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

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 27 January 2017
Accepted 13 March 2017
Available online 30 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

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[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/

Zoboli, 2006). Environmentally sound treatment of WEEE is challenging 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 disassembly strategies and configure disassembly systems (i.e., disassembly process planning) (Cui and Forssberg, 2003). A crucial societal aspect refers to the off-shoring of this phase to developing countries with cheaper workforce and less stringent regulatory frameworks (Chen et al., 2010).

The *third phase* concerns both the extraction of the valuable metals and purification of the recycled metals. Several mechanical and non-mechanical methods can be employed for the metals recovery process in order to reduce the environmental footprint of the recovery process. The most widely used recycling processes are pyrometallurgy, hydrometallurgy and biometallurgy (Silvas et al., 2015). Table 1 presents details of these technologies including technical characteristics such as emissions levels and main application.

Pyrometallurgical processing is the traditional technology used to recover non-ferrous metals and precious metals from WEEE. It consists of melting the crushed scraps in a high-temperature furnace (or a molten bath). The use of large smelters involves very high fixed costs and a rather concentrated industry of four global players: Boliden, Xstrata Copper (formerly Noranda), Aurubis and Umicore. These companies are large and knowledge intensive; for instance, UMICORE and Boliden, were among the top 500 companies on the 2010 EU Industrial R[2] (see Cui and Zhang, 2008). The main drawback to pyrometallurgy is that some metals, such as aluminium and iron, cannot be recovered, and the presence of flame retardants in the scrap results in the formation of dioxins, which require special filtering.

Hydrometallurgy involves a series of acid or caustic leaches of the solid materials to extract solid components. It has become more popular because of its better quality and purification of the precious metals. A crucial aspect of this technology is the choice of leaching agent. This depends on the metals being recovered and calculation of the ‘leaching parameters’ which dictate the economic efficiency of the overall procedure and the economic viability of the technology (Kamberovic et al., 2011). From an environmental perspective, not all the agents used are easily recyclable.

Finally, biometallurgy is relatively new technology, which has been used since the 1960s for the extraction of minerals in mines where it uses algae, bacteria, yeast and fungi to extract heavy and precious metals. Bioleaching of metals technology, employed initially in mining, is used currently to recover metals from e-waste by various companies including the Finnish Talvivaara (Talvivaara, 2010). The potential of this technology is huge because it is more environmentally friendly and involves lower operating costs (Cui and Zhang, 2008; Kamberovic et al., 2011). Research on biometallurgy focuses mainly on bioleaching of certain precious metals, such as silver and gold, in order to increase economic feasibility.

In this third phase, the first challenge is to identify the appropriate technology for materials recovery and to ensure a certain level of purification. The recovery and purification phases generally are integrated and, therefore, carried out by the same actors. The technological choice for purification has important consequences for the overall cleanness of the recycling procedure (STEP, 2009). The second challenge is complying with regulatory requirements. The complexity of the process requires inter-disciplinary research and innovation, among several actors (e.g., private firms and public research centres) located worldwide (Cui and Roven, 2011). In particular, eco-design of electrical and electronic equipment requires cooperation among different stakeholders, and specific efforts from producers (Zuidwijk and Krikke, 2008).

2.2. E-waste recovery: the role of raw materials prices

One of the aims of WEEE recycling is extraction and commercialization of recovered precious and noble metals. These materials include gold, copper and platinum, which are used widely as contact materials due to their high chemical stability and their good conducting properties – platinum is used in switching contact devices. For example, a mobile phone (without its battery) contains about 250 mg of silver, 24 mg of gold, 9 mg of palladium and 9 g of copper (STEP, 2009).

The largest WEEE stream is constituted by large household appliances (EUROSTAT, 2016), while the most valuable waste streams, in terms of recovery of precious materials, are constituted by smart phones, LCD monitors and notebook computers (Cucchiella et al., 2015). The extraction of precious metals drives a large part of the economic activities involved in WEEE recycling – especially in the case of mobile phones (OECD, 2011). The higher the prices of the metals involved, the more valuable the ores and metals derived from e-waste (Hagelüken, 2006). It follows that the dynamics of metal prices can affect efforts to improve the extraction of precious materials from e-waste and encourage related research.[3] A similar relation applies to hazardous materials, such as plastics, whose value increases when oil prices rise (Cui and Roven, 2011). Thus, the price of the inputs (required to produce electronic devices) is a strong economic incentive for their recycling and the development of recycling technologies to match their growing demand driven by the constant increase in the demand for the final products (Cui and Roven, 2011).

2.3. E-waste recovery: the role of regulation

The EU has implemented several policy initiatives to tackle various issues related to environmentally sound WEEE management (e.g. hazardous materials treatment, producer responsibility, recycling fees, etc.), while in the US regulation of WEEE is not governed by federal law (Sthiannopkao and Wong, 2013; Heart and Agamuthu, 2012).

EU regulation is based on two directives. The first is aimed at controlling use of hazardous substances (Directive 2002/95/EC or Restriction on Hazardous Substances – RoHS – Directive), and the second sets collection, recycling and recovery targets for all types of electrical goods (Directive 2002/96/EC or the WEEE Directive). The WEEE directive defines the ten WEEE categories.[4] The RoHS Directive forces producers to restrict use of six hazardous materials in order to increase the safety of (especially the first two phases of) the recycling process and to reduce the risk of dispersion. The WEEE Directive introduced the EPR, which encourages producers to design and produce electrical and electronic equipment that can be repaired, reused, disassembled and recycled.[5] It is interesting that in, OECD (2016) 35% of the EPR programme is focused on electronic goods. Both the WEEE and RoHS Directives focus on ‘eco-design’ of appliances and changes to the way new products are conceived, designed and assembled. In particular, the Eco-Design

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[2] Corresponding patents: J. Dunn, E.Wendell, D.D. Carda et al., Chlorination process for recovering gold values from gold alloys, US Patent, US5004500 (1991); F.G. Day, Recovery of platinum group metals, gold and silver from scrap, US Patent, US4427442 (1984); S. Aleksandrovich, E. Nicolaevich, E. Ivanovich, Method of processing of products based on ahalcogenides of base metals containing metals of platinum group and gold, Russian Patent, RU2112064, C22B 11/02 (1998).

[3] The influence of raw materials price in the direction and pace of knowledge search in this domain was confirmed by the interviewed experts.

[4] Large household appliances, Small household appliances, IT and Telecommunication equipment, Consumer equipment and photovoltaic panels, Lighting equipment, Electrical and electronics tools, Toys, Leisure and sports equipment, Medical devices, Monitoring and control instruments, Automatic dispensers.

[5] In other words, producers are responsible for their products' end-of life management to reduce environmental dispersion and limit potential criminal activity.

Table 1
Pre-processing technologies used for metallurgical recovery of electronic scrap.

Different technologies used to recover metals	Usage	Short description	CO2 Emissions	Applications	Limitation
Pyrometallurgical process	Traditional technology	The scrap is incinerated and smelted in furnaces at high temperature	High, due to combustion	Ex. Of solution Umicore has installed emission control device.	It does not permit recovery of aluminum and iron
Hydrometallurgical process	Most used technology	Consist of a series of acid or caustic leaches of solid material – Leaching involves using soluble constituents to extract solid components	Leaching gold used thiourea has less environmental impact compared to other substances.	Different applications	Different leaching methods have created environmental accidents
Biometallurgical	Promising technology	Recovery of metals using bio-technology methods-environmental friendly technology	Low	Very few applications	Not completely developed

Directive (2009/125/EC), which establishes a framework for eco-design requirements for energy related products, underlines the manufacturer's responsibility. It refers directly to the WEEE directive and emphasizes the importance of eco-design in relation to WEEE.

