sub> -Eq	21	27	41	1.2 billion
Ionizing Radiation	DALYs	$4.1 \times 10^{-8}$	$5.1 \times 10^{-8}$	$7.2 \times 10^{-8}$	2.3
Freshwater Aquatic Ecotoxicity	kg 1,4-DCB-Eq	13	14	20	630 million
Stratosphere Ozone Depletion	kg CFC-11-Eq	$2.0 \times 10^{-6}$	$2.6 \times 10^{-6}$	$3.9 \times 10^{-6}$	117
Human Toxicity	kg 1,4-DCB-Eq	42	150	470	9.8 billion
Cumulative Energy Demand	MJ-Eq	260	330	490	15 billion (4.2 Terawatt-hour-Eq)
Ore Use (of 4.1% REO)	kg	28	43	76	1.9 billion

*Table 5.1: Summary of LCA findings for the production of 1 kg of primary NdFeB magnet material with calculated approximations for global 2010 NdFeB sintered magnet production*

*Adapted from:*

[1] Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., ... Kramer, G. J. (2014). *Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets*. *Environmental Science & Technology*, 48(7), 3951–3958. <http://doi.org/10.1021/es404596q>

[2] Takeda, O., & Okabe, T. H. (2014). *Current Status on Resource and Recycling Technology for Rare Earths*. *Metallurgical and Materials Transactions E*, 1(2), 160–173. <http://doi.org/10.1007/s40553-014-0016-7>

health, and radiation. Data from this report, being from a scientific study, will be used for further quantification of impacts.

Specifically, the global warming potential of 1 kg of magnet is equivalent to

between 21 and 41 kg of CO<sub>2</sub> equivalent. The United States Environmental Protection Agency estimates that the average passenger vehicle in the US emits about 4.75 metric tons of CO<sub>2</sub> equivalent each year (United States Environmental Protection Agency, 2015). Thus, about 150 kg of NdFeB magnet is approximately equivalent to one US passenger vehicle on the road for one year. 2010 saw the production of approximately 45,000 tons of sintered neodymium magnets, meaning that greenhouse gas emissions from production of these magnets was approximately equal to that of 300,000 passenger cars on US roads (Takeda & Okabe, 2014).

Human toxicity of NdFeB production varies greatly depending on the technology used. Kilograms of 1,4-DCB-Eq, or 1,4 dichlorobenzene equivalent emissions, a toxic substance and possible carcinogen, are used to measure this category. Anywhere between 42 and 470 kg 1,4-DCB-Eq can be emitted for each kg of NdFeB produced (Sprecher et al., 2014). Hydrogen fluoride and heavy metals emissions are the major contributor to this measurement and are obvious concerns for human health.

Ionizing Radiation, another of the indicators, also raises concerns. This is measured in DALYs, or disability-adjusted life years, and indicates the potential for loss of healthy life. This radiation created by the manufacture of 1 kg of NdFeB magnets has the potential to cost between  $4.1 \times 10^{-8}$  and  $7.2 \times 10^{-8}$  DALYs. The production of all 45,000 tons of sintered NdFeB magnets in 2010 came at the potential cost of about 2.5 DALYs. While this is a small value,

continued, increased production of these magnets does have the potential for long-term radioactive harm to both humans and the environment.

Furthermore, the manufacture of NdFeB magnets utilized energy and raw ore. 2010 production utilized the equivalent of 4.2 terawatt-hours of energy. For comparison, the US electricity generation of the US in 2014 was approximately 4,000 terawatt-hours (United States Energy Information Administration, 2015). Also, approximately 1.9 million tons of ore was processed to extract the Nd needed for these magnets.

Economically the impacts of neodymium magnets are a bit more straightforward, though they are more difficult to interpret due to the multitude of different actors in the material markets and those that depend on them. The price of these magnets are heavily dependent on the price of neodymium since the other major component of the magnets, iron, is not near as valuable. Instability in the neodymium market then indicates instability in the neodymium magnet market. As China began controlling their exports of REEs in 2007, market prices began to climb (Kara et al., 2010). This sparked market and governmental concerns outside of China, especially in the United States, about where future sources of REEs would come from. The market price of neodymium between 2002 and 2012, highlighting the dramatic fluctuations in each quarter of 2011, is shown in Figure 5.2 (Massari & Ruberti, 2013; Otto, 2011). It is obvious that the stability of supply in the neodymium market has great economic impacts, directly on those industries that rely on neodymium magnets and indirectly on those industries that

rely on products that use neodymium magnets. It is therefore a priority, both economically and nationally, to ensure a stable supply is available. Due to a lack in transparency of direct market data for the neodymium and neodymium magnet market, economic impacts will not be quantified.

These measurable environmental impacts from the NdFeB magnet industry can be applied to magnets found in the headphone market. Of interest for comparisons would be the energy use and global warming potential of magnets

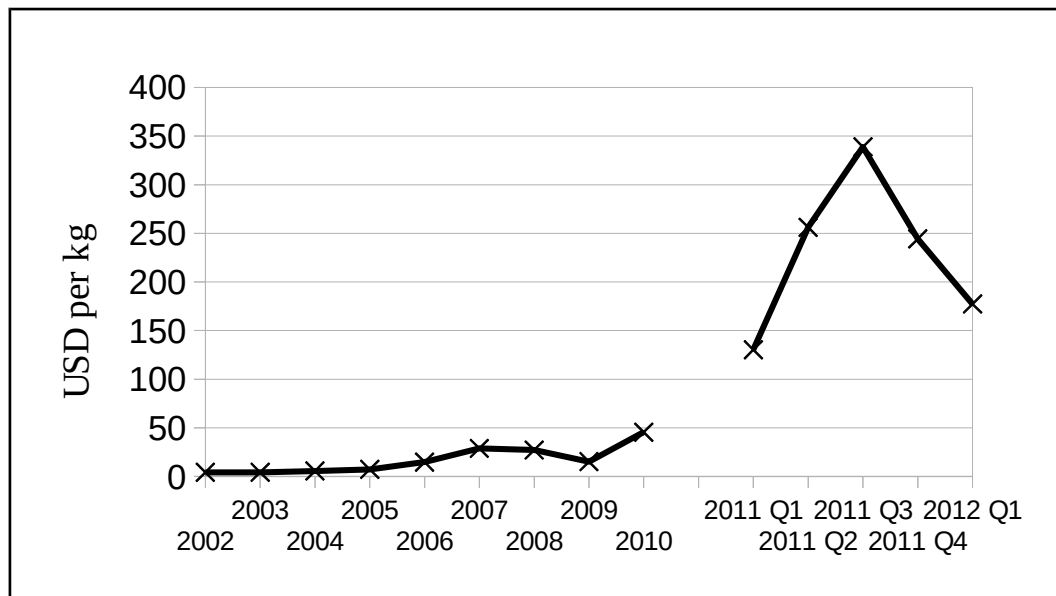


Figure 5.2: Price of Neodymium Oxide over Time in USD per kg

Adapted from:

[1] Massari, S., & Ruberti, M. (2013). *Rare earth elements as critical raw materials: Focus on international markets and future strategies*. *Resources Policy*, 38(1), 36–43. <http://doi.org/10.1016/j.resourpol.2012.07.001>

[2] Otto, E. (2011). *Rare Earth Metals: Critical To Energy Efficient Products, Mobile Electronics, & Electric Vehicles* (p. 76). Cormark Securities Inc. Retrieved from <http://ebookbrowse.net/110913-rare-earth-metals-initiating-coverage-2-pdf-d184831760>

directed toward this particular application. First though, a look at the mass of these magnets found in headphones is necessary.

