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The evolution of waste into a resource: Examining innovation in technologies reusing coal combustion by-products using patent data

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ABSTRACT

The reuse of waste begins with the development of new technologies for ways to use waste. Despite the critical role of innovation in waste reuse, innovation for waste reuse technologies has been largely overlooked in innovation studies. This paper presents the first patent study examining the innovation process for a specific waste reuse technology, to elucidate how waste evolves into a resource with a greater possibility of being used. This study specifically analyzes how innovation occurs, what drives it, and the consequences of this innovation. Coal combustion by-products (CCBs), which are solid residues generated from coal-fired utilities, are specifically examined as a test case because they have been promoted as a resource through century-long innovative efforts for use in construction, mining, and agricultural applications. Having examined more than 700 patents from the United States Patent and Trademark Office database, the results of this study show that innovation has primarily occurred: (1) to reuse CCBs, particularly fly ash, in various building, construction, and structural products; (2) by businesses, particularly those that need to use CCBs; and (3) since 1967, and the number of CCB-related patents peaked during the early 1980s and 1990s. For the drivers of innovation, this study identifies the impact of some market factors, such as cement and lime price, and institutional activities, such as the establishment of industrial associations that support CCB reuse, on patent filings. The role of regulation in innovation, however, is ambiguous with regard to CCB reuse. Although more CCBs have been used as more innovation occurs, the use of CCBs has increased with a lag, due to variation in the values of individual technologies and barriers to the implementation of technologies in the reuse market.

1. Introduction

Technology governs the life cycle of materials with regard to how they are mined, manufactured, used, and discarded. The interplay between technology and materials, however, is not well understood in the case of waste. Waste exists in the anthroposphere, often without the appropriate technology to use it, which is different from natural resources that are extracted according to the available technology. Taking no actions for waste bears costs to society and the environment, because discarding waste increases the anthropogenic disturbance when it is either landfilled or released back to nature. The alternative way, recycling and reuse of waste, requires the development of appropriate technologies that make reuse possible. Along with new knowledge about where and how to reuse waste materials, the hidden value of these materials have started to be recognized (Park and Chertow, 2014). This innovation process requires skills that are sometimes more creative than the original production process because reuse opportunities need to be explored given specific characteristics of the material (Reno, 2009). Therefore, innovation is a pre-requisite for facilitating waste reuse and forms a basis for the sustainable materials management that is envisioned by the United States Environmental Protection Agency (USEPA, 2003, 2009) and the concept of industrial ecosystem that has closed-loop material flows (Frosch and Gallopoulos, 1989; Graedel and Allenby, 2003).

Despite the importance of innovation in waste reuse, no previous studies have examined the innovation of a specific waste reuse technology. Only a few studies briefly examined the patent data for waste management, which includes disposal, incineration, and recovery, or waste recycling as a single component within a larger group of environmentally responsible technologies (Johnstone et al., 2010a; OECD, 2008). Instead, studies have focused on emission control technologies (Popp, 2003, 2006, 2010; Taylor et al., 2003), climate change mitigation technologies (Dechezleprêtre et al., 2011; Haščič et al., 2010), renewable energy technologies (Johnstone et al., 2010b), and technologies for green chemistry

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(Nameroff et al., 2004). Other studies have examined innovation as conditions of waste reuse or consequences thereof, but those studies addressed innovation in a broader sense by encompassing social, organizational, behavioral, and institutional dimensions (Boons and Berends, 2001; Harris and Pritchard, 2004; Mirata and Emtairah, 2005). Therefore, these studies lack a specific focus on technological innovation, how it occurs, what drives it, and its consequences.

Because of the lack of studies regarding the role of technological innovation in waste reuse, this is the first study to empirically examine the innovation patterns and processes of a waste reuse technology. It first identifies the patterns of innovation by counting the number of successful patent applications, and then discusses the underlying causes and effects of innovation. For driving forces behind innovation, it investigates relevant regulatory actions, institutional activities, and economic factors in relation to patterns of patent filings. To examine the consequences of innovation, patent patterns are compared to the amount of waste that is actually reused. A detailed study of innovation for a waste reuse technology can advance understanding of environmental innovation, particularly by investigating its unique characteristics compared to other environmental innovations.