Over time, the European Directives have been revised and updated. A 2012 revision to the WEEE Directive (Directive 2012/19/EU) reinforces compliance with Waste Shipment Regulation (WSR) 1013/2006 and imposes other obligations (e.g., forbidding the export of WEEE outside Europe, and imposing stricter regulation on recovery) related to the shipment of e-waste. The 2012 WEEE Directive also sets ambitious objectives for member states regarding collection and recovery supporting phase zero of waste collection. The collection target is fixed at around 85% of WEEE generated in 2020, corresponding to around 10 million tons of WEEE or 20 kg of WEEE per capita.

In addition to those 2002 directives targeting WEEE, the EU has adopted REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) (Regulation 1907/2006) on the production and use of chemical substances and their potential impact on human health and the environment, which has an important impact on the treatment of WEEE. Table 2 presents the main regulatory milestones for WEEE worldwide.

EU directives have had an important impact on international firms' management of WEEE. For example, Oracle has been obliged to offer a comprehensive end-of-life product take back system (Oracle, 2015). More generally, US companies that want to export to Europe have to adapt their production processes and end-of-life management of devices in line with EU regulation (Export.gov, 2015). By regulating the consumer market, the EU, through its legal institutions and standards, has imposed pressure – especially in the chemicals sector – via REACH (Bradford, 2015).

Among the developed countries, Japan was the first to regulate WEEE management through the imposition of EPR and enforcement of environmentally sound management of WEEE. Japan has also imposed fixed fees since 2001 which require consumers to pay a recycling price when they buy a new piece of electrical or electronic equipment (Chung and Murakami-Suzuki, 2008). Some developing countries are trying to regulate WEEE because their weak institutions and weak enforcement make them vulnerable to illegal WEEE management activities (Sthiannopkao and Wong, 2013). For instance, the Chinese government prohibited import of WEEE in 2000 and, in 2005, in order to meet the national environmental goal of implementing the circular economy principle, enacted a number of WEEE-specific laws covering take-back responsibility, control of hazardous substances and environmental impact of WEEE treatment facilities. These three related laws are in line with EU regulation and, ultimately, are aimed at making producers and manufacturers responsible for choosing less harmful, recyclable and degradable materials in the manufacture of electronic devices, and complying with trade and national standards for hazardous substances (Chung and Zhang, 2011). In contrast, India is lagging; the Ministry of Environment and Forest enacted the E-waste Management and Handling Rule only in 2011.

The strengthening of environmental regulation on transboundary movement of hazardous materials, encouraged the formulation in 1989 of the Basel Convention, an international treaty designed to reduce the movement of hazardous waste between nations, which came into force in 1992.[6] Although not originally aimed at WEEE, in 2002, during the sixth Basel Convention meeting, the participants recognized the increasing relevance of WEEE as a potential source of hazardous material. Since then, and particularly after the eighth meeting in 2008, the Basel Convention has published several initiatives to involve the private sector, particularly producers, in the environmentally sound management of WEEE. The 2011 Basel convention published its *Technical guidelines on transboundary movements* to provide guidance on how to deal with international flows of potentially hazardous WEEE (Basel Convention, 2011). Finally, although the Kyoto Protocol does not directly address WEEE recycling, it provides guidelines on the recovery of specific gases such as the fluorine greenhouse gases contained in air-conditioning units and refrigerators.

3. Methodology and data

For the empirical analysis, we use publications data on e-waste. We retrieved the sample of publications[7] from the WoS – Web of Science database using relevant search terms/words to search the titles, abstracts and author keywords.[8] Among the 3797 publications (i.e., articles, books, proceedings papers, reviews, etc.) published worldwide between 1985–2013, only 3779 contain the complete set of information (i.e., year of publications and WoS categories) needed for the analysis. Despite some potential bias towards English-language titles, lack of citations counts for books, and differences in coverage among research fields (especially arts and humanities), most studies use WoS journals and bibliometric analysis (Meho and Yang, 2007). Furthermore, extracting articles from the WoS ensures the inclusion of research published in highly ranked journals. For each article in the sample, we collected information on date of publication, and names, addresses

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[6] In particular, to prevent the transfer of hazardous waste from developed to less developed countries.

[7] The list of keywords used for data retrieval were discussed and validated in an interview with external experts. See Annex A for a complete list.

[8] The queries and step-by-step results are provided in Annex B.

Table 2
Milestone of regulatory activity in the WEEE domain at country level.

ACT	DATE	EFFECTIVE DATE	LEGISLATION	DESCRIPTION
WEEE Directive	2002	2005	EU	To foster an increase reuse and recycling of WEEE. It introduces producer responsibility. Distributers should be involved in recollection of old equipment
Revision WEEE Directive	2012	2016	EU	It fixes some objectives. By 2016 45% of WEEE put on the market should be recycled (no landfill), this should increase up to 65% in 2019
RoHS	2002	2006	EU	Ban on: lead, mercury, cadmium, hexavalent chromium, PBB and PBDE
Law for the promotion of Effective Utilization of Resources (LPUR)		2001	JAPAN	It covers specific appliances (PC and small-sized batteries). It encourages manufacturers to voluntarily help WEEE recycling
Law for Recycling Specified Kinds of Home Appliances (LRHA)		2001	JAPAN	It covers other types of appliances, such as: televisions, refrigerators, washing machines, etc. It establishes a fixed fee for covering the recycling and transportation costs and also some compulsory recycling rates.
Amendment to LPUR (J-Moss or JIS C 0950)		2006	JAPAN	Japanese version of the European RoHS Directive. However, it does not ban the six hazardous substances but it only binds producers to a content declaration
National Strategy for Electronics Stewardship		2011	US	Improve the design and management of electronics in the US
		2000	CHINA	Prohibition of import of e-waste and other hazardous waste
Management Measure for the prevention of Pollution from Electronic Products		2005	CHINA	Chinese version of the European ROhS. It limits the use of some hazardous material
Administrative Regulation for the Collection and Treatment of Waste Electrical and Electronic Product	2009	2011	CHINA	Legalize and regulate the labor intensive informal business of the recycling
E-waste (Management and Handling) Rule of 2011	2011	2012	INDIA	It establishes the producer responsibility in collecting WEEE and lists some hazardous material.

Note: Elaboration of the authors.

and affiliations of authors. Each journal is assigned to one or several WoS subject categories based on certain criteria and citation patterns (Pudovkin and Garfield, 2002; Leydesdorff and Rafols, 2009). Examples of these WoS subject categories are 'Materials Science, Multidisciplinary', 'Metallurgy & Metallurgical Engineering' and 'Environmental Science'.[9]

The empirical analysis was conducted in two stages. First, we analysed the data to identify time, geographic and institutional patterns of knowledge development in WEEE-related technologies. To check authors' affiliations, we searched on the words 'University' and 'Research Institute' in different languages; for other institutions we identified individual affiliations. Second, we focused on the disciplines in which the WEEE scientific articles were published to obtain information on the main topics covered. To do this, we used the global map of science (2010 update), a newly developed method that visually locates bodies of research within a science map, which allowed us to identify the areas where WEEE publications occur most often and whether this has changed over time (Rafols et al., 2010).

