Research Policy 46 (2017) 925–938

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Drivers of knowledge accumulation in electronic waste management: An analysis of publication data

Grazia Cecere[a,b,*], Arianna Martinelli[c]

[a] Telecom Ecole de Management, Institut Mines Telecom, 9 Rue Charles Fourier, 91011 Évry, France
[b] Université Paris Sud, RITM, 54 Boulevard Desgranges 92330 Sceaux, France
[c] Institute of Economics, Scuola Superiore Sant'Anna, Piazza Martiri della Liberta' 33, I-56127 Pisa, Italy

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 27 January 2017
Accepted 13 March 2017

Keywords:
Electronic waste
Innovation
Publication data
Environmental policies
Waste Electrical
Electronic Equipment

ABSTRACT

The increased number and shorter life cycles of electronic devices are resulting in a rapidly growing stream of Waste Electrical and Electronic Equipment (WEEE) worldwide. The environmentally sound disposal of this waste stream is a complex activity that involves several steps and stakeholders. The aim of this article is to investigate the process of knowledge creation in WEEE management, based on publications data retrieved from the Thompson Web of Science (WoS). Using a dataset of publications dated between 1985 and 2013, we evaluate the role of three major drivers of knowledge creation: innovation induced by the high price of precious materials; technological advances; and regulatory stringency. Analysis of the global map of science highlights patterns of increased diversification of research domains and an impact of regulation and raw price material on the development of new research in different disciplines. This contributes to the policy debate on how to encourage more research in the field of WEEE management.

1. Introduction

Knowledge is an essential input of innovative activity. In particular, according to the 'chain-linked model' (Kline and Rosenberg, 1986), knowledge, rather being the trigger, is one of the key components of the innovation process and affects the phases of design, production and marketing. Thus, the relationship between the development of new knowledge and innovation, is characterized by intensive feedbacks. The innovation process cannot be conceived simply as a response to scientific advances; rather, it should be considered a bi-directional relationship between knowledge dynamics and innovation dynamics (Antonelli, 2011). It follows that the drivers of innovative activities also influence the pace and direction of scientific discovery. The long debate on the role of 'demand pull' (Gilfillan, 1935; Schmookler, 1966) versus 'technology push' (Mowery and Rosenberg, 1979; Dosi, 1982) factors, ultimately was resolved by both being recognized as relevant for explaining why innovation emerges (Clark, 1985; Freeman, 1994). However, technology and demand might play different roles in different phases of innovation: the former is crucial at the beginning of technological development while the latter enhances the diffusion of innovation (Pavitt, 1984; Park, 2014). In addition, in specific contexts there are other factors that are important, such as, regulatory intervention, which is crucial for fostering environmental innovation (Porter, 1991; Jaffe and Palmer, 1997; Popp et al., 2011).

Building on the large literature on the sources of innovation, we examine the extent to which these sources also affect knowledge development in the field of Waste Electrical and Electronic Equipment (WEEE) or e-waste. E-waste refers to all electrical and electronic devices destined for reuse, resale, salvage, recycling or disposal.[1] These devices are characterized by their complex mix of hazardous, highly toxic materials and economically valuable noble metals. Therefore, the disposal of e-waste requires specific technologies to enable the separation, processing, disposal and recovery of these valuable resources (STEP, 2009), while reducing any negative social or environmental impacts due to the processing and management of its hazardous materials content (Mazzanti and Zoboli, 2006). Environmentally sound treatment of WEEE is chal-

* Corresponding author at: Telecom Ecole de Management, Institut Mines Telecom, 9 Rue Charles Fourier, 91011 Évry, France.
E-mail addresses: grazia.cecere@telecom-em.eu (G. Cecere), arianna.martinelli@santannapisa.it (A. Martinelli).

[1] It includes a wide range of electronic equipment such as refrigerators, solar panels and Information and Communication (ICT) equipment (personal computers and mobile phones). In Europe, the WEEE Directive sets 10 categories of WEEE: large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment, electrical and electronic tools, toys, leisure and sports equipment, medical devices, monitoring and control instruments, and automatic dispensers,

http://dx.doi.org/10.1016/j.respol.2017.03.005
0048-7333/

lenging for engineers, consumer electronics companies and policy makers since it involves the consideration of ecological design, technological opportunities and the price of noble and rare metals (Hagelüken, 2006). The relevance of this waste stream is underlined by the fact that e-waste is the fastest growing waste stream in the European Union (EU), and is increasing at an annual rate of 3%–5% (EUROSTAT, 2016). In 2010, Europe produced around 9.7 million tonnes of WEEE, corresponding to an average of 19.4 kg of e-waste per inhabitant and 0.05% of the overall average waste per inhabitant in the EU (EUROSTAT, 2015).

Despite growing concern about the expansion of WEEE, research on the drivers of knowledge in this domain and their interactions remains limited. Some studies examine the knowledge base related to waste recycling techniques, but do not focus specifically on WEEE (Garechana et al., 2012; Garechana et al., 2014a,b); others restrict their attention to the effect of a particular environmental policy (Corsini et al., 2015) (i.e., extended producer responsibility) on scientific production. The present article contributes by focussing on knowledge production in a specific and very valuable waste stream, that is, WEEE. In particular, we identify the locus of the research on e-waste management and the research fields involved, and the main drivers of research on WEEE management. Our findings contribute to the policy debate on how to promote the emergence of new research in specific scientific areas of e-waste management to ensure better recovery of the electronic and electrical materials. Our results also provide insights into how different knowledge disciplines interact and evolve.

