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Establishing and testing the “reuse potential” indicator for managing wastes as resources

Joo Young Park*, Marian R. Chertow

Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, 195 Prospect Street, New Haven, CT 06511, United States

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ABSTRACT

This study advances contemporary ideas promoting the importance of managing wastes as resources such as closed-loop or circular material economies, and sustainable materials management by reinforcing the notion of a resource-based paradigm rather than a waste-based one. It features the creation of a quantitative tool, the “reuse potential indicator” to specify how “resource-like” versus how “waste-like” specific materials are on a continuum. Even with increasing attention to waste reuse and resource conservation, constant changes in product composition and complexity have left material managers without adequate guidance to make decisions about what is technically feasible to recover from the discard stream even before markets can be considered. The reuse potential indicator is developed to aid management decision-making about waste based not on perception but more objectively on the technical ability of the materials to be reused in commerce. This new indicator is based on the extent of technological innovation and commercial application of actual reuse approaches identified and cataloged.

Coal combustion by-products (CCBs) provide the test case for calculating the reuse potential indicator. While CCBs are often perceived as wastes and then isolated in landfills or surface impoundments, there is also a century-long history in the industry of developing technologies to reuse CCBs. The recent statistics show that most CCBs generated in Europe and Japan are reused (90–95%), but only 40–45% of CCBs are used in the United States. According to the reuse potential calculation, however, CCBs in the United States have high technical reusability. Of the four CCBs examined under three different regulatory schemes, reuse potential for boiler slag and flue-gas desulfurization gypsum maintains a value greater than 0.8 on a 0–1 scale, indicating they are at least 80% resource-like. Under current regulation in the United States, both fly ash and bottom ash are 80–90% resource-like. Very strict regulation would remove many reuse options decreasing potential for these two CCBs to 30% resource-like. A more holistic view of waste and broad application of the new indicator would make clear what technologies are available and assist public and private decision makers in setting quantitative material reuse targets from a new knowledge base that reinforces a resource-based paradigm.

1. Introduction

Since the 1980s, most states in the United States have adopted what the United States Environmental Protection Agency (USEPA) has labeled the “solid waste management hierarchy” which has a strong basis in material conservation (USEPA, 1989). By placing waste reduction and reuse at the top of the hierarchy, management strategies that prioritize conserving embedded energy and materials are shown to be favored. The next tiers, recycling and composting, change the physical form of discarded materials but still preserve some of the embedded value, while waste to energy and landfilling, at the bottom of the hierarchy are least conserving. In 2003, USEPA envisioned a turn toward “sustainable materials management,” managing materials, either waste or non-waste, in an integrative and consistent way based on their product life cycles, thus shifting focus to long-term, multiple, and system-wide environmental impacts (USEPA, 2003, 2009).

Such a shift toward material conservation and reuse has also been observed elsewhere. Industrial ecology and related fields recognized that unused material flows can be highly wasteful and

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* Corresponding author. Tel.: +1 203 432 4985, +1 475 201 8237 (mobile); fax: +1 203 432 5556.

E-mail addresses: jooyoung.park.jp637@yale.edu, jooyoung.park.jp637@gmail.com (J.Y. Park).

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inefficient, causing both resource scarcity problems and waste problems, in comparison with a system based on closing loops along the model of food webs in nature (Chertow, 2000; Frosch, 1996; Graedel and Allenby, 2002). The concept of circular economy was adopted as a national policy in China (Yuan et al., 2006), while similar policies to enhance resource efficiency were established in Germany and Japan (Moriguchi, 2007).