The representation of science proposed by the scientists who developed this method builds on the WoS Journal Citations Report published in 2007. Each journal in the Thompson WoS dataset is assigned to a WoS subject category. The citation patterns of the journals in each category allow us to build a network. The resulting network is a science map in which each link is weighted by a similarity measure, calculated by comparing the node's neighbourhood (i.e. the nodes to which it is connected). Finally, the canonical science map is obtained by displaying the map based on the Kamada and Kawai algorithm to reveal similar proximate nodes. The resulting map tends to show more proximate WoS subjects with similar citation patterns. To facilitate interpretation of the map, factor analysis was performed to aggregate the disciplines (i.e., the network nodes) into a different number of macro-disciplines (e.g. 19, 6 or 4) (Riopelle et al., 2014). For the analysis in this article, we use the aggregation into six macro-disciplines,[10] represented on the maps using different colours. Having achieved a stable representation of the science, that is, a visualization of science, we can 'overlay' publications or references produced by a specific organization or research field onto this stable background, which allows comparisons that reveal unfolding patterns of knowledge creation (see Rafols et al. 2014 for an application to pharmaceutical).[11] This highlights how publication patterns change over time or differ according to type of institution. The reliability of this exercise is confirmed by studies that show that these maps are robust to the use of different classifications of publications, clustering algorithms and visualization techniques (Klavans and Boyack, 2009; Rafols and Leydesdorff, 2009). The advantage of this methodology over simple tabulation is mainly the possibility to use the relational dimensions of the science map and, therefore, to evaluate the cognitive sparseness of the research related to a technology. Therefore, it provides more information on the knowledge base underpinning a specific technological process.

Finally, in order to ascertain the role of our three drivers, we follow the literature and rely on the information provided by the title, abstract and keywords (Garechana et al., 2014b). We develop a list of keywords related closely to each driver and we searched for

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[9] Each subject is described in the WoS documentation. An example is 'Environmental Science covers resources concerning many aspects of the study of the environment, among them environmental contamination and toxicology, environmental health, environmental monitoring, environmental geology, and environmental management. This category also includes soil science and conservation, water resources research and engineering and climate change' (Scope Notes 2012 – Science Citation Index, 2012Scope Notes, 2012Scope Notes 2012 – Science Citation Index, 2012).

[10] The 6 macro-disciplines are Social Sciences, Psychology and Social Issues, Biology and Medicine, Environment Science &Technology, Physics, and Computer Science and Engineering.

[11] All the files and algorithms needed for the construction of a science map are available at http://www.leydesdorff.net/overlaytoolkit/. A user friendly toolkit is available to build a Science Map from the WoS using Pajek.

them in the publications' titles; abstracts and keywords. Although we do not screen the main text of the publications; we are confident that relevant motivations will be reported in the analysed text.

4. Empirical results

The first part of the empirical section examines general trends in the development of e-waste related knowledge; the second part analyses the global maps of science (Leydesdorff and Rafols, 2009; Leydesdorff et al., 2013) derived from the publication data.

4.1. Trends in the development of e-waste knowledge

Fig. 1(a–c) shows the evolution in the number of articles, and the price trends for precious materials (gold and silver) and copper. We focus on these three metals since, together with palladium, they are the most used in electrical and electronic equipment and, therefore, the most recycled from WEEE. Fig. 1 presents the regulatory milestones (indicated by a straight line). The first, in 2002, refers to the first WEEE Directive (see Table 2 for an overview); the second, in 2012, refers to the second WEEE Directive. All the graphs show the rapid increase in the number of published articles, evidence of an increased focus from scientists and practitioners, on WEEE.[12] Fig. 1 shows also that, despite differences in the magnitudes (displayed on the secondary axes, i.e., the range of the prices per troy ounce), there is a clear relation between the increase in the value of precious materials (Fig. 1a,b) and copper (Fig. 1c), and the number of publications over time. This relation is confirmed by the correlation coefficients of the number of articles and the prices of these metals (in US$ per troy ounce), which range between 0.87 and 0.9 ($p = 0.01$). Fig. 1 shows also that the steep increase in the number of publications coincides with implementation in 2002 of the first WEEE regulation and the RoHs Directive. Section 2.3 discusses the importance of this regulatory milestone at the global level for fostering scientific research in several scientific domains (see Section 4.2).

Analysis of author affiliations provides information on employing institutions and their geographical locations. Fig. 2 shows that the majority of the articles (about 70%) were published by researchers from universities or public research centres[13]; however, researchers employed by private firms. such as IBM, UMICORE, Siemens, Boliden and Cisco, were also quite active.

Table 3 shows that the US and China produce the largest part of the knowledge. US leadership is confirmed also by research carried out using patent data (Kitsara, 2014). However, the EU leads for total share of publications, with Germany, the UK, France and Italy accounting for, respectively, 6.9%, 5.3%, 3.9% and 3%. The prominence of European countries might be due to the stringency of European regulation, which specifically targets WEEE management and disposal.

Fig. 3 shows the evolution in the number of articles per country, normalized by the number of scientific technical journal articles per country, based on World Bank (2011) data. US organizations were very active before 2007 after which time they were overtaken by China. Although a 'latecomer' in this field of research (the first Chinese publication was in 2005), China has caught up quickly. The recent significant involvement of China in e-waste technologies is not surprising since China is both a huge market for electronic appliances and an importer of e-waste from the western world (Wang et al., 2013). Some of the earliest research on WEEE was carried out in Switzerland and the US, where researchers have been actively involved in the scientific area since 1985.

Table 3
The percentage of the country of origin of the publication analysed.

Country	Share
US	18.9%
China	18.4%
Germany	6.9%
UK	5.3%
Japan	4.6%
France	3.9%
Taiwan	3.5%
Italy	3%
Spain	2.7%
India	2.6%
South Korea	2.4%
Netherlands	2.2%
Sweden	1.9%
Brazil	1.9%
Switzerland	1.8%
Canada	1.7%
Poland	1.5%
Australia	1.2%

Source: Computed by the authors.

4.2. Knowledge evolution: examining the topics

In this section, we use the global maps of science (Leydesdorff and Rafols, 2009; Leydesdorff et al., 2013) presented in Section 4, to examine the scientific fields involved in research on electronic waste. We also analyse publication titles and abstracts, using text-analysis, to ascertain the relevance of the three drivers identified – technological change, demand pull, and price of raw materials – between 1985 and 2013, and across macro-disciplines.

Table 4 shows the number of publications in each sub-period examined, the number of journals involved, and the top five WoS journal subject categories. Confirming the results depicted in Figs. 1 and 2, the first two rows in Table 4 show a sharp increase in the absolute number of publications and in the number of journals. This suggests that research on e-waste is being published by an increasing number of journals; however, the number of journals with more than one article, based on the Concentration Ratio 5 (CR_5) and Herfindahl–Hirschman Index (HHI), suggests there are no 'established' or 'representative' journals.[14] The CR_5 index is the share of the total number of articles published by five journals; the CR_5 has increased from 17% to 22%, indicating that the journal publishing the largest number of articles on WEEE accounts for less than a quarter of scientific production in this area. The low and rather stable level of the HHI[15] indicates that scientific production on WEEE management is published by a large number of journals, none of which is prominent. Overall, this suggests that there is no particular journal specialized in WEEE and confirms that WEEE management involves a wide spectrum of disciplines.

