

A Strategic View for Rare Earths Production, in a Competitive and Sustainable form

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Abstract

The demand for rare earths (RE) has been intensified by their large use, especially in high technology sectors. Supply difficulties have forced RE users to seek alternative sources and invest in the development of recycling technologies and options of reuse for these elements. This article seeks to reveal the trends and ongoing changes in national and global prospects of RE. Additionally, it aims to analyze scientific collaboration networks in the area of industrial solid waste (ISW) and waste electrical and electronic equipment (WEEE) exploitation in Brazil, examining both researchers and institutions with greater representation in the field. For this purpose, social network analysis methods were used to build and analyze co-authorship networks based on scientific publications retrieved from the *Web of Science* (WoS) database. The results showed that the Brazilian collaboration network of ISW research was extremely fragmented and contained 105 different groups, which were not connected to each other. The institutional network of ISW research was composed of 125 institutions, 75.2% of them from Brazil. The Brazilian collaboration network of research in WEEE was small (37 researchers), but fragmented: researchers were divided into eight different groups that do not connect to each other. The institutional network of research in WEEE was composed by 12 institutions, nine of them from Brazil. Therefore, this article presents a network collaboration model to bring together actors involved in the management of waste electrical and electronic equipment (WEEE), emphasizing the potential for recovery of RE from these wastes, with the purpose of developing products and services.

Keywords: industrial waste, network, rare earths, recycling, waste electrical and electronic equipment

1. Introduction

The fastest growing industrial segment, in terms of waste generation and negative environmental impact, is the electrical and electronic equipment (EEE) sector (Unep, 2012; Leal et al., 2013). High consumption and low life expectancy of EEE are accompanied by small recycling rates and continuously decreasing size (Hilty, 2008). Rare earths (RE) contribute to the size reduction of EEE and their increasing demands for EEE manufacture generate a rapid growth in the generation of solid waste (Unep, 2009; Cgee, 2013).

Proper treatment of waste electrical and electronic equipment (WEEE) is a key issue in the environmental waste policy, as it requires high complexity and involves the combination of different materials and components. Many of these materials have high content of harmful substances (lead, chromium, mercury, cadmium, nickel, etc.), threatening the environment and public health safety. Conversely, strategic precious metals (gold, silver, copper and RE) can also be recovered from WEEE (Huisman et al., 2008; Meskers & Hagelüken, 2009; Wath et al., 2010).

Several studies discuss a variety of problems involved in managing WEEE. Difficulties range from mining activities at the beginning of the EEE productive chain to the problems of reuse and inadequate disposal, passing through the lack of infrastructure for their collection (Step, 2013).

The traditional views on the management of solid waste have been changing recently to a more holistic context (Nelen et al., 2014). Since concerns about finite reserves of raw materials aroused, a clear tendency of categorizing waste as a new source and "smart feature" for the industry, which generates richness and growth, has been observed (Stahel, 1995; Ciwm, 2014; Hu et al., 2011; Cohen, 2007; Campos et al., 2014a, Campos, 2015). Therefore, it is unacceptable that a large proportion of special and precious metals, including RE found in WEEE, still get lost in the recycling process (Hagelüken, 2005; Hagelüken, 2006; Chancerel et al., 2009).

In this context, it is important to consider that engaging in collaborative networks is an essential facilitator of innovation processes in science and technology (S&T) organizations, for both academia and industry. When collaborating, researchers can establish communication networks, share ideas, resources and information, generate new knowledge and ultimately create innovations, thus reducing the costs and increasing the productivity of research (Wagner and Leydesdorff, 2005). In industry, especially in high-tech fields, networks provide access to the knowledge and other resources that are necessary for the successful development of new products (Haeussler et al., 2012) and to enhance the innovation output and competitiveness of organizations (Baum et al., 2000).

In S&T organizations, collaboration networks act to provide a knowledge-sharing environment (Wagner & Leydesdorff, 2005), broaden the scope of projects (Beaver 2001), and improve research impact (Royal Society, 2011). Beyond the benefits seen in research environments, networks for technological development can also leverage knowledge creation and innovation. The competences and capabilities that are necessary to transform a scientific discovery into a product are distributed among various organizations (Powell 2002) and there is an increasing demand for interfunctional and inter-institutional cooperation, particularly in areas with a high-tech content (Ramesh & Tiwana 1999), such as the health sector (Fonseca & Fonseca, 2016) and reuse of WEEE and industrial solid waste (ISW) (Campos, 2015).