Despite increasing attention to the more integrated notion of wastes as resources, problems persist in analysis and implementation. Although material by-products have been reused since prehistoric times, modern technological societies have dramatically increased both the quantity and complexity of what constitutes today's discard streams, exacerbating the management challenges of how to determine which streams are wastes and which are resources. Incomplete and inconsistent waste statistics show continuing confusion around waste definition and categorization, challenging reuse efforts. In the same year that USEPA counted 230 million short tons of municipal solid waste (MSW), BioCycle Magazine's annual waste count was 383 million tons and the industry-focused Environmental Research and Education Foundation's count was 544 million tons (Chertow, 2002, 2009). Industrial waste, known to be in the billions of tons in the United States in comparison to MSW (U.S. Congress, 1992) is even more difficult to assess (Chalmin and Gaillochet, 2009; Chertow, 1998; Dernbach, 1993). Other discards add to the complexity of the waste stream such as the rapidly rising variety of electronic goods, advanced materials in construction and manufacturing waste, and pesticide residues in agricultural waste. It becomes difficult for public and private managers to keep up with the ever changing nature of what is a waste and what is a resource, how the categories and characterizations change over time, and how product and technological innovation alter the composition of discards.

Considering the lack of evaluative tools to support and ground the efforts toward waste reuse, this paper contributes a new quantitative tool, "the reuse potential indicator," to assist actual decision-making to manage wastes as resources. The reuse potential indicator provides information about the technical feasibility of reuse even before market conditions are assessed by addressing how development of a new technology alters the usefulness of waste materials. It represents the next evolutionary move toward what we have termed the "resource-based paradigm" to describe the collective turn away from the waste-based paradigm. Under the resource-based paradigm, waste materials are considered potential resources set to take advantage of unexploited opportunities for reuse unless or until proven otherwise (Dijkema et al., 2000).

In the following sections, a literature review is offered first to contextualize work related to the wastes as resources argument (Section 1.1) and to examine previous approaches to quantifying characteristics of waste (Section 1.2). In Section 2.1, the resource-based paradigm is briefly presented, and its quantitative metric, the reuse potential indicator is introduced in Section 2.2. Following a detailed methodological discussion of how to use the indicator, it is then applied in Section 2.3 to the case of coal combustion by-products (CCBs), the solid residues generated when producing coal-fired electricity, to quantify their reuse potential. The final sections discuss the reuse potential calculation results for CCBs and conclude with some management implications and limitations of the indicator.

1.1. Context for the wastes as resources argument

Transformation in managing materials, particularly closing the loop through the reuse of waste, is closely related to changes with how we view waste. Waste in general tends to be perceived with negative connotations to be something discarded, but it is often reused when its value is perceived and recognized. For example, excrement was considered as waste in Europe, but it was used with value in Asia. Reuse is a common practice in contemporary India and a large population and limited wealth probably contribute to the cultural practice of thriftiness. According to a recent study done by Bain et al. (2010), a cluster of 45 industries in Mysore, South India recovered over 99% of 900,000 tons of waste generated in the area annually, with most reused by the generators themselves. Such high recovery rates are rarely observed in industrial areas of developed countries. With respect to household-level reuse and recycling behaviors, attitudinal and contextual factors have been studied such as pro-recycling attitudes, concerns for community, perceived moral obligations, effects of income, and convenience of recycling channels, in determining recycling behaviors (Barr, 2007; Cheung et al., 1999; Chu and Chiu, 2003; Guerin et al., 2001; Martin et al., 2006; Tonglet et al., 2004).

Establishing a definition of waste, or determining what falls under the category of waste versus non-waste, has long been a contentious topic in the field of waste regulation. As Tromans (2001) has pointed out, the goal of regulation is to seek to establish a proper balance between dual objectives: on the one hand, protecting the environment and on the other hand, conserving natural resources. Over-regulation of waste by defining it widely would hinder the reuse that saves natural resources, whereas under-regulation of waste by defining it narrowly might cause environmental harms due to the careless handling of waste. The long history of debate around waste definition has been well documented in the case of the European Commission Waste Framework Directive (Tromans, 2001; Wilkinson, 1999, 2002), as well as in the case of the Resource Conservation and Recovery Act (RCRA) of the United States (Gaba, 1989). In most of the controversies, the materials in question were determined to be waste in order to limit the risk of pollution (Bontoux and Leone, 1997). However, in the most recent revision of the Directive, the European Commission incorporated the "end-of-waste" and "by-product" status in Article 6 and 5, respectively (Nash, 2009). Using the end-of-waste concept, the European Commission proposed clarification of the conditions when waste ceases to be waste. The end-of-waste criteria help to alleviate prejudice related to waste labeling, and increase confidence of users, thus encouraging reuse by defining technical and environmental requirements (Delgado et al., 2009).