### 5.5. Recycling

The recycling of neodymium magnets has been discussed in a number of research articles, though large-scale implementation has yet to be achieved. There are different methods proposed for recycling. Recycling has the ability to reduce the impacts of neodymium magnets by removing the mining and ore processing steps of the life cycle, and by extending the life of material of current in-use stocks.

While large magnets, like those found in wind turbines, can be directly reused with ease, smaller magnets retrieved from consumer electronics require some extra work to be recycled. Not only must they be removed from the devices they are embedded in, but they can contain differing forms and compositions. This is exactly the reason hard drive magnets have been the focus of recycling research thus far. Magnets in these hard drives are generally of the same forms and compositions (Binnemans et al., 2013). In this case, the magnets can more simply be remade into new magnets through powder processing or remelting (Binnemans et al., 2013). Magnets found in headphones however, are likely to have differing compositions. This would necessitate reprocessing to separate elements that can then be used in known proportions to manufacture new magnets (Binnemans et al., 2013).

A study by Ciacci, Reck, Nassar, and Graedel titled *Lost by Design* studies how various elements are utilized in global material flows in such a way that they can and cannot be recovered. They break down streams of these elements into in-use dissipation streams which represent an inherently unrecoverable use of the material, potentially recyclable streams, streams unrecyclable using current technologies, and unspecified streams (Ciacci, Reck, Nassar, & Graedel, 2015). Neodymium, when compared to many other elements, shows a fairly high potential for recovery. The study suggests that neodymium could potentially be recovered from over 75% of the material streams it exists in using existing technologies. This study does not cover the quality of functionality of the recovered material or detail the recovery methods used however, meaning that recovered neodymium may not necessarily be as useful as virgin material.

The exact process best suited for this recycling remains a topic of research. While scrap from production is currently being recycled by manufacturing companies, not much is publicly disclosed about the processes used (Binnemans et al., 2013). Methods available include hydrometallurgy, pyrometallurgy, electrolysis, electrolysis gas-phase extraction, and hydrogen decrepitation (Binnemans et al., 2013; Dragland, 2014; Takeda & Okabe, 2014). Many of these processes rely on the source material, the magnets to be recycled, to be of similar composition and without impurities or contaminants. Furthermore, existing research largely leaves the collection and separation of magnets from their source, headphones in this specific case, untouched. Hydrogen decrepitation is a

promising method for use with scrap headphones however, and utilizes relatively low amounts of energy to retrieve a new workable raw material (Sprecher et al., 2014). This method exposes neodymium magnet material to hydrogen gas at atmospheric pressure and room temperature, effectively demagnetizing it and disintegrating it to a powder (Sprecher et al., 2014; Miha Zakotnik, Delvin, Harris, & Williams, 2006). To allow the material NdFeB material to be exposed to the hydrogen gas, the protective magnetic coating must be at least partially removed, or the magnet lightly crushed (Miha Zakotnik et al., 2006). The resultant powder, after it is separated by a sieve from the rest of the material such as any remaining coating, can be remanufactured into new magnets utilizing a few different methods that could produce various qualities of new magnets (Walton, 2011). Resintered magnets using this powder may have lower qualities than new magnets, but could probably still be used in a number of applications (M. Zakotnik, Harris, & Williams, 2009). This lower quality could also be the result of the choice of re-manufacturing methods chosen.

Sprecher et al. again provide a useful impact assessment for the production of recycled magnets vs primary magnets. A summary of these impacts is presented in Table 5.2. A hypothetical scenario using hydrogen decrepitation for recycling as described above is presented. Furthermore, hand picking to separate magnets from electronic scrap was compared to shredding. The researchers highlight the fact that method is stated to use 88% less energy than primary production and scores lower in nearly all impact categories. Clearly such a recycling method, if

realized and implemented on a large scale, would have tremendous positive impacts for the environment and human health.

<b>Table 5.2: LCA Scenarios for Production of 1 kg of NdFeB Primary and Recycled Magnet Material utilizing Hydrogen Decrepitation</b>				
Impact Name	Units	Primary <sup>[1]</sup>	Recycled by Hand Picking <sup>[1]</sup>	Recycled by Shredding <sup>[1]</sup>
Eutrophication Potential	kg NO <sub>x</sub> -Eq	0.19	0.0077	0.032
Acidification Potential	kg SO <sub>2</sub> -Eq	0.44	0.027	0.20
Photochemical Oxidation	kg ethylene-Eq	0.017	0.0011	0.0080
Climate Change	kg CO <sub>2</sub> -Eq	27	3.3	10
Ionizing Radiation	DALYs	$5.1 \times 10^{-8}$	$2.0 \times 10^{-8}$	$8.1 \times 10^{-8}$
Freshwater Aquatic Ecotoxicity	kg 1,4-DCB-Eq	14	5.3	11
Stratosphere Ozone Depletion	kg CFC-11-Eq	$2.6 \times 10^{-6}$	$9.3 \times 10^{-8}$	$1.0 \times 10^{-6}$
Human Toxicity	kg 1,4-DCB-Eq	150	3.6	28

*Table 5.2: Summary of LCA findings for the production of 1 kg of primary NdFeB magnet material (baseline) compared with the production of 1 kg of recycled NdFeB magnet material using hand picking or shredding to separate the magnets from their source*

*Adapted from: Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., ... Kramer, G. J. (2014). Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets. Environmental Science & Technology, 48(7), 3951–3958. <http://doi.org/10.1021/es404596q>*

## 5.6. Case Studies: Magnet use in Consumer Headphones

To find details about these magnets found in headphones, six individual devices have been selected for laboratory disassembly. These devices include a set of what has been identified by several unofficial websites as Apple's third generation earbuds, a set of Panasonic RP-HV154 earbuds, a set of Hama HK-249

earbuds, a set of JVC HA-FR201 in-ear headphones, and two sets of Sony supra-aural headphones with model numbers MDR-24 and MDR-A110 (“Apple earbuds,” 2013, “Apple earbuds,” 2015, “Apple earbuds,” n.d.). The devices have been selected not only to quantify the magnets they contain, but to inform three discussion topics relating to detailed material flow analysis, correlation between headphone size and magnet size and/or type, and market trends over time. While these six headphones do not represent a statistically significant proportion of the market, they are not intended to. These disassemblies are intended to provide some quantitative data for informative analysis through individual examples and qualitative information about the market.