Collaboration is a hallmark of S&T institutions and engagement in networks has become the most important organizational innovation associated with the spread of the knowledge economy. The competitiveness of S&T organizations is related to the scope of the networks in which they operate, as well as to the intensity of their use (Zaheer et al., 2010). Several studies have shown the increasing scale and importance of collaboration networks and several institutions have adopted a network perspective, by analyzing co-authorship and co-inventorship networks, to understand and evaluate collaborations, as well as to identify the important players in these networks (Royal Society, 2011; Netherlands Observatory of Science and Technology 2010; Marsan & Primi 2012; Fonseca & Fonseca, 2016; Fonseca et al., 2016).

The analysis of co-authorship in scientific papers provides a vision of cooperation patterns between individuals and organizations (Melin & Persson, 1996; Newman, 2004; Glänzel & Schubert, 2005). The co-authorship of a technical document is an official statement of the involvement of two or more authors or organizations (Newman, 2004) and, despite the debate about its meaning and interpretation, co-authorship analysis is still widely used to understand and assess scientific collaboration patterns. In co-authorship networks, nodes represent researchers, organizations or countries, which are connected when they share the authorship of a paper. Inter-institutional cooperation can be defined in terms of papers co-authored by researchers from two or more institutions.

Collaboration networks represent, therefore, the most important collective construction of knowledge, considering the complexity of the challenges and the need to add competitiveness to the companies responsible for introducing innovations in the market. Open innovation, now so present in the organizational world, is a reflection of what collaboration networks have so well demonstrated: union of skills to build knowledge.

To discuss the issue of WEEE exploitation in a technological and multidisciplinary perspective, the next section will characterize the RE scenario (metals of economic value present in the WEEE) in the global and Brazilian context. Then, scientific collaboration networks of Brazilian researchers and institutions working in the area of ISW and WEEE exploitation will be analyzed. Finally, based on the current scenario, a network collaboration model will be presented to bring together players acting in the post-consumption waste management of the electrical and electronic sector. A particular emphasis will be given to the potential for RE recovery from these residues, with the purpose of developing products and services.

2. Rare Earths Overview

Although abundant, rare earth elements (REE) or rare earth metals occur together at low concentrations in nature. They are soft, malleable, ductile, colored in shades of dark gray to silver and receive this name for their difficulty to extract due, in part, to their similarities. The group of RE represents 17 metallic chemical elements: Scandium (Sc), Yttrium (Y) and 15 Lanthanides (lanthanum (La), cerium (Ce), praseodymium (Pr),

neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu).

REE status is consolidated by their chemical and physical properties, as well as by the need for alternatives for their application in modern technologies. Although research efforts on the subject have been plentiful, there are no efficient substitutes for the various uses of REE. The main applications of RE compounds include: permanent magnets for miniaturized motors and wind power turbines; composition and polishing of windows and special lenses; catalysts for cars; petroleum refining; luminophores for cathode ray tubes of color televisions and flat screens for televisions and computer monitors; nuclear magnetic resonance; laser-generating crystals; superconductors and hydrogen absorbents; and precision weapons (Dnmp, 2015).

Since 2010, the REE international market has been dealing with an instability period. China has a prevailing role in the market, guaranteeing almost 95% of the world's production in 2010. Its threat to stop RE supply by restricting the export and making it insufficient for the traditional buyers caused large price variations. Such restrictions were justified as environmental protection actions, based on the difficulty of extraction and radioactive characteristics of some REE. As lower prices were offered to international companies settling in Chinese territory (Lapido-Loureiro, 2013), this restriction was perceived as China's attempt to extend its domain to the manufacture of high technology products that utilize REE. This could threaten not only the most important industries established in Japan, United States and Europe, but also military applications that depended on the use of REE (Cgee, 2013).