In relation to the WoS journal subject categories, Table 4 shows that the ranking among those most relevant to electronic wastes has remained fairly stable over time and is mainly in three

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[12] Annex C provides the number of publications per year in the sample.

[13] Some examples of public research centres are National Taiwan University Science & Technology (Taiwan), University of Michigan, Dept. Geological Science (US), Ecolé Mines Ales (France) and Wuhan University (China).

[14] Results not reported here show that the ranking of the journals in which these articles are published is not stable over time.

[15] The HHI generally is used in competition law to assess the degree of competition in a market by measuring the relative market share of a firm in relation to all its competitors. It is defined as the sum of the squares of the market shares of the firms within the industry, where market share is expressed as a fraction. Increases in the HHI generally indicate a decrease in competition and an increase in market power, while a decrease indicates the opposite. This framework can be applied to any situation where the aim is to measure the dispersion of shares beyond the original formulation of market shares.

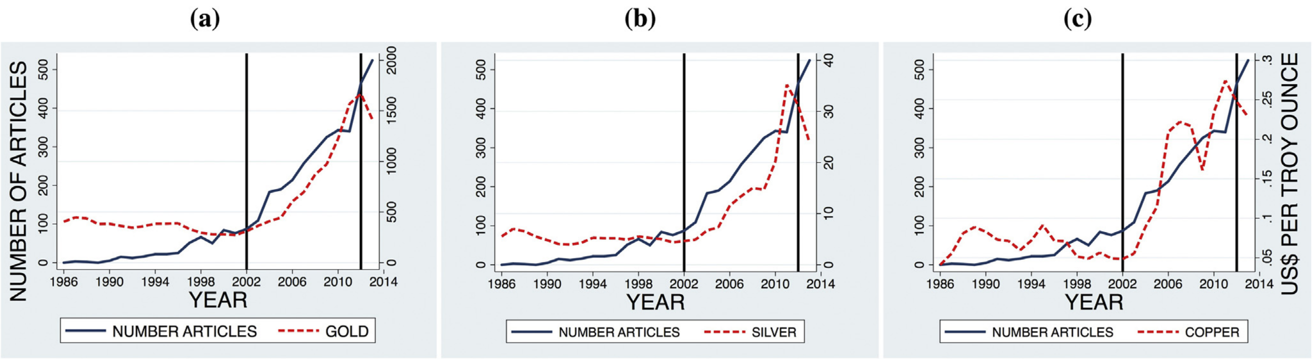

Fig. 1. Evolution of number of articles on WEEE compared with the price (expressed in constant US Dollars for Troy Ounce) of Gold, Silver, and Copper.
Source: Authors' calculation on data retrieved from http://www.indexmundi.com/.

Table 4
Sample size and characteristics over the considered sub-periods.

	Before 2002	2002–2007	2008–2014
Number of articles	451	1040	2288
Number of journals	316	521	1036
Number of journals with more than 1 article	54	140	287
CR_5	17%	19%	22%
HHI	0.013	0.015	0.014
Top 5 ISI Subject categories	Engineering, Electrical & Electronic Engineering, Environmental Environmental Sciences Materials Science, Multidisciplinary Metallurgy & Metallurgical Engineering	Engineering, Electrical & Electronic Engineering, Environmental Engineering, Manufacturing Environmental Sciences Materials Science, Multidisciplinary	Engineering, Electrical & Electronic Engineering, Environmental Environmental Sciences Materials Science, Multidisciplinary Metallurgy & Metallurgical Engineering

Note: CR_5 indicates the share of articles published by the top 5 journals. The Herfindahl–Hirschman Index (HHI) indicates the dispersion of publications activities across the journals.

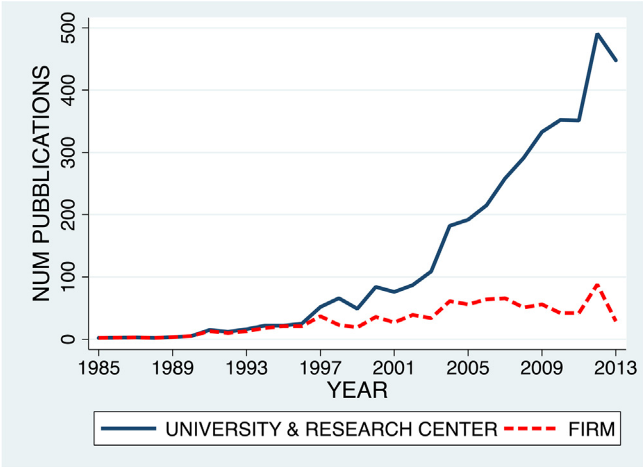

Fig. 2. Evolution of total number of articles per University as well as Research Centre and Firm.

Source: Authors' calculation.

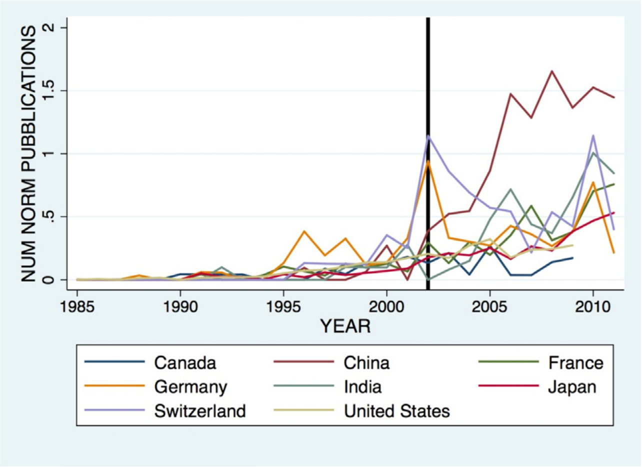

Fig. 3. Number of publications in the field of WEEE normalized by all scientific and technical publication (per thousand of publications) of each country (collected by World Bank).

Source: Authors' calculation.

macro-disciplines: Environmental Science and Technology, Physical Science and Technology and Computer Science and Engineering. The cognitive variety among the top WoS subject categories (i.e., Environmental Science, Electrical and Electronic Engineering) suggests some multi-disciplinarity in research on electronic waste. However, in order to add to our analysis the dimension of the cognitive distance between these active and diverse scientific areas, we draw on the global map of science to visualize the extent of exploration of the scientific space (Börner et al., 2003).

4.2.1. *Mapping before 2002*

The network depicted in Fig. 4 represents the global map of science developed using scientific publications relevant to e-waste, published before 2002. The size of the nodes (i.e., the WOS subject categories) is proportional to the number of publications in that specific subject; however, to improve readability of the map, node labels are shown only for those nodes where the number of publications is in the 95th percentile.[16] Finally, based on node colour, we

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[16] For summary statistics on the distribution of the number of publications per WOS subject category, see Annex E. The complete set of maps is available on request.