Each of the headphones selected are intended to provide specific insights. The Apple earbuds represent a large and well known segment of the market. Due to their popularity and uniformity, pertinent market data is available. As a result, this case study attempts to actually quantify related yearly neodymium magnet flows. Furthermore, these Apple headphones are essentially complimentary with the purchase of specific company products and thus represent the distribution of headphones as an included accessory, whether desired or not. The Panasonic earbuds represent a budget option, being priced at about eight USD. They are presented as a counterpart to the Hamas earbuds which are one of the cheapest commercial options available. The JVC in-ear headphones are representative of the in-ear headphone category and its specific design considerations. Finally the two Sony supra-aural headphones selected are of similar design but sold during

different years around the surge of neodymium use in headphones. As such, they represent an evolution of design over time within a specific headphone category, price-point, and design while also highlighting the differences of the supra-aural headphone category in relation to the other categories.

Of note is the absence of a circumaural headphone case study. This category was intentionally left out for two reasons. First, while budget models exist, headphones in this category are generally associated with the higher end of the price spectrum. Second, the relatively large size of headphones in this category allows for the use of alternative speaker designs, especially in the high-end market. This makes assumptions based on only one headphone sample uncharacteristic of the market.

#### 5.6.1. Apple Case Study

Apple Inc. is a company that designs, manufactures, and markets a wide variety of electronic devices, software, services, and peripherals including the iPhone and iPod (Apple Inc., 2013). The company has played an important role in the electronics industry, marketing numerous lines of devices under widely recognized names such as Mac, iPod, iPhone, and more recently, iPad. The company has experienced significant growth over the last two decades and owes its success largely to the popularity of its iPod series of portable media players. The resounding success of the iPod shortly after 2001 was in part aided by the inclusion of complimentary white headphones with each device, and the marketing of these headphones as a status symbol (Chazin, 2007; Leopold, 2014).

With these unique headphones, the public could easily identify who was listening to an iPod and who was not, even when the actual iPod was out of sight in a pocket or bag. In this way, Apple successfully marketed their product through their users. The company has been one of just a handful of world market giants in portable media players and smartphones for many years, its iPod holding 73.4% of the US portable media player market in July 2008 and its iPhone possessing a 23% market share of the global smartphone market in early 2012 (Apple Inc., 2008; “IDC: Smartphone Market Share 2014, 2013, 2012, and 2011,” 2014). These devices not only sold with headphones, but have generated a huge market of headphone and speaker accessories designed and manufactured by various companies. Apple therefore has a strong influence on the sale of audio related equipment, including speakers and headphones.

Apple sells their Apple branded earbuds or 'earpods' as an included accessory with each iPhone and iPod sale, while other products like MacBooks and iPads do not come with headphones (Apple Inc., 2015; Apple Live Chat Support, 2014). Some of these headphones, like the ones sold alongside the iPhone, include a small built-in microphone and buttons (Apple Inc., 2015). Third generation earbuds sold for 29.00 USD when purchased separately from the online Apple Store in 2010, though they were included alongside many Apple iPod and iPhone products (Apple Inc., 2010). Earpods, which were introduced in 2012 and can arguably be referred to as 'fourth generation' Apple headphones since they are the continuation of the company's earbud line, are generally included with the

purchase of higher-priced Apple iPods and all iPhones today (Apple Inc., 2015). They can also be purchased separately and are listed for 29.00 USD on the official online Apple Store (Apple Inc., 2015). While these 'earpods' look significantly different from the outside, inside their construction is quite similar to both Apple's previous headphone model and standard earbuds (iFixit, 2013).

In order to assess the impact of Apple's free headphones on neodymium use, market analysis and lab methods were used. As a set of headphones is included with each iPhone and iPod sale in all of the company's world markets, it can be assumed for this research that the sum of the sales of iPhones and iPods in a given year is less than or equal to the sum of Apple's earbud and earpod sales for that year (Apple Live Chat Support, 2014). Apple reports their annual sales figures for these devices to the United States Securities and Exchange Commission each year, though this report does not mention the company's sales of headphones specifically (Apple Inc., 2011, 2013, 2014). Sales of Apple headphones sold as separate accessories or through other means are therefore excluded here.

Since Apple's 2009 sales of iPhones and iPods totaled 20.731 million units and 54.132 million units respectively, this sums to 74.863 million devices sold with earbuds during that year. Sales of these two devices during 2010 totaled 90.301 million units, and 2011 saw 114.913 million units sold. In 2012, iPhone sales exploded to 125.046 million units sold while iPod sales declined to 35.165 million units, revealing the growing significance of the smartphone market in driving headphone manufacturing. 160.211 million headphones were sold alongside these

devices that year. Further growth in headphones sold was seen in 2013 as 150.257 million iPhones sold with 26.379 million iPods. This totals 176.636 million earbuds and earpods sold during 2013. 2014 saw 169.219 million and 14.377 million headphones sold alongside iPhones and iPods respectively. During these five years just over 800 million Apple headphones were sold as included accessories with Apple iPhones and iPods of all models, all containing a neodymium magnet in each speaker.

To quantify the mass of neodymium magnets sold by Apple through their iPhone and iPods sales, the mass inside a single pair was found. A pair of standard third generation Apple earbuds was disassembled to extract and weigh the magnet found inside. For this, the Mettler Toledo PL83-S balance was used, each measurement was conducted five times, and the average of the results was taken. Before disassembly, the weight of the earbuds with their wires and microphone was 11.29 grams. The individual speaker assemblies inside their casings weighed about 2.60 grams each. The magnet after it was removed from the left speaker was 0.405 grams, though it appeared to be composed of two metal disks: a smaller disk which was identified to be a neodymium magnet, and a slightly larger disk. The magnet extracted from the left earbud is shown in Figure 5.3 alongside the undamaged, accompanying right ear assembly cut from its wire. Attempts to separate these two metal components were not successful, so the volumes and densities were used to calculate the mass of each part. Of interest to note here is the clear stripping of a portion of the metallic coating that protects the



Figure 5.3: Apple earbud magnet next to an Apple earbud

Note: The magnet is comprised of two metal disks. Here the upper, smaller disk is the neodymium magnet.

$$\begin{aligned}
 \text{Density}_{\text{NdFeB magnet (sintered)}} &= 7.5 \text{ g/cm}^3 \\
 \text{Mass}_{\text{total}} &= 0.405 \text{ g} \\
 \text{Diameter}_{\text{larger disk}} &= 0.66 \text{ cm} \\
 \text{Thickness}_{\text{larger disk}} &= 0.05 \text{ cm} \\
 \text{Diameter}_{\text{smaller disk}} &= 0.59 \text{ cm} \\
 \text{Thickness}_{\text{smaller disk}} &= 0.11 \text{ cm} \\
 V &= \pi(d/2)^2 \times h \\
 \rho &= \frac{m}{V} \quad m = \rho \times V \\
 m_{\text{larger disk}} &= m_{\text{total}} - m_{\text{smaller disk}} \\
 V_{\text{smaller disk}} &= \pi(0.59 \text{ cm}/2) \times 0.11 \text{ cm} = 0.0301 \text{ cm}^3 \\
 m_{\text{smaller disk}} &= 7.5 \text{ g/cm}^3 \times 0.0301 \text{ cm}^3 = \mathbf{0.226 \text{ g}} \\
 V_{\text{larger disk}} &= \pi(0.66 \text{ cm}/2) \times 0.06 \text{ cm} = 0.0171 \text{ cm}^3 \\
 m_{\text{larger disk}} &= 0.405 \text{ g} - 0.226 \text{ g} = 0.179 \text{ g} \\
 \rho_{\text{larger disk}} &= \frac{0.179 \text{ g}}{0.0171 \text{ cm}^3} = \mathbf{10.5 \text{ g/cm}^3}
 \end{aligned}$$

Figure 5.4: Calculations for finding the mass of neodymium magnet in one speaker of Apple earbud and density of connecting material

neodymium magnet. While this does not seriously affect the measured mass of the magnet, it does hint that the upper disk is indeed a neodymium magnet. The density of a sintered neodymium magnet is about 7.5 grams per cubic centimeter (Magnaworks Technology Inc., n.d.; NeoMag Co., Ltd., 2013). From this it was deduced that the mass of the sintered neodymium magnet contributed between 0.205 and 0.226 grams to the weight of the combined disks, amounting to between 0.41 and 0.45 grams of sintered magnet per set of headphones. From here, it will be assumed that 0.45 grams of sintered neodymium magnets are used in each pair of headphones. Calculations are shown in Figure 5.4.