Coal combustion by-products (CCBs) are selected for the empirical portion of this study. CCBs refer to several types of solid residues, such as fly ash, bottom ash, boiler slag, flue-gas desulfurization residues, and fluidized bed combustion ash, which are generated during coal-fired electricity production. Fly ash is a fine particulate captured by particulate control equipment, whereas bottom ash and boiler slag are coarser and heavier fractions that are collected at the bottom of the furnace. Bottom ash consists of porous particles that have fallen from pulverized dry-bottom boilers, and boiler slag comes from pulverized wet-bottom boilers (slap-tap furnace) or cyclone boilers where it is quenched with water and fractures into an angular, glassy slag (EPRI, 2009; Pflughoeft-Hasset et al., 1999). Different types of flue-gas desulfurization (FGD) residues are generated from a sulfur dioxide scrubbing process depending on the type of sorbent used, the extent of oxidation, and post-scrubbing processes including dewatering, drying, and blending (Kosson et al., 2009). FGD gypsum is formed when wet residues from limestone-based scrubbing process are subject to forced oxidation (Ward, 2010). Fluidized bed combustion (FBC) ash collectively refers to the fly ash and bed ash generated by a FBC boiler in which a mixture of coal and a sorbent such as limestone is fluidized by combustion air that is forced upwards. CCBs have evolved from materials that were mostly discarded in the 1930s, to materials that are reused more and more often, through the development of reuse applications over a century. Some countries, such as France, Germany, South Korea, and the Netherlands, were reusing greater than 90% of the fly ash, bottom ash, and boiler slag during the late 1980s and early 1990s (Manz, 1997). Recent statistics showed that Japan and 15 countries in Europe reused more than 96% and 89% of CCBs, respectively (European Coal Combustion Products Association, 2008; JCOAL, 2009). Therefore, CCBs can be seen as a category that straddles the boundary between what is defined as a waste and what as a resource, thus provide an interesting example at the interface where technology meets waste.

2. Literature review of environmental innovation studies

The role of government regulation in inducing changes of environmental technology has been a main focus of the environmental technology literature. This type of research was motivated by Hicks' "induced innovation" whereby a change in the relative price of production factors, which can be influenced by government interventions, would motivate firms to invent new production technologies to economize the use of input factors (Hicks, 1932). Porter has also argued that regulation can increase profits while inducing R&D investment because innovation that involves a high degree of uncertainty is not the result of an optimization process (Porter and van der Linde, 1995). When addressing the effect of regulation on innovation, regulatory stringency, which is often measured by pollution abatement expenditures, has been of interest (Brunnermeier and Cohen, 2003; Lanjouw and Mody, 1996; Pickman, 1998); however, increasing focus has been placed on the different forms of regulation (Jaffe et al., 2002; Magat, 1979). Compared to direct command-and-control type regulations, market-based instruments are known to often be more effective for encouraging the adoption and diffusion of new technologies. For example, Popp (2003) empirically showed that trading of sulfur dioxide allowances under the 1990 Clean Air Act led to more environmentally-friendly innovation in scrubbers. The strong relationship between regulation and environmental innovation, however, sometimes makes regulation a major barrier for inducing and adopting environmental technology (Office of Technology Policy, 1998). Whether regulation acts as a driver or a barrier for innovation depends on its design and implementation. For example, the negative influence of regulation can be particularly aggravated when it is overly unpredictable, prescriptive, and inflexible (Johnstone and Haščič, 2009).

Whereas regulatory pressure has been studied as the primary determinant of environmental innovation, innovation is also influenced by other factors. It is generally accepted that technology push factors are particularly important during the initial stage of innovation, whereas market demand factors are important for the diffusion phase (Pavitt, 1984). In a case study of environmental product innovation in Germany, price was observed to be the primary obstacle in the commercialization of environmentally superior products (Rehfeld et al., 2007). In addition, organizational measures such as certified environmental management systems and other firm specific factors, can influence environmental innovation (Horbach, 2008). Different factors may exert different levels of influence on environmental innovation. In an empirical study, Cleff and Rennings (1999) observed that environmental innovation at the product level is influenced more by market factors, whereas environmental process innovation is influenced more by regulations. They argued that a simplistic regulatory stimulus, such as the innovation response approach, is not appropriate for addressing all environmental innovations.

In this study, findings from previous studies are expanded and built upon, and the innovation for a waste reuse technology, its patterns, drivers, and consequences, are investigated to determine whether observations of other environmental innovations are also applicable to waste reuse innovation. Because waste reuse requires the involvement of diverse actors, such as waste generators, processors, marketers, and users in different sectors of industry, innovation for a waste reuse technology may have more complicated underlying drivers. Whereas the role of regulation in innovation has been examined as a strong driver in the environmental innovation literature, this may not be the case for waste reuse innovation. Waste reuse and innovation can be influenced by regulations that support waste reuse, regulations that address the disposal of waste, and regulations that have an indirect impact on reuse by changing the quantity and quality of waste.

3. Methods

3.1. Data collection and management

To track innovation, particularly invention in CCB reuse technology, this study examined patent statistics. Despite their shortcomings, patent statistics are the most widely used measure of