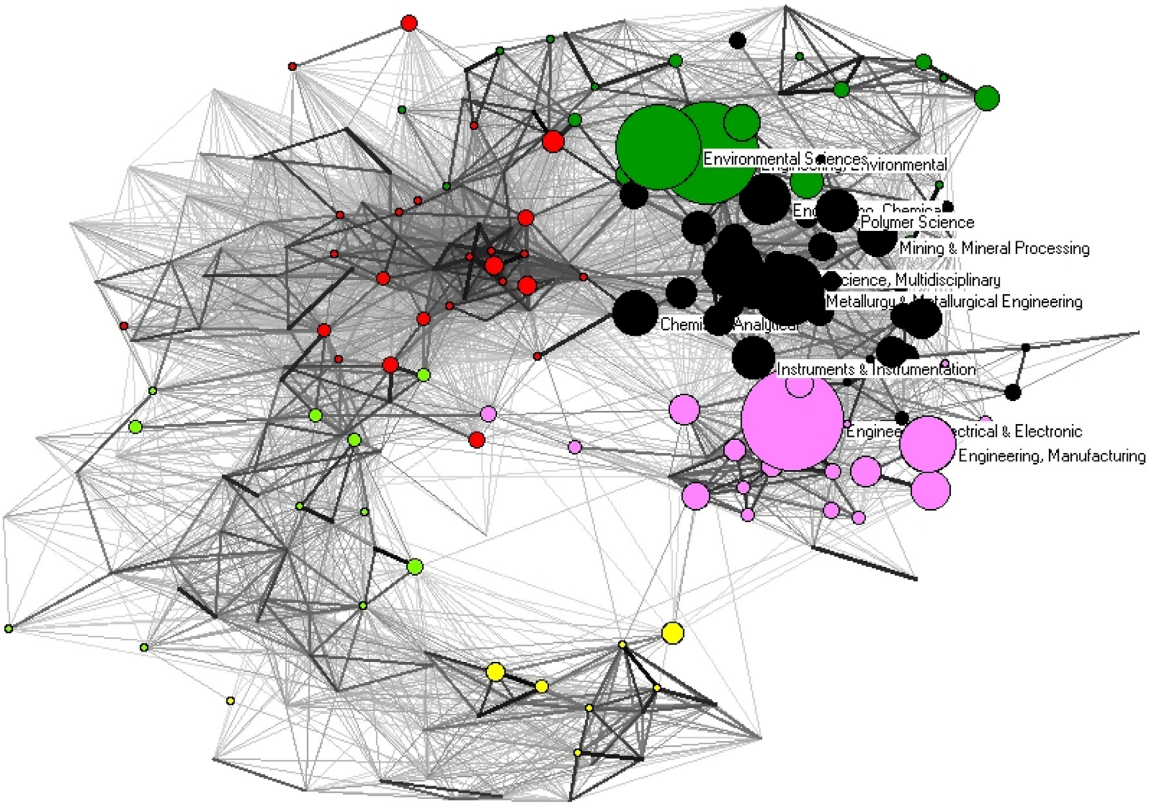

Fig. 4. Global map of science for electronic waste publications (before 2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Legend: Colours refer to different macro- disciplines. Dark Green: Environment S&T, Yellow: Social Sciences, Light Green: Psychology and Social Issues, Red: Biology and Medicine, Black: Physics, Pink: Computer Science and Engineering.

can identify six clusters of similar scientific domains (i.e., macro-disciplines) in the global map of science (2010 update) (Riopelle et al., 2014).

Fig. 4 shows that, between 1985 and 2001, most research on e-waste was in three macro-disciplines: "Environment S&T" (green nodes); 'Computer Science and Engineering' (pink nodes); and 'Physics' (black nodes). However, not all the disciplines in these clusters are involved equally; for instance, within the green cluster most research relates to Environmental Science and Environmental Engineering. In order to assess the relevance of our drivers in the context of these maps, we performed a text analysis to identify articles specifically mentioning concepts related directly to our three drivers.[17] This allows qualitative assessment of each article and quantification of how many articles are affected by each driver. The results of the text analysis are reported in Table 5.

The last row in Table 5 shows that the most prominent driver during the period analysed is price of rare material, with 43% of the articles focused on recycling of precious metals. Ranked second is technical change (25.17%), followed by regulatory intervention (12.42%). Across scientific macro-areas, we see that these drivers affect scientific disciplines in different ways. For instance, precious metals prices and technical change respectively, affect mostly Physics, and Environmental Science &Technology.

In the Physics macro discipline (black nodes in Fig. 4), the most active domains are Metallurgy, and Metallurgical Engineering. The articles in these two domains cover analysis of different types of minerals and their technical characteristics, and provide an evaluation of the alternative technologies needed to implement and improve the recycling process. For instance, different hydrometallurgical and pyrometallurgical processes are analysed and compared to assess their environmental impact. This suggests that the trajectory highlighted in Section 2.1, in which new recovery technologies are aimed specifically at reducing the emissions resulting from the treatment of toxic heavy metals and the recovery of precious materials (Inoue, 1999; Zhang and Forssberg, 1997), are identified within our set of publications. The findings in these articles confirm that hydrometallurgy is the most interesting method from both a green and a recycling process quality perspective (Hoffmann, 1992). Other nodes, such as Chemical Engineering and Polymer Science, are also prominent within Physics. All the research in this area focuses on chemical treatments for various waste recovery processes (Garechana et al., 2014a), but especially WEEE recycling (e.g. hydrometallurgical technology).

Evidence of the increasing importance of environmental issues is the fact that precious metals prices and technical changes also affect the Environmental S&T macro-area. The prominence of Environmental Science and Environmental Engineering suggests some complementarity: new technologies for the recycling of precious metals involves finding environmentally sound ways to deal the hazardous materials contained in e-waste and the toxic material used in the recycling process (Sjodin et al., 2001; Chien and Wang, 2000).

The third driver considered in this paper, regulatory intervention, seems to have a smaller impact, which is evident mostly in the Computer Science and Engineering macro-cluster. Within this cluster, Electrical and Electronic Engineering is the most prominent scientific discipline and the second most active discipline in the period before 2002. Research in this area is aimed at improv-

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[17] The list of keywords used to search the articles' abstracts and titles are available on request.

Table 5
Text analysis of the drivers along time and across macro-disciplines.

	DRIVER								
	TECHNOLOGY			REGULATION			PRECIOUS METAL PRICE		
	PRE 2002	2002–2007	2008–2013	PRE 2002	2002–2007	2008–2013	PRE 2002	2002–2007	2008–2013
Psychology and Social Issues	0.00%	0.10%	0.00%	0.00%	0.10%	0.22%	0.2%	0.2%	0.3%
Physics	9.48%	7.69%	12.64%	1.55%	15.87%	8.96%	20.2%	9.2%	11.1%
Computer Science and Engineering	0.79%	1.83%	2.00%	5.99%	33.37%	11.54%	7.1%	6.3%	3.9%
Biology and Medicine	1.35%	1.63%	1.77%	0.44%	0.96%	1.92%	1.1%	0.7%	0.7%
Environment S&T	13.42%	8.27%	7.10%	3.99%	14.81%	7.47%	15.1%	12.3%	19.8%
Social Sciences	0.13%	0.00%	0.00%	0.44%	1.06%	1.84%	0.2%	0.9%	0.3%
TOTAL	25.17%	19.52%	23.50%	12.42%	66.15%	31.95%	43.9%	29.6%	36.1%

ing the design of products to reduce energy consumption and to improve the recovery of precious and rare minerals. The articles in this area touch, in particular, on topics related to regulatory changes and how to re-design electronic appliances to comply with the ban on the use of some hazardous materials[18] following implementation of the RoHS. The attention to green design began at the end of the 1990s when EU policy interventions became focused on eco-design and producers' social responsibility (Bertram et al., 2002). Moyer and Gupta (1997) underline that researchers in the field were concerned about the impending EU regulation (released in 2002). Although the articles analysed are the outputs of research carried out before the implementation of major regulatory acts, scientists and stakeholders likely expected more stringent regulation, which, possibly, led to more scientific research. In particular, In the case of the REACH Directive, participation in ex-ante discussions has been shown to have worked to channel information to scientists and stakeholders and allow their participation in the design of regulation (Udovyk and Gilek, 2014).