Since Apple's newer earpods are similar in construction, it is assumed that the mass of the magnets inside them are the same as Apple's earbuds. This assumption is supported in part by an article published by the website iFixit. This article details a disassembly of these new earbuds and provides a picture comparing the construction of the first generation and third generation Apple earbuds to the fourth generation 'earpods' (iFixit, 2013). This image is shown in Figure 5.5 with the addition of black bars to highlight the approximate diameter of the magnets in the image. It is evident from the photo that the size of the magnet in these new earpods is similar to the size of one found in the previous generation.

From this, the neodymium demand of Apple's complimentary headphones can be quantified by simply multiplying the mass of the magnet in each set of headphones with the iPod and iPhone sales each year. The results are shown in Figure 5.6. While Apple was responsible for 34 metric tons of neodymium

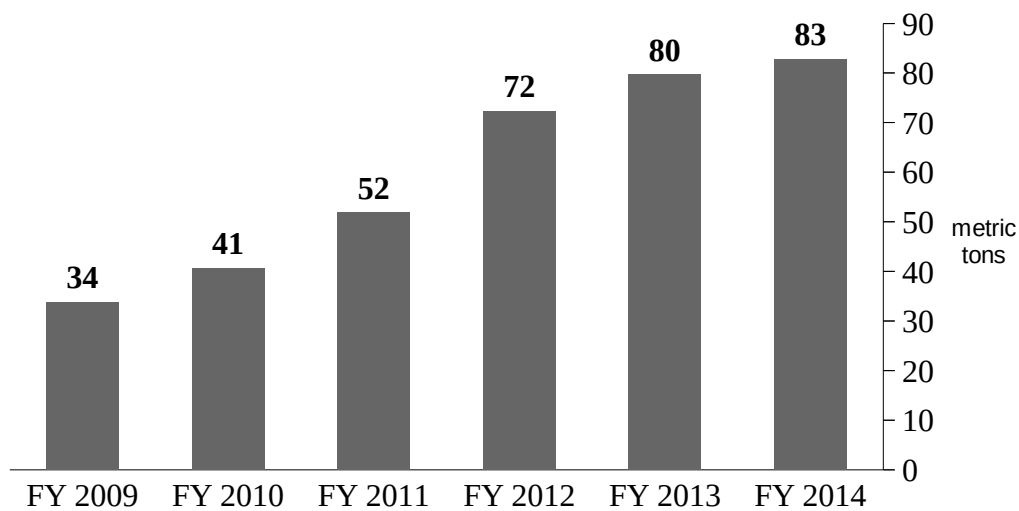
magnet distribution through headphones during FY 2009, it distributed nearly 83 tons in FY 2014. The impact of smartphone sales on Apple headphone distribution is clear since iPod sales declined each year during this period. Overall, during this five-year period, Apple sold 361 metric tons of neodymium magnets through their complimentary headphones.



*Figure 5.5: Comparison of internal design of different generations of Apple headphones with approximate magnet diameter indicated by black line. From top to bottom: third generation, first generation, fourth generation ('earpods').*

*Note:* The relative size of the magnet contained (seen as the inner disk) does not appear to change significantly between the third and fourth generations.

*Image source:* iFixit. (2013, August 6). *Apple EarPods Teardown*. Retrieved July 10, 2015, from <https://www.ifixit.com/Teardown/Apple+EarPods+Teardown/10501>



*Figure 5.6: Metric Tons of Neodymium Magnets Sold Alongside Apple iPods and iPhones During Company Fiscal Years*

#### 5.6.2. Panasonic Case Study

Panasonic manufactures a wide variety of electronics for consumers and businesses. Sales of headphones, and even audio-visual equipment are only a small portion of this company's portfolio. As such, information on the sale of headphone units is unavailable. Still, as this is a company whose products are sold at retail and online stores worldwide, the sale of headphones are likely substantial.

A set of Panasonic RP-HV154 earbuds was selected here for disassembly. This specific model of earbuds was purchased in Germany and is available on the German Panasonic online shop for 6.99 EUR or approximately 8.00 USD as of March 2015 (Panasonic Deutschland, 2015). They are visually similar in construction to the Apple headphones disassembled earlier, and their specifications



*Figure 5.7:* Panasonic RP-HV154 earbud magnet next to earbud

on the website specifically state that they utilize 'Hochwertiger Neodym-Magnet,' or high quality neodymium magnets (Panasonic Deutschland, 2015). Since sales figures for these headphones are not publicly available, a mass flow cannot be calculated.

Disassembly revealed that an earbud from this set of headphones indeed contained a neodymium magnet as advertised. This magnet, like the one found in the Apple earbud, was paired with a metal disk inside the speaker housing. This disk was not bonded to the magnet however, allowing for the mass of the magnet to be more simply found. The magnet also had a hole through it. This magnet is pictured in Figure 5.7 next to the remaining earbud.

The magnet properties, measured with the Sartorius BP 210 S scale and E-Top micrometer are as follows. The mass of the magnet was found to be 0.329 grams after averaging the five measurements. This puts the mass of the magnets found in one set of these earbuds at 0.658 grams, more than the mass of the magnets in the Apple headphones. The diameter of the disk was measured at 6.5 mm and its thickness measured 1.5 mm. The diameter of the hole in the center of the disk was measured to be 2.2 mm. This puts the volume of the magnet at  $0.045 \text{ cm}^3$ , which makes the density  $7.31 \text{ g/cm}^3$ . This is very close to the  $7.5 \text{ g/cm}^3$  density of neodymium magnets (Magnaworks Technology Inc., n.d.; NeoMag Co., Ltd., 2013).

#### 5.6.3. Hama Case Study

Hama is a multimedia accessories company based in Germany. Its products are sold worldwide. While Hama sells headphones in a wide range of prices and qualities, a set of budget earbuds was selected to discover if there is indeed a lower limit to the price of headphones containing neodymium magnets. The headphones here are of model HK-249 purchased at German retail store for 2.49 EUR or about 3.00 USD. The packaging and documentation for the headphones state nothing about the magnet type used.