The 2010-2012 scenario resulted in high prices and a supply deficit for the majority of RE. This fact led to a series of new start-up businesses in RE around the world, which applied large investments to additional geological exploitations and technology development. At the same time, downstream RE users were forced to look for alternative sources of supply and invest in the development of recycling technologies and options for reuse of these elements (Golev et al., 2014). In addition, countries that have relied on their own mineral deposits saw the opportunity to encourage REE local production, developing technologies and strengthening their industries in medium and long terms (Cgee, 2013).

Brazil is the second largest holder of RE (Dnmp, 2015) but, according to Lapido-Loureiro (2013), only Catalan (GO) and Araxá (MG) cities have identified resources that exceed China reserves. Large quantities of RE, with great potential for exploitation, are concentrated in the niobium mining tailings of the Brazilian Company of Metallurgy and Mining (BCMM) in Araxá (Dnmp, 2015; Landgraf, 2013). Although Brazil has a favorable geology, it still needs to enable the productive chain of these minerals.

With a limited number of economically viable places to mine RE and a decrease in the quantities exported by China, recycling has become fundamental to the availability of REE around the world. Although a great amount of REE has the possibility of being recovered, only 1% of all elements are currently recycled. The recycling process is complicated by the usual presence of two radioactive elements, thorium (Th) and uranium (U), which make the mining, refining and recycling activities more hazardous (Rocio et al., 2012).

2.1 Brazil and the Regulatory Milestone for Rare Earths

Considering the fact that the REE exploitation is highly toxic and contains radioactive elements, Brazil ceased to invest in technology for the extraction of these minerals a long time ago (Rocio et al., 2012). However, the potential of Brazilian reserves and the price increase of RE in the international market, show that this business can be economically feasible. The financial activity of the RE world market has increased from \$1 billion in 2009 to \$11 billion in 2011 (Mckinsey, 2011).

China's decrease in RE extraction and mining and export restrictions led many countries to look for sources within their own territories. Brazil was no exception and this possibility, starting with the necessary regulation, has been widely discussed.

The establishment of a regulatory milestone, the Draft Law that establishes the Program to Support Technological Development of Rare Earth Mineral Elements and Creation of Productive Chain (PADETR), can create mechanisms for foreign companies to explore the sector by instituting a specific legislation. Partnerships with the private sector are important for the government to obtain sufficient technology to enhance its presence in the segment (Brazil, 2013).

2.2 Trends in the Rare Earths Global Market

The scientific community has demonstrated concern for the future offer of REE due to the current monopolistic offer, environmentally-unsustainable mining practices, and rapid demand growth. The search for a sustainable future will encourage the application of permanent magnets in wind power turbines and electric vehicles, which

demand an intense use of neodymium and dysprosium, leading to significant and disproportionate increases in the demand for these two elements. In addition, if there is no efficient reuse and recycling, or development of technologies that use smaller quantities of dysprosium and neodymium, the stabilization of CO₂ concentration in the atmosphere will be compromised (Alonso et al., 2012).

In 2013, a study conducted by the Center for Strategic Studies and Management (CGEE) – corporate body supervised by the Brazilian Ministry of Science, Technology and Innovation (MSTI) – about the uses and applications of RE in Brazil 2012-2030 (Cgee, 2013) revealed trends and ongoing changes in the world overview of RE. The following ones stand out:

2.2.1 Green Economy

Economic recovery of RE by recycling used products, including the economic use of WEEE as the best example.

2.2.2 Information Society

2.2.2.1 Intensification in the use of control systems in the area of defense and security. Electronic devices industry is dependent on the provision of RE. Intensive use of RE in sophisticated communication equipment.

2.2.2.2 Miniaturization of Equipment has been Contributing to Increase the Demand of RE.

2.2.3 Global Governance

Geopolitical issues associated to the production of RE require global governance efficiency. International institutions (World Trade Organization – WTO, United Nations – UN, and others) have little coercive power to solve current problems in the global market of RE.

2.2.4 The Global Market for Applications that Contain or Use RE

2.2.4.1 Intensive use of networks, digital media and consumer awareness in relation to environmental preservation and the rational use of natural resources.

2.2.4.2 Tendency of concentration in China of high technology industries that use RE.

2.2.4.3 North Atlantic Treaty Organization (NATO) and other alliances need access to raw materials for the use of RE in defense equipment.

2.2.5 New Competitor Materials or Substitutes of RE

2.2.5.1 The increasing speed of research and technological innovations that are associated to applications that contain or use RE creates uncertainties to the development of new RE replacement materials.