4.2.2. Mapping between 2002 and 2007

Fig. 5 shows the global map of science for the period 2002–2007. Comparison with Fig. 4 suggests that previously active research areas continue to be prominent; however, areas such as Instruments and Instrumentation, Mining and Mineral Processing, and Polymer Science have been replaced by Energy and Fuel, Industrial Engineering and Telecommunications.[19]

Table 5 highlights an important change in the relevance of the drivers examined. The increasing regulatory stringency, linked to the implementation of the WEEE Directive and RoHS regulation in 2002, is reflected in the prominence of regulation as a driver of research published between 2002 and 2007 (66%), followed by the precious metals price (29.6%) and technical change (25.17%).

As in the previous period, regulation mostly affects Computer Science and Engineering. Articles published in this area directly address some of the requirements of the WEEE Directive such as the need for optimal material and product flow management at the end of the product life cycle, mechanization of the disassembly phase of specific components such as the cathode ray tube (CRT), and evaluation of mechanical compared to manual WEEE processing for some components.[20] Regulatory compliance also affects research in Physics and Environment S&T. Articles published in this area stress the need for eco-design to facilitate recycling to be a priority for firms (see Eikelenberg et al., 2004).

The second driver in the period 2002–2007 is the price of precious metals. Again, the two most affected macro-areas are Physics and Environmental S&T, but in this period the latter is the most important one. Articles published in this area not only focus on metals recovery technology but also on improvements to the separation phase. Fundamental to increasing the efficiency of metals recycling is the quality and purity of the shredded scrap, which dictates the quality of the recovered metal and its purity. Research in several domains, particularly Metallurgy and Metallurgical Engineering and Material Science, and Multidisciplinary (all Physics domains), is pivotal to efficient precious metals recycling (Silvas et al., 2015).

During the period 2002–2007, technical change is relatively less important compared to the other two drivers. However, as in the previous period, the two most affected macro-areas are Environment S&T and Physics. Articles published in these areas are aimed at making the recycling process more efficient and 'greener' by reducing the consumption of energy in WEEE recycling[21] and developing new biometallurgical processes, which are cleaner and less energy intensive (Cui and Zhang, 2008). This result suggests that our finding of energy-related research in the area of waste management (Garechana et al., 2012) is confirmed also for WEEE management.

An interesting trend observed between 2002 and 2007 is the increasing relevance of Social Sciences research (yellow nodes) and, particularly, in the area of Management and Operations Management. Analysis of the literature in this area shows that WEEE operations management is aimed at improving every step in the recycling process (e.g., compaction methods to reduce the volume of the waste) (Niu and Li, 2007) and the design of an efficient logistics network for WEEE (Chang et al., 2006). The literature on the management of waste overlaps with several logistics management topics (Maslennikova and Foley, 2000; van den Brink and Szirmai, 2002), suggesting that e-waste management is becoming a problem for producers, which need to improve eco-design and production in order to meet increasingly demanding policy requirements.

4.2.3. Mapping between 2008 and 2013

Fig. 6 depicts the most recent developments in scientific research on electronic waste. Compared to Fig. 5 we observe notable differences among the 11 WoS subject categories in the 95th percentile; Energy and Fuel, Industrial Engineering, and Telecommunications have become secondary to Multidisciplinary Chemistry, Physical Chemistry and Civil Engineering.

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[18] Examples are 'Examining the environmental impact of lead-free soldering alternatives' (by L. J. Turbini, G. C. Munie, D. Bernier, and J. Gamalski) published in 2001, and 'Isolating LCD's at the end-of-life using active disassembly technology: a feasibility study' (by J. D. Chiodo, J. McLaren, E.H. Billett and D.J. Harrison) published in 2000.

[19] Note that as for the previous figure, only nodes in the 95th percentiles of the distribution of publications are labeled in Fig. 5.

[20] Examples are: 'Data gathering using RFID technology from disassembly and recycling systems' (by Cosic, I, Lazarevic, M., Anisic, Z.; et al.) published in 2006, 'Robot-based disassembling of cathode ray tubes' (by Kohlmaier, M.; Wittmann, C.) published in 2004, and 'Copper recovery from waste of electrical and electronic equipment' (by Kljajin, M.; Kozak, D.; Ivandic, published in 2003.

[21] An example is 'Piezoelectronic ceramic fiber composites for energy harvesting to power electronic components' (by R. Cass, F. Mohammadi, S. Leschin) published in 2007.