It should be noted that, in a listening test comparing the Panasonic and Hama headphones, there was a significant volume difference. Sound quality aside, the volume on a portable media player when set using the Panasonic earbuds dropped noticeably when switching to the Hama headphones. The opposite effect was



*Figure 5.8:* Hama HK-249 earbud magnet next to earbud

*Note:* This is a ferrous magnet unlike the neodymium magnets found in the previous earbuds

observed when the procedure was done starting with the Hama headphones and switching to the Panasonic headphones.

When disassembled, a Hama earbud revealed what appeared to be a ferrous magnet instead of a neodymium magnet. This type of magnet, being significantly weaker than a neodymium magnet, is likely at least part of the reason this set of headphones required more power to produce the same volume. Other than this difference, the construction of the speaker was similar to that of the Apple and Panasonic headphones. The magnet next to the remaining earbud is pictured in Figure 5.8.

The magnet was slightly bigger, but lighter than the Panasonic magnet. It weighed 0.287 grams, had a diameter of 6.3 mm, and a width of 2.0 mm. There

are thus 0.574 grams of magnet in one set of these headphones. This gave it a volume of  $0.063 \text{ cm}^3$ , and a density of  $4.52 \text{ g/cm}^3$ . This confirms that the magnet is ferrite, and not neodymium. This discovery proves that a price point exists at which neodymium is no longer cost effective to include in a set of headphones. An informal disassembly of a pair of free airline headphones before this research was conducted also revealed ferrous magnets instead of neodymium.

#### 5.6.4. JVC Case Study

Another giant in the global audio industry is JVC, also known as Victor Company of Japan, Ltd. Again, useful sales data is not available for JVC, but again, global sales of headphones each year is probably sizable. For this analysis, a pair of JVC XX Series inner-ear headphones with model number HA-FR201 were used.

As with Apple's earbuds the Mettler Toledo PL83-S balance was used, with each measurement being conducted five times and the average of the results used like always. The earbuds with wires and microphone were measured to weigh 15.13 grams, and the earbuds themselves weighed about 1.76 grams each after they were severed from their wires. The magnet, once removed from the left earbud, proved much smaller than the one used by Apple, weighing in at 0.088 grams. Once again though, it was composed of two disks of apparently different material. The extracted left earbud magnet is pictured in Figure 5.9 alongside the intact right earbud. Judging by the appearance of the disks, it was determined that the larger one was a sintered neodymium magnet. Again, using the equations

presented in Figure 5.4, the volumes of each of the disks were used to find their respective masses, and to determine the density of the unknown disk. It was determined that the neodymium magnet disk had a mass of between 0.051 and 0.057 grams depending upon the measurement used for its thickness: 0.09 or 0.1 cm. This amounts to between 0.102 and 0.113 grams of neodymium magnet in each set of JVC model HA-FR201 headphones. For future discussion, it will be assumed that the magnet weighs 0.054 grams and there is thus 0.108 grams of neodymium magnet in these headphones.



*Figure 5.9: JVC XX Series Model HA-FR201 earbud magnet alongside earbud*

*Note:* The magnet is comprised of two metal disks. Here the right, larger disk is the neodymium magnet.

As sales data was not available for JVC's products, the number of this particular model of headphones sold cannot be determined, nor can their total headphone sales. This does however make clear the fact that the size of magnets used in headphones can vary greatly, with in-ear headphones likely having smaller

speakers than earbuds. The JVC magnets were about one fourth the size of the Apple magnets.

#### 5.6.5. Sony Case Study

Yet another major player in the audio industry is Sony, though their wide range of products means that headphone sales are likely a minor fraction of their operations. Two Sony headphones were selected to represent supra-aural headphones, which can have larger speakers than earbuds or in-ear types, in this research. A set of Sony MDR-24 and Sony MDR-A110 were chosen. They both consist of a headband and foam-padded speakers and are roughly the same size and style.

The models selected are assumed to be sold during to different periods of time, though it must be mentioned little documentation could be found to verify their production and sales dates. They were likely purchased in the US and fall under the category of budget headphones. The MDR-A110 headphones are listed on Sony's Asia Pacific product page under 'Archived Headphones,' while the MDR-24 headphones cannot be located on any of the company's websites (Sony Electronics Asia Pacific, 2015). Both are no longer sold by Sony, but this listing of one and not the other on the manufacturer website would indicate that the production and sale of the MDR-24 headphones predate the archive of products the company actively maintains and publishes online. Furthermore, a website called Radiomuseum has a listing of the MDR-24 headphones, including a picture of headphones identical to those used here, which states they were sold, or

possibly first sold, in 1992 (Selyem-Tóth, n.d.). The accuracy of this listing could not be verified however. Still, absence of a listing for the MDR-24 headphones on the manufacturer's website and report that they were sold around 1992, combined with the fact that the MDR-A110 headphones are recorded on the website provide evidence that the MDR-24 significantly predates the MDR-A110.

Upon disassembly, the Sony MDR-24 and MDR-A110 speaker housings bore striking similarities in design. It would appear that the same molds and casts were used for the metal and plastic portions of the speaker housings, with the largest differences being how they were mounted onto the headband styled on the outside facing parts. The similarities in the speaker housings can be seen in Figure 5.10.

After the magnets were removed, it was discovered that although these two different models of headphones shared many features in speaker housing design, they did not have the same magnets. A ferrous magnet was found in the MDR-24 speaker while a neodymium magnet was found in the MDR-A110 speaker. Furthermore, while these magnets shared nearly identical outer and inner diameters and each sat behind an identical looking metal disk in the speaker housing, they had very different widths.

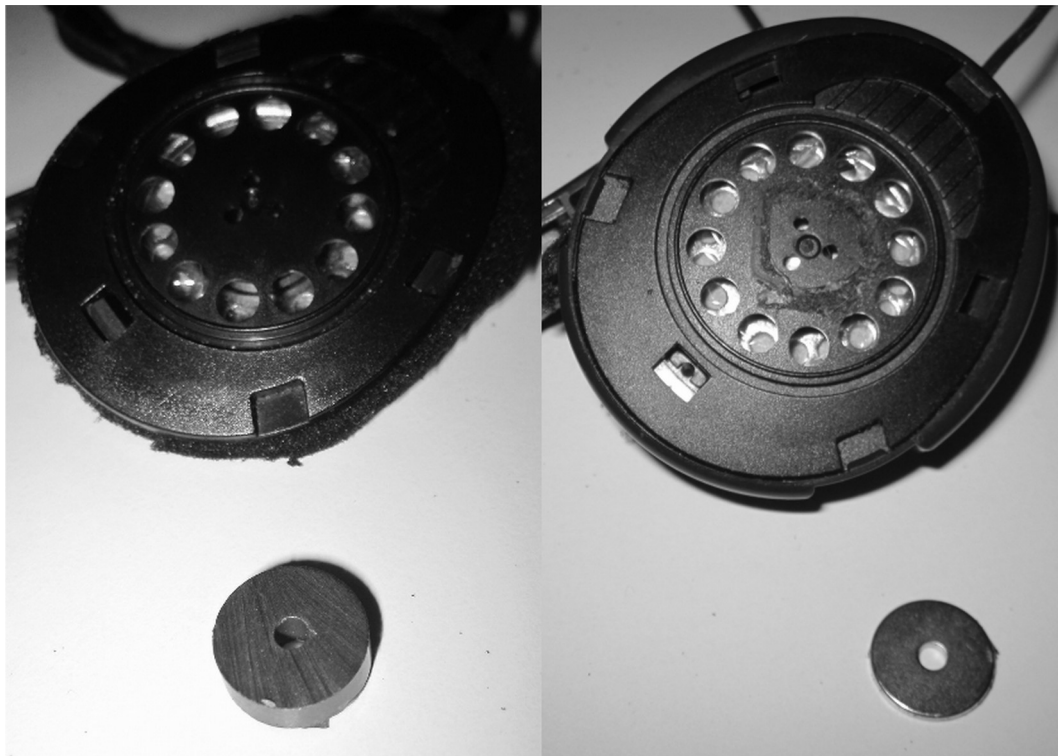
The MDR-24 ferrous magnet, pictured in Figure 5.11 on the left next to the remaining non-disassembled speaker, weighed 2.464 grams. There is thus 4.928 grams of ferrous magnet in this set of headphones. It had a diameter of 13.0 mm and had a hole through its center with a diameter of 2.7 mm. Its width was measured to be 4.1 mm. This gives it a volume of  $0.523 \text{ cm}^3$  and a density of 4.71