1.2. Quantitative metrics for waste

As support for the wastes as resources argument grows, decision-makers would benefit from the use of a quantitative tool to increase scientific and evidence-based judgment. There have been other attempts to provide quantitative metrics for waste. Based on the recognition that waste is a physical metabolite of production and consumption, some studies used thermodynamic indicators such as exergy to measure the potential of waste to cause environmental harm (Ayres et al., 1998; Rosen and Dincer, 1997) or how much loss in material quality is accompanied by consumption (Connelly and Koshland, 1997, 2001). A research group at MIT developed an index based on thermodynamics and information theory to quantify the energy required to separate a valuable material, considering the fact that end-of-life products lose more value as they are mixed with other waste streams (Dahmus and Gutowski, 2007; Gutowski, 2008; Gutowski et al., 2008). While thermodynamic indicators provide some insights concerning the physical characteristics of waste, it cannot define a general statement about the quality of waste (Baumgärtner and Arons, 2003; Bisson and Proops, 2002) owing both to theoretical and practical limitations of the measurement (Gaudreau et al., 2009).

Thermodynamic indicators mainly consider physical aspects of waste, while waste is also determined by subjective "unwantedness."

To address this aspect, waste can be defined as "the opposite of value" (Gille, 2007). Being outside of value systems, waste has been handled historically either very casually or by being removed to distant or shunned places. Waste, however, is not fixed in value. Through continuous evaluation, waste moves around different "regimes of value" by gaining and losing value (Gille, 2007). In economic terms, price is what signals changing values of waste depending on the economic context (Hosoda, 2000).

Baumgärtner explains three conditions that determine the "price ambivalent" character of waste (Baumgärtner, 2004; Baumgärtner and Winkler, 2003). First, supply is independent of its price and demand (rigid supply due to joint production); second, substitution is limited due to technical or market conditions; and third, the only alternative to reuse is costly disposal (price is bounded by negative disposal costs). Stated differently, Baumgärtner's three conditions explain that a material becomes waste not solely because of its physical and/or chemical characteristics, but principally because of the mismatch between its generation and consumption. Waste has the distinction of being unintentionally generated decoupled from its demand, whereas virgin materials are extracted intentionally according to demand. While higher prices can facilitate more reuse of waste, price alone is a poor indicator for determining waste status and waste quality because it does not adequately capture externalities and it lacks the ability to address material characteristics such as toxicity (USEPA, 2009).

2. Materials and methods

2.1. Resource-based paradigm

This paper introduces the term "resource-based paradigm" to encompass and advance evolving efforts to define wastes as resources. Along with the notion of a closed-loop system, circular material economies, and sustainable materials management, the resource-based paradigm is based on the view that what we formerly perceived as wastes should instead be considered to be potential resources until determined otherwise. Table 1 summarizes the core idea of the resource-based paradigm as differentiated from the waste-based one. More detailed discussion of these two paradigms can be found in Park (2013).

2.2. Reuse potential indicator

2.2.1. Rationale and definition

The underlying idea of the reuse potential indicator is that what creates a reuse opportunity for a waste material is the knowledge of where and how to use it. Despite inherent value, some materials are disposed of in landfills because we do not know how to reuse them. Conversely, some materials are commonly recovered based on accumulated knowledge. What determines the "possibility" of reuse for a material is the extent of knowledge that has led to technological innovation for reuse.

Table 1
Resource-based paradigm versus waste-based paradigm.