2.2.5.2 Increase in the incentive to search for alternative materials as a response to the dependence of China in relation to the provision of RE.

2.2.6 Deposits and World Production of RE

Better knowledge of the geology of REE deposits. Greater characterization of REE minerals. Economic feasibility of products. Possible articulation of productive chains that depend on RE.

2.2.7 International Prices of RE

Tendency to stabilize prices in the near future due to the fall of China's monopoly, wide spread of RE-containing products recycling and diversification of RE supply chain.

2.2.8 National Policies in RE-Producing and Processing Countries

Impacts of RE productive chains in environmental policies at national level. The emergence of regulatory frameworks in RE-producing and consuming countries, in addition to China, is expected. Examples of these mechanisms include royalties and tax incentives.

In order to design and optimize productive chains, with respect to environmental principles, it is necessary to ensure energy conservation and waste management throughout the stages of the productive chain. The projects of environmentally sound industrial processes should be developed with a systemic view, adopting a strategy that considers environmental issues as key objectives in order to achieve better performance, both economic and environmental (Nikolopoulou & Ierapetritou, 2012).

It is important to mention that the Clean Technology (cleantech), or greentech, category has evolved since it was first defined in 2002. In 2012, Kachan & Co. has revisited its definition of the category and offered a new taxonomy, in which shows where a clean technology “fits”. It helps entrepreneurs, investors, service providers and large corporations understand the breadth and depth of the cleantech category. Nowadays, the cleantech sector can be categorized as spanning eight over-arching energy, manufacturing, environmental and resource categories:

Clean energy; Energy storage; Efficiency; Transportation; Air and environment; Clean industry; Water and Agriculture (Kachan et al., 2012).

Energy storage, for instance, encompasses technologies that preserve energy for use at a later time, with applications both in electronics and grid-scale power storage. Opportunities in Air & Environment include carbon sequestration, trading/offsets, emissions control technologies, bioremediation, recycling and waste technologies. Cleantech for industrial use is based largely on advanced materials, along with design innovation, equipment efficiency, production, monitoring, compliance and advanced packaging. With regard to the mining, companies are increasingly motivated by the dramatic new economic benefits promised by new breakthroughs in green mining (Kachan et al., 2012).

3. Methods: Analysis of Scientific Collaboration Networks

The creation and maintenance of a cooperation network is essential to preserve, disseminate and share knowledge and other information resulting from diverse competences of research groups. In the same way, collaboration networks are essential to leverage the innovation process (Cereja, 2006; Fonseca, 2011). The next section aims to analyze scientific collaboration networks in the area of ISW and WEEE exploitation in Brazil, examining both researchers and institutions with greater representation in the field. For this purpose, social network analysis methods (Scott, 2001) were used to build and analyze co-authorship networks based on scientific publications retrieved from the *Web of Science* (WoS) database.

The data mining strategy was based on retrieving ISW and WEEE-related scientific articles, involving Brazilian-based researchers (as authors or co-authors) from 2010 to 2014. Queries were directed to the title, abstract and keywords of publications, and to the address/affiliation of authors. The search query for ISW used the terms "waste or recycl* or reuse" AND "solid and industrial" AND "Brasil or Brazil", recovering 138 records. For WEEE, the search query used the terms "waste or recycl* or reuse" AND "electrical or electronic" AND "equipment or device" AND "Brasil or Brazil", recovering 39 records. The 5-year period timeframe intended to reflect more accurately the state of the art of scientific research in the field, which ultimately reflected the performance of Brazilian researchers (Campos, 2015; Fonseca, 2015; He & Fallah, 2009; Eslami et al., 2013).

Collected data was imported into the VantagePoint® software (Search Technology Inc.) using specific filters for the WoS database. After standardization of the various record names of an author and institution, cleaned data were formatted into an adjacency matrix to map co-authorships (co-occurrences) and imported into the Gephi software (Bastian et al., 2009) for visualization and analysis. Networks were created for both collaborating researchers and research institutions using author affiliations to identify this information. Nodes represented researchers (authors) or institutions, and links between them indicated that their members shared the authorship of one or more scientific papers.