*Figure 5.10:* Above: Speaker housing of two Sony supra-aural headphones without foam padding. MDR-24 right and MDR-A110 left. Below: Same speaker housings showing inside magnet mounts.

$\text{g/cm}^3$ . This density is very close to the density of the ferrous magnet found in the Hama earbuds.

The MDR-A110 neodymium magnet, pictured in Figure 5.11 on the right next to its own remaining non-disassembled speaker, weighed 1.206 grams. There is thus 2.412 grams of ferrous magnet in this set of headphones. It had a diameter of 13.1 mm and a hole through its center with a diameter of 2.7 mm, quite similar to



*Figure 5.11:* Left: MDR-24 speaker and ferrous magnet. Right: MDR-A110 speaker and neodymium magnet.

the MDR-24 ferrous magnet. Its width however, was measured at 1.2 mm. This puts this magnet's volume at  $0.157 \text{ cm}^3$  and its density at  $7.66 \text{ g/cm}^3$ . Again, the density matches the expected density of a neodymium magnet.

### 5.6.6. Case Study Summary

A summary of the findings of these case studies is presented in Table 5.3 below.

Table 5.3: Summary of Case Study Headphones and Magnets					
Manufacturer	Model	Headphone Type	Magnet Type	Magnet Mass (g)	Mass of Magnets Total (g)
JVC	HA-FR201	In-Ear	Neodymium	0.054	0.108
Apple	Third Generation	Earbud	Neodymium	0.226	0.452
Panasonic	RP-HV154	Earbud	Neodymium	0.329	0.658
Sony	MDR-A110	Supra-Aural	Neodymium	1.206	2.412
Sony	MDR-24	Supra-Aural	Ferrous	2.464	4.928
Hama	HK-249	Earbud	Ferrous	0.287	0.574

Table 5.3: Summary of case study headphone disassembly and magnet removal results showing magnet data.

Some interesting findings are as follows. The mass of the neodymium magnets clearly correlate with the size of the headphone and/or headphone type. This also seems to go for headphones with ferrous magnets. All magnets were found paired with a non-magnetic metal disk placed between it and the diaphragm coil except the magnet found in the Hama earbud. The inclusion of this metal disk does not seem to be dependent on magnet type. The density of a ferrous magnet seems to be  $4.6 \text{ g/cm}^3$  based on the findings from the two ferrous magnets here. Also, the densities of the neodymium magnets found in the Panasonic and Sony MDR-

A110 headphones are 7.31 and 7.66 g/cm<sup>3</sup> respectively. This is around the value of 7.5 g/cm<sup>3</sup> reported by Magnaworks Technology Inc. and NeoMag Co., and thus adds credibility to the fact that the magnets found in the Apple and JVC headphones are neodymium and supports the use of of this figure in calculations relating to them (Magnaworks Technology Inc., n.d.; NeoMag Co., Ltd., 2013).

## **6. Discussion**

The quantitative findings from literature and the case studies presented can answer, or at least inform discussion about, the questions posed earlier. The size of headphone market and neodymium's important place in it are clear. The global market for headphones is large, as is the mass of magnets found in these headphones. Uncertainties exist in what exactly the market size is however. Neodymium magnets are found in most of these headphones and their size does depend on headphone type. Alternative magnets are sometimes used though. Finally the impacts of these magnets are quantifiable, and measures can be taken to reduce their impacts.

### **6.1. Global Market Estimates**

The worldwide headphone market is clearly sizable and neodymium magnets are likely the dominant magnet type used. 284 million units were expected to be sold in 2013. Apple alone sold nearly 1 billion headphones as included accessories alongside their iPhones and iPods worldwide over the course of six years. While not all headphones sold contain neodymium magnets, the price point at which these magnets are used in headphones is extremely low. This price point

is low enough for neodymium magnet containing headphones to be included as complimentary accessories to some products and for headphones sold as low as the \$8 USD mark to contain these same magnets. This likely means that the vast majority of the headphone market utilizes neodymium magnets. This is especially the case since utilizing neodymium magnets in headphones is also considered a notable selling point.

Six headphones were analyzed and found to have a range of magnet sizes and utilize mostly neodymium magnets. Masses ranged from 0.108 grams in a set to 2.412 grams. Two headphones utilized ferrite magnets. One likely used this alternative magnet since it was produced long before the other headphones were. The other likely utilized ferrite magnets due to cost constraints.

Much more detailed information about the headphone market would be needed to accurately know the mass of neodymium magnets they contain. Such detailed market data is not publicly available, but a rough estimation can be done to know on what scale this value would be. It was stated before that approximately 70% of UK headphone sales were either in-ear or earbud designs. If we were to assume that this is the case for the global market and draw from the case studies that contain neodymium magnets specifically, a very rough value emerges. Assume the three headphone case studies presented that contain neodymium magnets represent 70% of the 2013 284 million headphones sold, and that the single neodymium containing supra-aural headphone represents the remaining 30% of the market. Averaging the mass of the magnets in the in-ear and earbud categories

gives us a value of 0.406 grams of neodymium magnets in each set for 70% of the market while the remaining 30% contains magnets of 2.412 grams per set. The weighted average magnet mass for each set of headphones on the market would then be about 1.01 grams. The mass of the magnets sold through headphones in 2013 would then be about 286 tons. Of 45,000 tons of sintered neodymium magnets produced in 2010, this would be about 0.64%. It can be assumed that these headphones are not generally collected for recycling and, if they are, the magnets they contain are not being recovered for magnet recycling. If disposal of headphones is assumed to be roughly equal to sales, this means that about 300 tons of neodymium magnets are being effectively removed from material streams at the end of their useful lives each year.