	Waste-based paradigm	Resource-based paradigm
Underlying thoughts	Waste can cause harm to public health and safety until shown otherwise	Waste is a potential resource until shown otherwise
Main strategy	Safe disposal and containment	Environmentally sound processing and reuse
Language and taxonomy	Waste	Secondary materials
Operationalized metric for waste	None	Reuse potential

By measuring the extent of technological development, the reuse potential indicator expresses the usefulness of the material by a real value between 0 and 1. It equals 0 when all materials are discarded and 1 when all materials can be reused (Fig. 1). If a certain secondary material has a reuse potential value of 0.45, it implies that 45% of it can be reused through current technologies. In other words, the material is viewed as 45% "resource-like" or 55% "waste-like." Even though the reuse potential indicator does not directly analyze physical, chemical, or mineralogical characteristics of a material, it indirectly reflects material characteristics as a function of technology development. If the reuse potential is high, it means that the material has more components that can be recovered by available technology. Low reuse potential can arise either because the material contains a high concentration of toxic elements that are costly to be removed, or because of a lack of technology development.

Reuse potential, owing to its reliance on technological development, is dynamic and not an inherent property of waste. The reuse potential increases as technological options increase, enabling more material recovery. This indicates that the concept of reuse potential is inherently time dependent. It can track how materials change from waste into a potential resource or vice versa, representing an evolutionary process or even a devolutionary one. Reuse potential also depends on the assumption of geographical boundaries, since reusability varies regionally owing to differences in material quality and the level of technological development. Thus, defining temporal and geographical scope is important for calculating a reuse potential. Lastly, reuse potential is influenced by the level of generation. As a larger quantity of a given material is generated, *ceteris paribus*, the necessity for technological development would increase, and the reuse potential value would decrease without development of additional technologies.

2.2.2. Calculation of reuse potential

Fig. 2 shows how the reuse potential can be calculated using a hypothetical example. The *x*-axis represents the amount of a material that can be reused through available technologies, while the *y*-axis represents the net marginal revenue earned by selling processed materials minus disposal costs at capacity. We assume that a certain waste material is generated in the amount of 1000 metric tons per unit time and six technologies have been developed for reusing this material. Each technology can process this material into different forms for different uses at different costs. For example, reuse technology A can produce the highest net marginal revenue minus the disposal costs at capacity and be able to use about 100 metric tons of this material, whereas technology F can recover about 125 metric tons but with negative net marginal revenue minus the disposal costs. Thus, only technology A through C would contribute to the actual recovery of the material. The remaining technologies, D, E, and F, have yet to reach the necessary commercialization stage because of higher costs, thus they need to be excluded from the calculation. Through technologies A, B, and C, approximately 650 metric tons of the original 1000 metric tons of material are economically recoverable, rendering a reuse potential

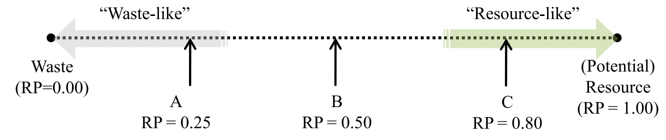

Fig. 1. The scale of reuse potential (RP). Reuse potential can be expressed as a real value between 0 and 1, where 0 represents "waste" (all the materials that are generated are likely to end up discarded, waste-like) and 1 represents potential "resource" (all the materials that are generated can be used, resource-like). Movements along this line represent the evolution of waste materials.

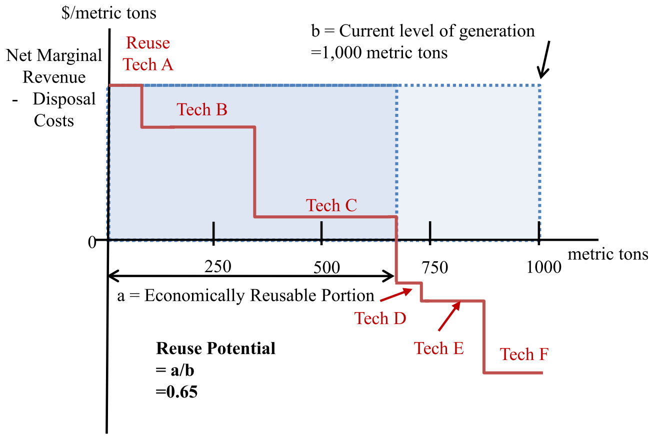

Fig. 2. Reuse potential methodology. The *x*-axis represents the amount of a material reused in metric tons and the *y*-axis represents the net marginal revenue minus disposal costs in dollars per metric ton of material reused (the graph simply shows the average level of net marginal revenue minus disposal costs at capacity, not considering a decrease in unit costs due to economies of scale). Through technologies A, B, and C, 650 metric tons of materials can be economically reused out of 1000 metric tons generated, yielding a reuse potential of 0.65.

of 0.65. This material can be said to be “65% resource-like” or “35% waste-like.”