The importance of a researcher or organization was evaluated by calculating their degree centrality, a measure of prominence or influence in the network (Freeman, 1979). Degree centrality is based on the number of a node's direct connections. The more relational ties a node has, the more power or prestige it has in a network.

4. Results and Discussion

4.1 Analysis of Scientific Collaboration Networks in Industrial Solid Waste (ISW) and Waste Electrical and Electronic Equipment (WEEE)

4.1.1 Brazilian Research Network in ISW

The Brazilian collaboration network of ISW research was composed of 627 researchers, 95.5% of them affiliated to Brazilian institutions. This network, shown in Figure 1, was extremely fragmented and contained 105 different groups, which were not connected to each other. This fragmentation indicates that the network was not integrated, and suggests that Brazilian ISW researchers rarely collaborated.

The trans and multidisciplinary approach of the ISW theme covers several areas, from engineering (including mining, materials and metallurgy, electrical, chemical and production engineering) to chemistry, biochemistry, food science and technology, agronomy, architecture and ecology. This could lead to a network arrangement in different research groups, which would have no incentive or reason to cooperate in scientific articles. However, team diversity facilitates innovation (Post et al., 2009).

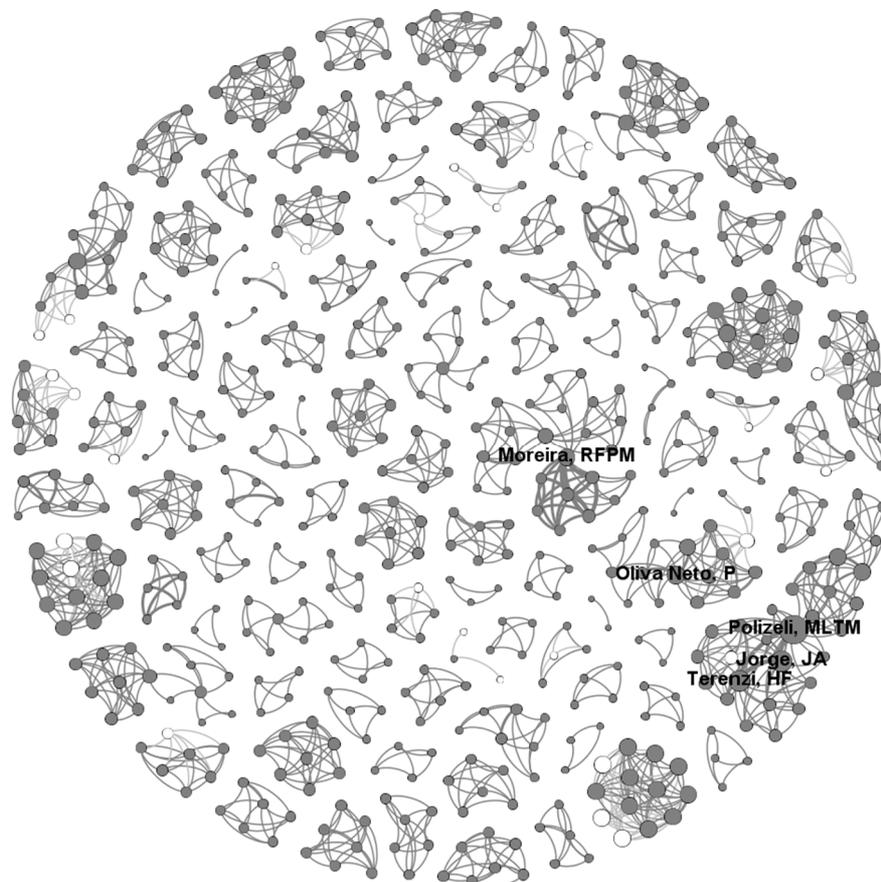


Figure 1. Brazilian collaboration network of researchers working on industrial solid waste

Relationships between two researchers were mapped according to the co-authorship of scientific publications. Each node represents a researcher and two researchers were considered connected if they shared the authorship of an article. The color of the node indicates that the researcher is Brazilian (gray) or foreign (white). The size of the node reflects its degree centrality. The names of the five most central researchers are indicated. Source: Prepared by the authors

Multidisciplinary research teams increase and accelerate the success of innovations in several ways: i) intellectual diversity allows the evaluation and “filtering” of new ideas in a more robust and efficient manner, avoiding failures; ii) different experiences of team members help to develop a “connective thinking” between very different ideas, substantially improving the initial idea; iii) team diversity includes the networks of each individual, facilitating the discovery retention (Disis & Slattery, 2010).