There is one observation about the headphone market masses of neodymium magnets that could indicate a significant miscalculation in the total market estimation presented above. While the headphone market is stated to amount to 284 million headphones in 2013, Apple seems to have sold 177 million headphones around that year. Though the dates of measurement do not directly correlate, since Apple's fiscal year does not start in January, this would indicate that Apple alone was responsible for over 60% of the headphone market that year. While Apple devices are certainly popular and their headphones are thus found everywhere, this seems to be a disproportionately large percentage. This could be the result of the 284 million headphones reported by Futuresource Consulting only including individually sold or retailed headphones (CEATEC JAPAN, 2013).

If this is the case, headphones sold alongside products as included accessories, like Apple's, and headphones sold in bulk to companies for use, such as airlines, may not be included. If this is the case, the headphone market would certainly be much larger and may even be reaching billions of units each year. Sources confirming this could not be found however, so for the sake of further discussion, the 284 million units reported by Futuresource Consulting will be assumed correct (CEATEC JAPAN, 2013).

## 6.2. Magnets and Headphone Categories

A correlation does exist between magnet properties and the type of headphones they are found in. Headphones that produce louder volumes and utilize larger speakers use larger magnets. The in-ear headphones presented contained notably smaller magnets than the earbuds, which in turn contained notably smaller magnets than the supra-aural headphones. The volume of sound required from each of these devices corresponds to this magnet size. A comparison between the Apple and Panasonic and Hamas earbuds reveals a potential, approximate lowerbound price-point for the use of neodymium magnets. The JVC, Apple, and neodymium containing Sony headphones provide a comparison of volume and magnet size.

The Apple and Panasonic earbuds together represent a very common type of headphone and construction for this type. Since the Panasonic set shows that the price point for headphones containing neodymium magnets is quite low, somewhere around 8 USD, it seems safe to assume that the majority of

headphones in the earbud category priced between 8 USD and 50 or 100 USD contain such a magnet of about this size. The Hama headphones however, sold at around 3.00 USD contained a ferrite magnet. The pricepoint for the use of neodymium magnets in headphones is then quite low: somewhere between 3 and 8 USD. Most of the headphone market probably exists above this price-point, further emphasizing that neodymium magnets are likely used in the vast majority of headphones.

The difference in magnet sizes between Apple's, JVC's, and Sony's headphones is not all that surprising. These three headphones belong to three different categories: in-ear, earbud, and supra-aural headphones respectively. As earbuds sit in the ear and direct sound in the direction of the user's ear canals, some sound is lost to the environment. In contrast, in-ear headphones are placed inside the user's ear canal and, through a rubber fitting, can form a seal. This directs nearly all of the sound produced by the speaker within the headphone directly into the user's ear canal and little sound is lost. The earbud must therefore work harder and produce more sound than the earbud. The supra-aural headphones, like the earbuds, direct sound toward the ear, but are not sealed from the environment. Furthermore, they contain much larger speakers and sit on, rather than in the ear. More sound can be lost with this design, meaning that a larger speaker and larger corresponding magnet are needed.

### 6.3.Impacts and Potentials for Impact Reduction

To quantify the impacts of these neodymium magnets, a comparison must be made between specific environmental and social measurements and a unit of neodymium magnet. Utilizing the results presented in Sprecher et al. and our previous rough estimate of 286 tons of neodymium magnets for the amount of magnets used in headphones in 2013, some impact estimates can be calculated. Results comparing the total impact of these 286 tons of magnets via different production methods are shown in Table 6.1. High-tech, baseline, and low-tech primary magnet production method impacts are compared to the impacts of hypothetical magnets recovered using hydrogen decrepitation and separated from source materials by hand or through shredding. Notable figures include the climate change potential, ionizing radiation, and human toxicity.

The headphone industry in 2013 contributed significantly toward climate change through the use of magnets. Between 6,000 and 11,000 tons of CO<sub>2</sub>-Eq were emitted, depending on how efficient and responsible mining and manufacturing operations were. This is the equivalent of between 1,300 and 2,300 average passenger vehicles in the United States on the road that year, assuming the previously stated 4.75 tons per passenger vehicle per year. While significant, this is actually a surprisingly small amount. Still, if recycling methods could be utilized this could be significantly reduced, though it must be noted that collection programs for headphones would likely significantly increase this impact through the need for extra transportation to implement such a program worldwide.

It could piggyback on other emerging electronics recycling programs to reduce this increase though.

<b>Table 6.1: LCA Scenarios for Production of 286 tons of Primary and Recycled NdFeB Magnet Material</b>						
Impact Name	Units	High-tech	Baseline	Low-tech	Recycled by hand picking	Recycled by shredding
Eutrophication Potential	ton NO <sub>x</sub> -Eq	40	54	86	2.2	9.2
Acidification Potential	tons SO <sub>2</sub> -Eq	110	130	190	7.7	57
Photochemical Oxidation	tons ethylene-Eq	4.0	4.9	7.4	0.31	2.3
Climate Change	tons CO <sub>2</sub> -Eq	6,000	7,700	11,000	940	2,800
Ionizing Radiation	DALYs	0.012	0.015	0.021	0.0057	0.023
Freshwater Aquatic Ecotoxicity	tons 1,4-DCB-Eq	3,700	4,000	5,700	1,500	3,100
Stratosphere Ozone Depletion	kg CFC-11-Eq	0.57	0.74	1.1	0.027	0.29
Human Toxicity	tons 1,4-DCB-Eq	12,000	43,000	130,000	1,000	8,000

*Table 6.1: Scaling of Sprecher et al. LCA findings for 286 tons of NdFeB magnets estimated used by the headphone industry in 2013*

Ionizing radiation attributed to the magnets used in headphones globally is actually quite small. While the REE mining industry is certainly sizable and represents a radiation concern through its waste, the headphone industry is only a small fraction of this. At most, 0.021 DALYs could be attributed to the use of neodymium magnets in the headphone industry. The use of shredding for

recycling could actually increase this radiation impact potential, though only by a minute amount.

The headphone industry does represent a significant impact on human toxicity. This depends greatly on how well managed mining operations are. Recycling has the potential here to significantly reduce this potential harm though. Depending on how operations currently are and how recycling operations could be handled, this impact could be reduced by a factor of nearly 100.

The energy use for the production of NdFeB magnets for headphones amounts to 94 terajoules of energy or about 26 gigawatt-hours. This is the equivalent of a 71 MW power plant operating constantly for a year. Stated differently, a 70 MW power plant would be necessary to continuously provide the energy needed to keep up with magnet production for headphones alone. This could be the equivalent of 35 2-MW wind turbines if they had winds consistent able to produce this capacity every hour of the day all year. These 35 wind turbines might use around 17 tons of neodymium magnets themselves, assuming 500kg of magnets each.

Apple provides a case study for impact assessment, since sales figures were available. Apple's sales of complimentary headphones alongside their iPods and iPhones are particularly interesting because it illustrates the material impact of a relatively cheap marketing practice. Over six years, 360 metric tons of neodymium magnets were sold in the form of these free accessories, with 83 metric tons alone being sold during the 2014 Apple fiscal year. Taking the 2014

fiscal year, 83 tons of NdFeB magnets necessitated the extraction of 3,500 tons of ore, assuming a rare earth ore concentration of 4.1%. Furthermore, the equivalent of about 7.5 GWh of energy were needed to extract this ore and eventually produce these magnets. This overall had an impact of about 2,200 tons of CO<sub>2</sub> equivalent emissions toward climate change. While these impacts are relatively small when compared to many other industries, it is certainly sizable. Surely, these headphones are used a marketing strategy, but this practice ensures a large number of headphones make it to consumers who do not intend to use them, or do not value them. To be sold as an included accessory, whether the consumer values them or not, the value of the product and the materials contained within must be inconsequential compared with the product they are sold with.