2.3. Test case: coal combustion by-products (CCBs)

The developed reuse potential indicator is tested with the case of coal combustion by-products (CCBs). CCBs are solid residues generated when coal is combusted to produce electricity. According to the location of collection, the type of boilers, and the type of pollution control technologies, CCBs are classified into fly ash, bottom ash, boiler slag, and flue-gas desulfurization (FGD) residues including FGD gypsum. Fly ash is a fine, powdery material in flue gas that is captured by particulate control equipment, while bottom ash and boiler slag are coarser and heavier fractions that are both collected at the bottom of the furnace. FGD materials are the by-products of a sulfur dioxide scrubbing process, typically using calcium-based sorbents such as lime or limestone.

CCBs straddle the line between wastes and resources, which makes them an interesting test case in this study. They constitute one of the largest annual waste streams in the United States, close to 120 million metric tons (ACAA, 2011), taking up considerable space in landfills and surface impoundments. On the one hand, the massive generation of CCBs and also catastrophic events such as the Tennessee Valley Authority’s enormous ash spill in December 2008, have made them negatively perceived as “hazardous waste” (ACAA, 2010). On the other hand, CCBs are resources for which reuse applications are widely developed and their reuse has been practiced actively. Fig. 3 shows a century-long history of the development of CCB reuse technologies based on patent filings and the increasing quantity of CCBs used in the United States. While the reuse rate of CCBs in the United States fluctuates around 40–45%, the reuse rates have reached substantial levels of 89% in Europe (15 countries) and 96% in Japan (European Coal Combustion Products Association, 2008; JCOAL, 2009). The variation depends on the level of CCB generation, regulation, and market conditions.

Fly ash and bottom ash have become widely used as aggregates in concrete, road base, pavement, and fills, in place of natural aggregates such as sand and gravel, because their composition is similar to that of natural soils (EPRI, 2009a; USEPA, 1988). Fly ash is particularly a representative substitute of cement used in concrete, structural fills, and stabilization of soil and waste, especially due to its role in improving the quality of concrete (NETL, 2006; Ramme and Tharaniyil, 2004; Ward, 2010). Bottom ash and boiler slag are suitable ingredients for snow and ice control, blasting grit, roofing granules, asphalt, and construction aggregates (EPRI, 2009a; FHWA, 2011; Ramme and Tharaniyil, 2004; Ward, 2010). FGD gypsum chemically resembles natural gypsum with purity ranges from 96% to 99% (NETL, 2006), thus it is effective as a wallboard ingredient, a retarder for concrete, and an additive to cement clinker, replacing natural gypsum. Calcium and sulfur in FGD gypsum make it a useful fertilizer providing essential plant nutrients (Chen and Dick, 2011; Dick and Kost, 2006). Calcium also helps to enhance flocculation and improve water infiltration in highly dispersed soils, such that FGD gypsum can be used as a soil amendment.

While CCBs have many broad uses, leaching of toxic elements in CCBs such as arsenic, lead, selenium, cadmium, and mercury (Ramme and Tharaniyil, 2004; USEPA, 1988, 2011) can harm human health and ecological receptors by contaminating groundwater, surface water, and soil (USEPA, 1988). Especially in the case of surface impoundments that manage CCBs with water, risk from leaching is higher due to a hydraulic head (USEPA, 2010a). The risk assessment study conducted by the USEPA showed some exceedances of risk criteria for cancer and non-cancer risks, especially for unlined units, surface impoundments and co-disposal units of CCBs (USEPA, 2007b, 2010b). Actual damage cases were also observed in the field (USEPA, 2007a, 2010a). Massive quantities in the disposal units tend to multiply the risks from CCBs, but their beneficial reuse may show a significantly different risk profile according to the quantity of CCBs used and their chemical form in products. Environmental concerns from the use of CCBs will be discussed more in