The empirical analysis is conducted on a sample of 3779 publications (articles, books, proceedings papers, reviews, etc.), published between 1985 and 2013, in order to examine time and geographical patterns and to build global maps of science (version updated in 2010) (Leydesdorff and Rafols, 2009; Leydesdorff et al., 2013). The advantage of publications data compared to other indicators, such as patents (Johnstone et al., 2010; Park, 2014), is that they provide a broader picture of the innovation process, which captures the complexity of the knowledge involved, potential organizational innovations and emerging best practice (Börner et al., 2003; Noyons, 2004).

The paper is organized as follows. Section 2 provides a review of the main drivers of research in e-waste. Section 3 introduces the notion of e-waste and the technologies used for its disposal. Section 4 describes the sample and the methodology. Section 5 discusses the empirical results. Section 6 concludes the paper.

2. Drivers of green innovation and knowledge

One of the most important aspects of the economics of innovation literature is identifying the sources of innovation. Several factors, such as technology push, demand, input prices and regulatory interventions, have been studied both theoretically and empirically (Peters et al., 2012; Di Stefano et al., 2012). However, no one factor emerges as being the sole driver of innovation (Ruttan, 1997; Dosi, 1997). In the specific context of eco-innovation, the existing literature highlights the importance of technology push factors, based on the quality of the stock of knowledge and the level of the technological capabilities acquired through science-based research, for the production and diffusion of innovations (Costantini et al., 2015; Johnstone et al., 2012; Popp et al., 2011). Furthermore, Horbach (2008) and Horbach et al. (2012) show that, in the case of green innovation, technology push goes beyond the accumulation of knowledge capital and the provision of infrastructure and encompasses the adoption of environmental management systems and the introduction of organizational innovations.

Work in the more classical economic framework suggest that innovation could be induced by relative changes in production prices (Hicks, 1932; Ruttan, 1997; Mokyr, 2011). In this respect, Lanjouw and Mody (1996) show that energy price increases have influenced the production of patents in the energy field. Park (2014) studies patenting activity in coal combustion by-products and shows that the number of patents in reuse technologies increased in response to a change in the prices of cement and lime, which, in the construction sector, can be replaced by recycled waste material. Park suggests that high prices for natural materials can promote developments to transform waste material into potentially useful resources and can spur innovation in the domain of waste management.

In relation to the role of regulation on the development of innovative activities, seminal contributions by Porter (1991) and Porter and van der Linde (1995), suggest that raising environmental standards can have a positive effect on the introduction of green innovation. In particular, Porter (1991) underlines that waste in the form of pollution produces inefficiencies, and that regulation forces firms to evaluate their resources allocation. Several studies show that stricter regulation can stimulate innovation (Jaffe et al., 2002, 2005) and, especially, in emerging sectors such as recycling and incineration (Mazzanti and Nicolli, 2011; Costantini et al., 2015). Johnstone et al.'s (2010) findings further stress the importance of regulatory stringency in relation to patenting in different areas of energy innovations. Furthermore, environmental policy often is aimed, directly or indirectly, at increasing the prices of inputs in order to exploit this channel, to enhance the link between policy and technology and promote inputs innovations (Popp et al., 2011).

2.1. Technology and organizations

E-waste treatment is a multi-stage process that involves the cooperation and integration of various actors such as consumers, producers, policy makers and recycling organizations. All these actors are constrained by the available types of equipment and treatment technologies, the socio-economic conditions and regulatory requirements (STEP, 2009). E-waste disposal involves three phases: (i) collection of e-waste, (ii) pre-processing (i.e., separation and disassembly); and (iii) end-processing (i.e., metals recovery and purification).

Given the high risk of dispersal of hazardous materials, the collection of e-waste –*first phase*- is a crucial step and is covered by the EU WEEE Directive (2002, 2012). This directive obliges manufacturers and importers in EU member countries to comply with the Extended Producer Responsibility (EPR) principle, which imposes producers' responsibility for the collection and environmentally sound disposal of e-waste from consumers (Widmer et al., 2005). The EPR is encouraging producers to improve eco-design of products in order to facilitate the separation of different components and to permit more efficient recovery (OECD, 2016).

The *second phase* consists of the pre-treatment of the e-waste, involving disassembly of the scrap, separation of the components, and shredding. The objectives of this phase are, first, to identify and upgrade the valuable materials content, and to remove and dispose safely of hazardous materials. The greater the complexity (understood as the number of different components, the number of different materials, the presence of hazardous material) of the waste, the more difficult the separation and collection of valuable scrap materials. Second, WEEE must be shredded into small particles (Cui and Forssberg, 2003). This is a mostly mechanical process (e.g., mechanical screening, shape separation, magnetic separation, eddy current separation, electrostatic separation, jigging). Several studies have focused on improving outcome quality since the efficiency of the recycling process and the quality of the recycled metals, depend heavily on the efficiency of the separation phase. Improvements focus mostly on the design of disassembly facilities, and development of procedures and software tools to establish