#### 6.3.1. Envisioning a Viable Recycling Process

While there are various recycling processes that could be used to recycle the neodymium magnets found in headphones, one stands out. A process utilizing hydrogen decrepitation can be envisioned that would potentially work well with scrap headphones. Such a process would work as follows.

Scrap headphones, once collected, could be de-wired and the magnet containing speakers and housings placed in a shredder. Since most headphones are comprised of a metal or plastic housing, foam, and a few other simple plastic and metal parts, these lightly-crushed parts, except for those attracted to the magnets like iron, could be easily separated from the magnets and magnetic parts. The remaining magnets and, what is likely mostly iron or steel, are further lightly

crushed to expose the NdFeB material sealed under the protective coatings. The process of hydrogen decrepitation could then be used to demagnetize the magnets and turn them into a powder that is easily separated from the remaining metallic parts and coatings with a sieve. The collected powder could then be reprocessed into what might be lower-quality, but still useful magnets due to the likely nonuniform compositions of the source magnets. Such a process would be possible because of the somewhat standard design and material makeup of headphones, as well as the larger ratio of magnet to other components, especially in earbuds and in-ear headphones. It remains to be seen though, if such a process would be technically feasible.

### 6.3.2. Impact Reduction through Switching Magnets

To assess the potential for a switch from neodymium magnets to ferrite magnets in headphones, a comprehensive study of the impacts of the magnets and the impacts of consequential changes to the headphone design must be done. A full life cycle impact assessment must be done. Unfortunately, while the impacts of neodymium magnets exist in literature, the impacts of ferrite magnets have not been explicitly published. Some potential results can be discussed however. Julio Navarro, Fu Zhao, and John Sutherland published a comparative life cycle assessment study comparing motors utilizing NdFeB magnets and ferrite magnets in 2014. In their study they note that while ferrite magnets have lower impacts than NdFeB magnets, except for the categories of smog and ozone depletion potential, the changes made to the design of a motor to compensate for the lower

power ferrite magnets negates these effects (Navarro et al., 2014). The ferrite motor must have a larger mass of magnetic material and larger amounts of other materials such as steel and copper to have the same capabilities as a NdFeB motor (Navarro et al., 2014).

This is not a direct analogy to headphones, but highlights some concerns. Ferrite magnets, having weaker magnetic fields than NdFeB magnets, would likely require a headphone to have either more copper in the speaker coil, more electricity running through the wire, or both to produce the same audible volume as a NdFeB magnet based headphone. Indeed, this appeared to be the case in an informal audio comparison of the Hama and Panasonic headphones that used ferrite and NdFeB magnets respectively. When used with a single device playing the same audio track, the volume on the device had to be significantly increased to make the Hama headphones produce the same volume as the Panasonic headphones. While this could be evidence of the differing magnets, this could also have been the result of several other factors including the quality of the cheap ferrite magnet used in the Hama headphones, or perhaps poor design that does not optimize the electricity to sound ratio of the Hama headphones. Perhaps the missing metal disk found in all but the Hama headphones between the magnet and the speaker diaphragm could be the critical factor for this. Still, this could be evidence that, if ferrite magnets were to replace NdFeB magnets in headphones directly, there could be design challenges that might make impact reductions through use of the lower impact magnets null.

## 7. Conclusions

This report aimed to qualify and quantify the mass stream of neodymium through the low to mid-end headphone market and its environmental impacts. Literature and case studies were used to introduce the issue of waste electronics and material flows, the audio industry's role in the flows of neodymium specifically, and to answer key questions.

### 7.1. Summary

The size of the headphone market was found to be on the scale of several hundred million headphones each year. Specifically, around 284 million headphones were found to be sold in 2013. One potentially significant discrepancy was noted here however, likely caused by differing interpretations of what the headphone market specifically includes. Apple alone was found to be responsible for over 100 million headphones each year between 2011 and 2014, with 2014 numbers totaling 180 million. It was determined that the 284 million value likely did not include headphones not explicitly sold via retail outlets. The true size of the headphone market is thus likely far greater than 300 million units per year.

Most headphones on the market today were determined to use neodymium magnets, though there is still a lower-bound price point at which ferrite magnets are used. Furthermore, neodymium magnets are a relatively recent addition to this market, claiming the majority of headphones sometime in the last three decades.

The mass of the magnets found in headphones correlates with the type of headphone. In-ear style headphones likely use smaller magnets than earbuds, which in turn use smaller magnets than supra-aural headphones. This is due to the amount of sound that must be produced to reach the listener's ears. All categories of headphones discussed utilize neodymium magnets. The average mass of magnets found in headphones is about 1.01 grams.

The mass of neodymium magnets moving through the headphone market, and likely disposed of each year, was found to be around 286 tons. The mining and production of these magnets from virgin materials required around 26 gigawatt-hours, emitted 6,000 and 11,000 tons of CO<sub>2</sub>-Eq, and had notable impacts on human health. Radiation concerns, though highlighted in REE mining literature, were found to be minimal, at least for the part of the magnet production for the headphone industry. Again, these values could be significantly larger due to the discrepancy noted earlier.

There do exist recycling technologies for neodymium magnets, and some have even been trialed on a small scale. One specific reclamation method, hydrogen decrepitation, was found to be promising if applied to headphones. This remains to be proven practically however. Still, environmental impacts could potentially be significantly reduced using a recycling method. An alternative way to reduce impacts could be to design headphones that replace neodymium magnets with ferrite magnets. Quantitative proof of this reduction could not be calculated however, and there would certainly be tradeoffs.

## 7.2.Future Work

This research can serve as the groundwork for future research in neodymium and the audio industry. Future research may attempt to remedy the discrepancy in headphone market size discussed here and calculate more definitive results. More detailed analysis of the recycling potential of magnets found in headphones or the audio industry in general could be done, eventually leading to detailing a working system if potentials are viable. The economic impacts of this flow of neodymium magnets could be analyzed, as well as the economic side of recycling feasibility. Finally, a detailed analysis of the impacts and repercussions of an industry-wide switch from neodymium magnets to alternatives, such as ferrite magnets, would lead the groundwork for discussion in this area.

## 7.3.Concluding Statements

Neodymium magnets are indeed entrenched in headphones worldwide and make up a component of new WEEE streams. While their masses are small and environmental and health impacts are relatively minute in comparison to worldwide magnet production and rare earths mining, they are notable and offer potential for change. Headphones represent a flow of neodymium magnets, and thus rare earths, into waste streams worldwide, effectively dispersing this valuable material in such a way that it cannot be recovered. Recycling, though not a near-term solution, could offer significant savings of raw materials and reduction in environmental and health impacts through this flow in headphones. Other

solutions might include a switch in magnet materials, though this may be difficult in a market that has become adapted to using these neodymium magnets.

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