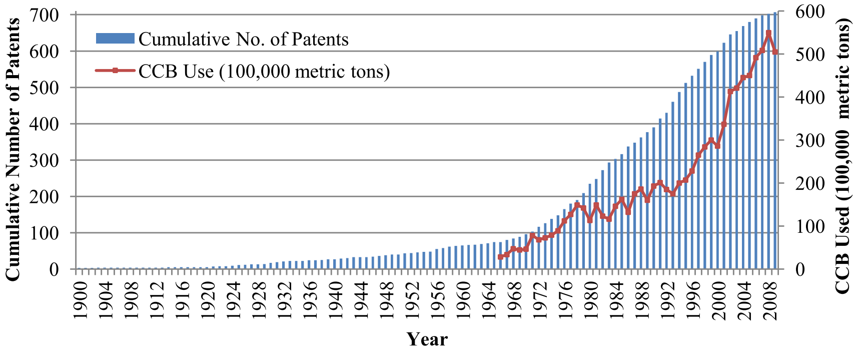

Fig. 3. Cumulative number of patents filed (bar graph, readings on the left axis) in years between 1900 and 2009, and total amount of CCBs used in 100,000 metric tons (line graph, readings on the right axis) each year between 1966 and 2009. Data for the bar graph were compiled by the author (Park, 2013), while data for the line graph comes from Kelly and Sullivan (2006).

detail when calculating the reuse potential in the following sections.

2.3.1. *Reuse potential of CCBs*

To quantify the resource-like aspect of CCBs, the reuse potential indicator was calculated for fly ash, FGD gypsum, bottom ash, and boiler slag. Because the value of reuse potential changes according to geographical and temporal factors, we limited the analysis to the United States in the year 2009 where sufficient data were available for a first empirical attempt to apply what has heretofore been a hypothetical construct only.

To calculate reuse potential, reuse categories were first determined based on the classification system used in the 2009 CCB utilization survey conducted by the American Coal Ash Association (ACAA). Per reuse category, the most widely applied technology was selected and considered in the calculation. In this way, only commercialized reuse technologies were included in the calculation. To illustrate, Table 2 shows the variety of commercial use applications for fly ash (Column A) and how the initial stages of the calculation are made.

Next, for each application, the amount of CCBs that could have been used further ("further use potential," column C of Table 2) was estimated and recorded along with the actual amount of reuse in 2009 ("actual reuse in 2009," column B of Table 2). The estimation was made in two different approaches depending on data availability, either considering technical specifications or substitution between CCBs and natural substitutes. Estimates based on substitution assumptions ignored the possibility that competing substitutes for CCBs (e.g., blast-furnace slag) could reduce the potential demand for CCBs, because their existence does not influence the quality and usefulness of CCBs. Also, estimates were made in a range according to varying assumptions and later converted into three different levels (i.e., low, median, high) to show the extent of uncertainty and variation involved in the calculation. Two examples of calculation steps are presented in Table 3 to show how further use potential values were determined.

Finally, the potential demand for CCBs (sum of further use potential and actual use) calculated for each application category was summed up and divided by the total quantity of CCBs generated in 2009 (e.g., 57,152,649 metric tons for fly ash) to derive the final reuse potential value (Gray rows of Table 2). All calculation processes and associated assumptions are presented in the Supplementary material.

Table 2
Calculation of reuse potential in the case of fly ash.