The five most central authors in the ISW network were Polizeli, Jorge, Terenzi, Oliva Neto and Moreira (Figure 1). Polizeli, Jorge and Terenzi were affiliated to the University of São Paulo (USP), Oliva Neto belonged to the Paulista State University (UNESP) and Moreira was linked to the Federal University of Santa Catarina (UFSC).

The institutional network of ISW research was composed of 125 institutions, 75.2% of them from Brazil (Figure 2). The most central institutions in the network were, in order of importance, USP, Brazilian Agricultural Research Corporation (Embrapa) and the Federal University of Minas Gerais (UFMG), UNESP, UFSC with the same degree centrality in the network.

4.1.2 Brazilian Research Network in WEEE

The Brazilian collaboration network of research in WEEE was comprised of 37 researchers, 33 of them Brazilians and four of them of foreign nationality (Figure 3). The network was small, but fragmented: researchers were divided into eight different groups that do not connect to each other. The most centralized authors in the network were Veit and Malfatti, both affiliated to Federal University of Rio Grande do Sul (UFRGS). Even though affiliated to the same university, the researchers do not collaborate among themselves.

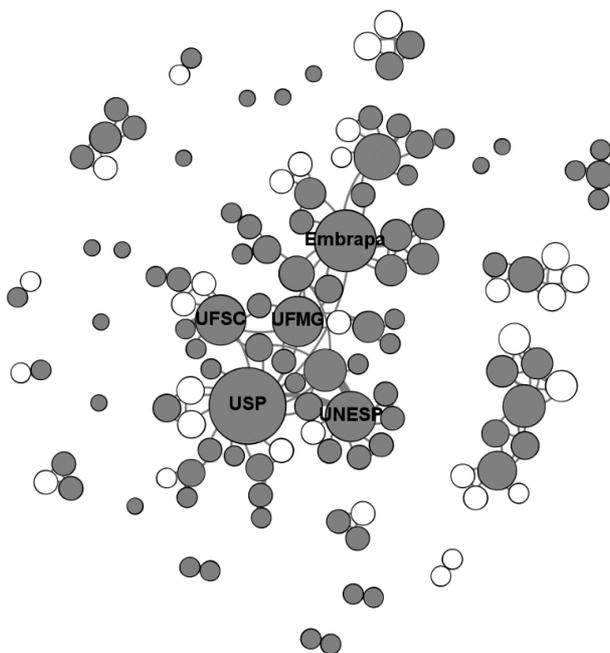


Figure 2. Collaboration network of institutions that carry out research on industrial solid waste

Relationships between two institutions were mapped according to the institutional affiliations of the authors of scientific articles. Each node represents an institution and two institutions were considered connected if their members shared the authorship of an article. The color of the node indicates whether the institution is Brazilian (gray) or international (white). The five most central institutions in the network are indicated: USP: Federal University of São Paulo, Embrapa: Brazilian Agricultural Research Corporation, UNESP: Paulista State University, UFSC: Federal University of Santa Catarina, UFMG: Federal University of Minas Gerais. Source: Prepared by the authors.

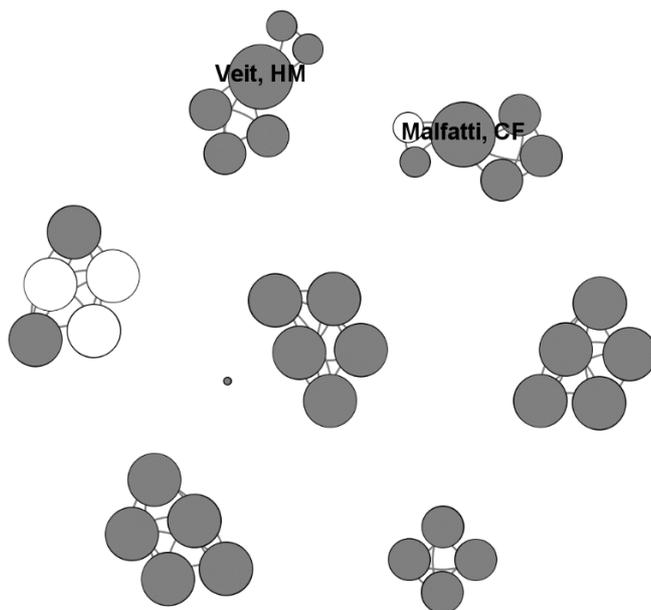


Figure 3. Brazilian collaboration network of researchers working on waste electrical and electronic equipment