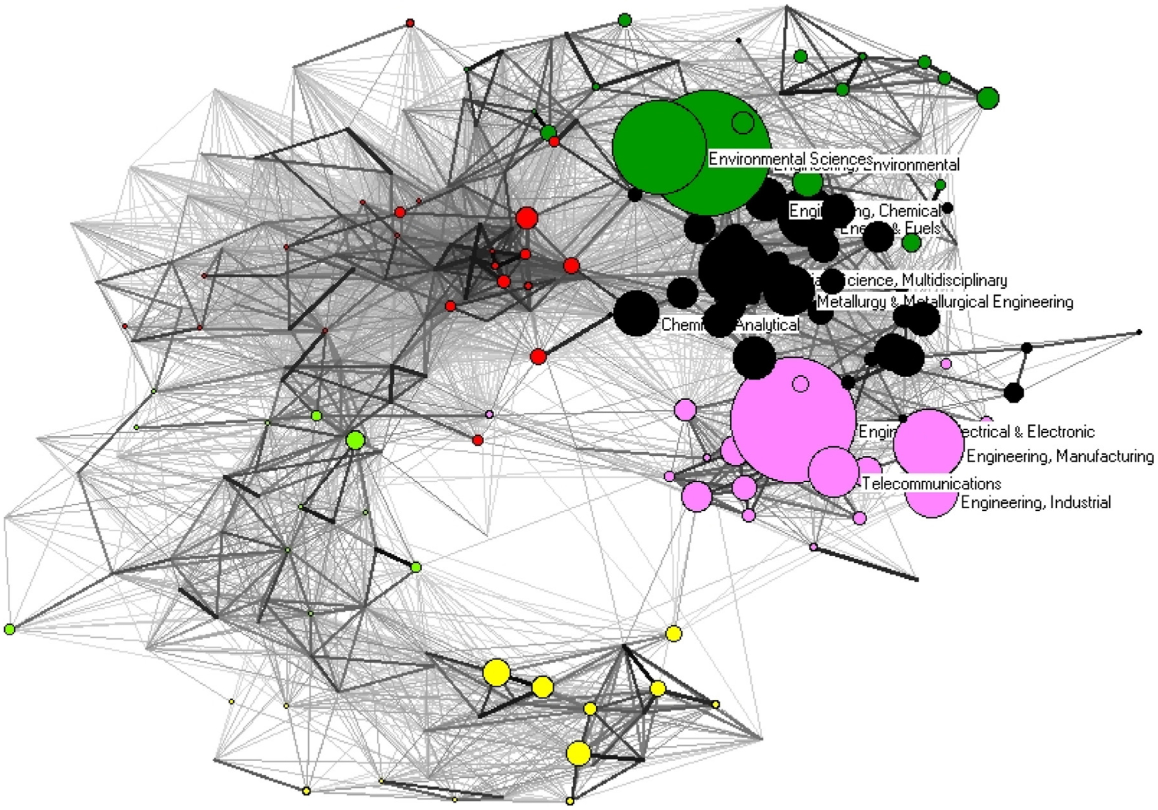

Fig. 5. Global map of science for electronic waste publications (2002–2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Legend: Colours refer to different macro- disciplines. Dark Green: Environment S&T, Yellow: Social Sciences, Light Green: Psychology and Social Issues, Red: Biology and Medicine, Black: Physics, Pink: Computer Science and Engineering.

Table 5 shows that, in this period, the precious metals price is again the most important driver of research, with 36.1% articles mentioning precious metals recycling, followed by 31.95% mentioning regulation and 19.52% technical change.

The price of precious metal mostly affects Environment S&T and the articles published highlight that researchers are working on how to improve the separation phase to improve the quality of the recovered raw materials. As in the previous periods, regulation mostly affects Computer Science and Engineering and Physics, fostering scientific research into compliance with EU regulatory requirements (particularly WEEE and RoHS), and improving eco-design to facilitate the dismantling and recycling of specific components.

Technical change has most impact on Physics, with contributions focusing generally on hydrometallurgy and biometallurgy. In the latter area, research focuses on the quality and environmental impact of bioleaching. Finally, during the period 2008–2013, there is an increase in the importance of the macro-clusters Social Science (yellow nodes), and Psychology and Social Issues (light green nodes). This indicates that growing societal concern over WEEE management is fostering research in the 'soft sciences'. The two research areas (nodes) most involved are Management and Environmental Studies. Management is topologically closer to engineering and encompasses the growing body of work analysing the economic and managerial implications of different recovery technologies. Environmental Studies deals with the complex interactions between people (especially consumers) and the environment, and firms' behaviour towards WEEE and end of life management (Tasaki et al., 2006).

4.2.4. *Geographical distribution of knowledge development*

We are interested in whether there are other differences related to geographical locations. Based on author affiliations, we can identify three country groups (European, developing and other developed countries) and analyse their publications.[22] From a regulatory view point, the EU is prominent (see Table 2) and is setting the standard for other world countries. The series of EU regulations has increased the attention of engineers to management and regulatory issues (Koh et al., 2012) in Europe and in developing countries. There is a major stream of work analysing the ways that several governments are seeking inspiration from European e-waste policies to tackle their e-waste problems (OECD, 2011). Research is aimed, in particular, at optimizing the implementation of directives by focusing on an eco-design strategy (Zuidwijk and Krikke, 2008). Greater attention is being paid to illegal trade in electronic waste, and the implementation and enforcement of regulation in developing countries. The literature underlines that e-waste management is a trans-national problem and involves several illegal activities.

5. Conclusion

Several scholars have studied the sources of technical change extensively, but have failed to identify a sole driving force (Ruttan, 1997; Dosi, 1997). For instance, technology and demand play a role in different phases: the first is crucial at the beginning of tech-

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[22] See Annex D for the assignment to each group. Note, also, that if a publication is authored by individuals in different geographical areas we double count the publication.

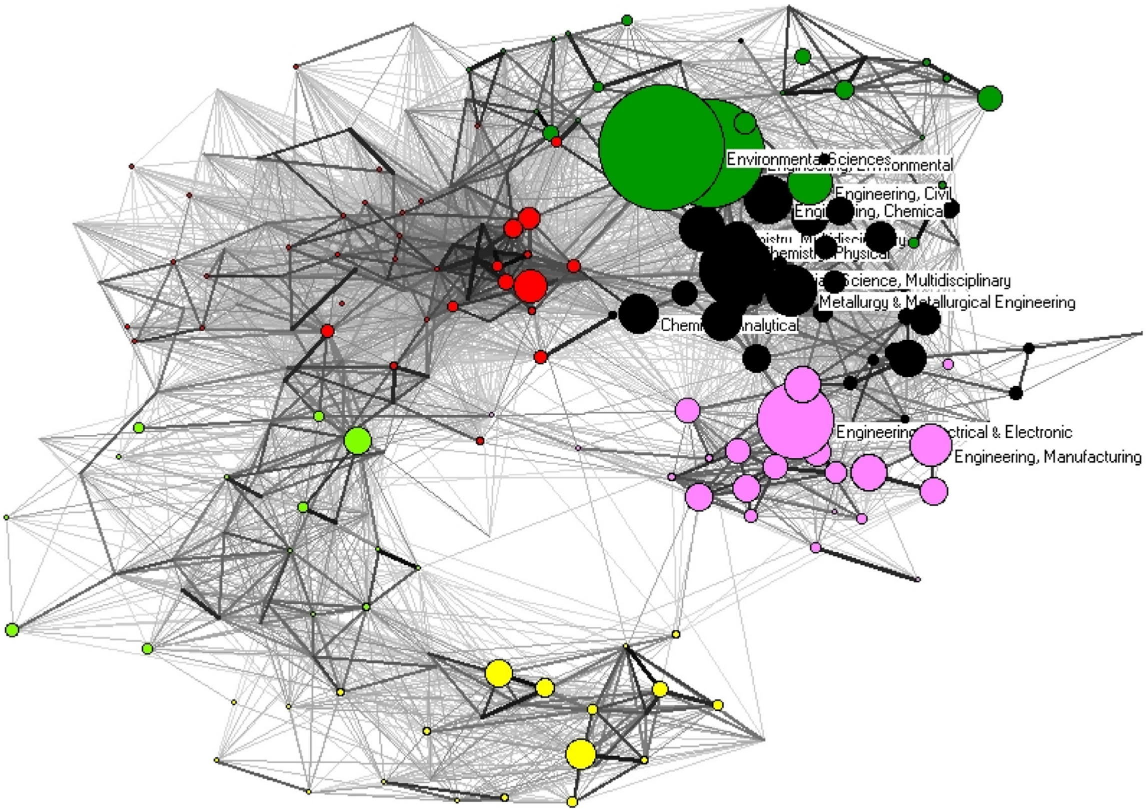

Fig. 6. Global map of science for electronic waste publications (2008–2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Legend: Colours refer to different macro- disciplines. Dark Green: Environment S&T, Yellow: Social Sciences, Light Green: Psychology and Social Issues, Red: Biology and Medicine, Black: Physics, Pink: Computer Science and Engineering.

nological development, and the second matters in the innovation diffusion phase (Park, 2014). In addition, regulation and induced innovation have been identified as drivers of knowledge development (Popp et al., 2011).