Relationships between two researchers were mapped according to the co-authorship of scientific publications. Each node represents a researcher and two researchers were considered connected if they shared the authorship of an article. The color of the node indicates that the researcher is Brazilian (gray) or foreign (white). The size of the node reflects its degree centrality. The names of the two most central researchers are indicated. Source: Prepared by the authors.

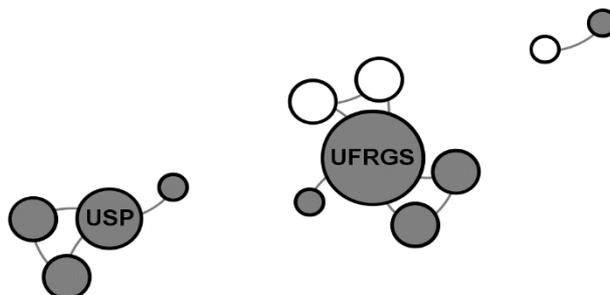


Figure 4. Collaboration network of institutions that carry out research on waste electrical and electronic equipment

Relationships between two institutions were mapped according to the institutional affiliations of the authors of scientific articles. Each node represents an institution and two institutions were considered connected if their members shared the authorship of an article. The color of the node indicates whether the institution is Brazilian (gray) or international (white). The two most central institutions in the network are indicated. UFRGS: Federal University of Rio Grande do Sul, USP: University of São Paulo. Source: Prepared by the authors.

The institutional network of research in WEEE was composed by 12 institutions, nine of them from Brazil (Figure 4). The most central institutions in the network were, in order of importance, the UFRGS and USP. UFRGS was considered the most central institution in the network probably by the presence of Veit at that institution. As he was the most important scientist in the network of researchers, his influence is also reflected in his institutional affiliation.

The network of researchers and institutions, both small, reveal an incompatibility with the demand in this area. The EEE is the fastest growing segment in terms of waste generation, which stimulates the scientific interest to understand how to safely eliminate and recycle WEEE (Unep, 2012). Studies show a variety of problems and obstacles involved in managing this type of waste in Brazil, among them the lack of specialists and advanced technologies, capable of improving the reuse network of these materials (Hilty, 2008; Tanskanen, 2013; Step, 2013; Campos et al., 2014a; Campos, 2015).

4.2 Implementation Basis of a Collaborative Environment in the Area of Rare Earth Metals Exploitation from Waste Electrical and Electronic Equipment

The complexity of the RE global market and the problems of post-consumption waste management in the electrical and electronic industry require systemic actions to find innovative, fast and effective solutions, with scientific and technological basis, in order to reduce environmental impacts.

The implementation of a collaborative networking environment, with the purpose of facing and solving problems of EEE post-consumption management combined with RE market difficulties, should be primarily based on three guidelines: i) the regulatory imperative; ii) the combination of skills; and iii) the promotion of new businesses. Since regulating and developing technology is not sufficient, the transformation of this knowledge into new businesses is an indispensable requirement to reframe the current destination of WEEE (Campos et al., 2014b; Campos, 2015).

In this context, the management of post-consumption WEEE is reflected in the combination of all actors involved, from WEEE disposal by users, passing by all the "consolidators" involved in the chain (waste picker, transporter, recycler, transformer), to its reintegration in its own chain or in another. It also includes other valuable links in the productive chain, as shown in the development model for the network collaboration environment (Figure 5).

The post-consumption WEEE flow is chaotic and uncontrolled, as evidenced by the incipency of environmentally-adequate alternatives for its final disposal, absence of technology to attend the exploitation market of these residues, especially those with added value such as the RE, and lack of operational clarity in the legislation. This way, the network proposal (Figure 5) emerges as a solution, especially for seeding businesses in this area (Campos, 2015).

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