The article builds on the innovation literature, which identifies three main drivers of knowledge development (i.e., stringency of regulation, technical progress and induced innovation) to analyse the drivers of knowledge creation for management and recycling of e-waste. Interest in this area is motivated by the fact that WEEE is the fastest growing waste stream in the EU. Also, given the number of precious and noble metals and the hazardous materials needed to manufacture these complex electronic products (OECD, 2011), disposal and re-utilization of e-waste is an issue for engineers, consumer electronics companies and policy makers. However, it is an under-investigated topic in social science and, especially, public policy analysis.

This article contributes to filling this gap by shedding light on the locus of research relating to e-waste management, the research fields involved and the main drivers of scientific research. This research agenda was tackled using publications data retrieved from the Thompson Web of Science (WoS) dataset using keywords. The empirical analysis was carried out on a sample of articles published between 1985 and 2013. Based on these data, we developed global maps of science (Leydesdorff and Rafols, 2009; Rafols et al., 2010) to identify the most active scientific domains in e-waste management, and their relationships. Using keywords, we assessed the role of the three drivers identified, across scientific macro-discipline and across time.

The global map of science shows that research in WEEE management spans several macro-disciplines with the most prominent being Environment S&T, Computer Science and Engineering and Physics. Within these macro areas the most active subject area is Environmental Science, an interdisciplinary domain whose inclusion of several knowledge domains allows a holistic approach to the solution of complex environmental problems. The global maps of science highlights the increasing number of articles on e-waste published in social science areas such as economics and management. These articles often relate to organizational issues in the area of compliance with producer responsibility.

The keyword analysis shows that, consistent with the literature, all three drivers are at work, but their relevance varies across disciplines and over time. For instance, the impact of technology tends to be less volatile over time, but also less relevant. Its impact is limited to Physics and Environmental S&T, where most of the research is in the form of chemistry studies related to reducing the environmental impact of the recycling process. Regulation appears relevant throughout the period considered, since it encourages innovation in the design of electronic products and influences process and organizational innovations to reduce the environmental impact of electronic waste. The impact is particularly strong in Computer Science and Engineering; in fact, regulatory compliance requires a redesign effort in relation to several electronic appliances. Finally, the role of regulation is particularly strong during period 2002–2007, following EU policy interventions including the WEEE Directive and RoHS, which triggered research in various disciplines. In relation to raw materials prices, we found a strongly significant correlation between the number of articles and silver and gold prices. We found, also, that a significant number of articles in all three periods are related to the extraction of these metals from WEEE.

Alongside the role of technology, the price of materials has a strong impact on Physics and Environmental S&T, with articles focused on environmentally sound extraction of these raw metals from WEEE. Analysis of author affiliations highlighted the primary role of universities and research centres. In relation to the geographic location of the production of knowledge in this field, it is concentrated on a few countries including the US, China and Germany. Although developing countries are often involved in some phases of e-waste development, they do not contribute to the creation of knowledge in this field.

The present article contributes to innovation research by providing a better understanding of the nature of the knowledge generating process in electronic waste and, in particular, on the drivers that are at work in different areas of WEEE management. This is important for more informed and more effective policy intervention.

Our study has some limitations. First, our study does not find any particular causal effects among the forces identified and the creation of knowledge. Our analysis of the scientific literature allowed us to make an assessment only of the role of policy and market factors in the development of this increasingly important technological field. Second, we use publications rather than patents, which do not allow us to focus on technological innovations. Nevertheless, although our approach allowed us to capture important organizational innovations (e.g., in logistics and management) not captured by patents, in our view, a natural extension of this work, would be patent analysis. Third, the analysis in this paper exploits only Thompson WoS data. Although this might introduce some bias towards English journals and hard science, WoS data provide a sample of publications from influential and comparable (in terms of quality) journals.

Acknowledgements

We would like to thank the external anonymous experts for their comments and advices. The errors are our own.

Annex A.

The empirical analysis was performed on a set of articles retrieved from ISI Web of Science. The search in the database was made using a list of relevant words in the TOPIC field. The words searched for were:

1. electronic AND scrap;
2. electronic AND waste;
3. e-scrap;
4. escrap;
5. WEEE;
6. waste electrical and electronic equipment;
7. electronic equipment WEEE;
8. e-waste;
9. ewaste;
10. printed circuit board AND recycling;
11. Printed circuit board scrap;
12. electronic AND waste;
13. electronic AND separation AND recycling;
14. electronic AND separation AND scrap;
15. ROHS;
16. Recovery precious metal AND electronic scrap;
17. Recovery precious metal AND electronic waste;
18. Electronic waste AND recycling;
19. Electronic scrap AND recycling.

The search in the ISI Web of Science database was performed on 10th February 2014.

Annex B.

Query number	Number of articles	Query
# 16	3797	#15 OR #14 OR #13 OR #12 OR #11 OR #10 OR #9 OR #8 OR #7 OR #6 OR #5 OR #4 OR #3 OR #2 OR #1 Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 15	505	TS = (electronic equipment WEEE) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 14	231	TS = (electronic scrap AND recycling) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 13	1085	TS = (electronic waste AND recycling) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 12	72	TS = (recovery precious metal AND electronic waste) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 11	58	TS = (recovery precious metal AND electronic scrap) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 10	198	TS = (printed circuit board scrap) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 9	512	TS = (rohs) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 8	184	TS = (electronic AND separation AND recycling) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 7	92	TS = (electronic AND separation AND scrap) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 6	347	TS = (printed circuit board AND recycling) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 5	555	TS = (waste electrical and electronic equipment) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 4	746	TS = (weee) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 3	21	TS = (e-scrap) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 2	434	TS = (electronic AND scrap) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013
# 1	2813	TS = (electronic waste) Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH Timespan = 1985–2013

Annex C.

Year of publication	Number of publications	Year of publication	Number of publications
1985	2	2001	76
1987	3	2002	87
1988	2	2003	109
1990	5	2004	183
1991	15	2005	190
1992	12	2006	214
1993	16	2007	257
1994	22	2008	291
1995	22	2009	325
1996	25	2010	343
1997	51	2011	340
1998	66	2012	465
1999	50	2013	524
2000	84	Total	3779

Annex D.

European countries: Germany, France, Belgium, UK, Netherlands, Poland, Italy, Sweden, Denmark, Spain, Czech Republic, Portugal, Austria, Greece, Slovenia, Croatia, Lithuania, Finland, Hungary, Slovakia, Romania, Bulgaria, Estonia, Ireland;

Developing countries: China, South Africa, India, Russia, Belarus, Ukraine, Argentina, Brazil, Venezuela, Bolivia, Mexico, Colombia, Chile, Morocco, Tunisia, Pakistan, Egypt, Yugoslavia, Turkey, Malaysia, Thailand, Vietnam, Philippines, Sri Lanka, Serbia, Jordan, Georgia, Bangladesh, Iran, Saudi Arabia, Ghana, Nigeria, Algeria;

Other developed country: US, Canada, South Korea, Japan, Israel, Australia, Norway, Switzerland, Taiwan, United Arab Emirates, Singapore, New Zealand

Annex E. Descriptive statistics of the publications per WoS category for the global map of science.

	Average	Median	75 Quantile	95 Quantile	Min	SD	Max
Fig. 4 (Pre 2002)	4.116	1	3	16	0	12.829	112
Fig. 5 (2002–2007)	9.638	1	5	39	0	35.404	330
Fig. 6 (2008–2013)	19.871	2	11	74	0	71.787	783

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