Reuse category (*A*)	Actual reuse in 2009 (*B*) (Metric tons)	Further use potential (*C*) (Median value, metric tons)
Concrete, concrete products, grout	8,887,220	7,968,018 (*D*)
Blended cement, raw feed for clinker	2,209,815	322,085
Mineral filler in asphalt	0	362,840
Blasting grit, roofing granules	43,282	48,750
Gypsum panel products	0	0
Aggregate	79,213	–
Case 3: reuse potential = $(B + C)/57{,}152{,}649$ metric tons = 0.35		
Flowable fill, structural fill, embankments	4,455,399	13,790,000
Road base, Sub-base	180,083	351,880
Soil modification, soil stabilization	607,846	736,553
Waste stabilization and solidification	3,189,017	131,396
Case 2: reuse potential = $(B + C)/57{,}152{,}649$ metric tons = 0.76		
Snow and ice control	0	0
Mining applications	1,948,788	84,058
Agriculture	93,357	29,939 (E)
Miscellaneous, others	728,564	–
Case 1: reuse potential = $(B + C)/57{,}152{,}649$ metric tons = 0.81		

Table 3
Examples of further use potential estimation.

Example 1 (technical specification): further use potential of fly ash in concrete category (estimate *D* in Table 2)	
Concrete production in 2009	$A = 258{,}551{,}000$ cubic yards
Typical range of fly ash content in concrete	$B = 125 - 180$ pounds/cubic yard of concrete
Potential demand estimated based on technical specifications	$C = A^*B = 14{,}659{,}595 - 21{,}109{,}817$ metric tons
Amount of fly ash that qualifies for the ASTM requirements for use in concrete (1/3 of fly ash generated in the United States)	$D = 19{,}050{,}880$ metric tons
Potential demand adjusted for fly ash quality	$E = C \cap D = 14{,}659{,}595 - 19{,}050{,}080$ metric tons
Actual amount of fly ash reuse in 2009	$F = 8{,}887{,}220$ metric tons
Further use potential	$G = E - F = 5{,}772{,}375 - 10{,}163{,}660$ metric tons
Example 2 (substitution): Further use potential of fly ash in agriculture category (estimate *E* in Table 2)	
Lime sold or used for fertilizer and agricultural lime	$A = 52{,}000$ metric tons
The substitution ratio between fly ash and lime	$B = 50\%–100\%$
Typical ratio of specific gravity for fly ash to lime	$C = (2.00 - 2.80)/3.3$
Potential demand for fly ash able to be used in agriculture	$D = A^*B^*C = 15{,}758 - 44{,}121$ metric tons
Further use potential	$E = D = 15{,}758 - 44{,}121$ metric tons

As shown in Table 2, reuse potential values for CCBs were calculated for three different cases. Case 1 considers all reuse categories and the associated technologies appearing in the ACAA's CCB utilization surveys in which reuse is allowable under the United States law and actually was documented and reported in 2009. Case 2 excluded in the calculation three land applications from the list of Case 1 reuse categories for: a) snow and ice control, b) mining, and c) agricultural applications. These three land applications of CCBs are still controversial when considering the potential adverse impact on human health and the environment (Dewan, 2009; Lombardi, 2010), while the remaining reuse categories included in the second case are generally accepted as safe, classified as "bound" applications according to the system used in the United Kingdom (Northern Ireland Environment Agency, 2010; The Environment Agency, 2008). Case 3 further excluded applications such as fills, road base, and soil/waste stabilization, even though these are allowable under USEPA's classification. Case 3 only considers so-called "encapsulated uses" according to USEPA's rulemaking such as CCB uses in cement, concrete, wallboard, and plastics, where CCBs are retained in a matrix that hinders leaching of any toxic constituents in CCBs (USEPA, 2010a). No adverse health risks are expected from using products encapsulating CCBs according to some leaching and risk assessment studies (EPRI, 2008, 2009b). While Case 1 assumed that all applications could reuse CCBs in an environmentally safe way, Case 3 took the most conservative view that safe reuse of CCBs was limited to encapsulated reuse categories only. The "Miscellaneous, Others" category was excluded in the second and the third case because of the lack of information about the environmental implications of CCB reuse.

3. Results: reuse potential of coal combustion by-products

Fig. 4 presents reuse potential values for each of the three cases. When considering all reuse categories reported by ACAA (Case 1), the median reuse potential values for the four CCBs analyzed were

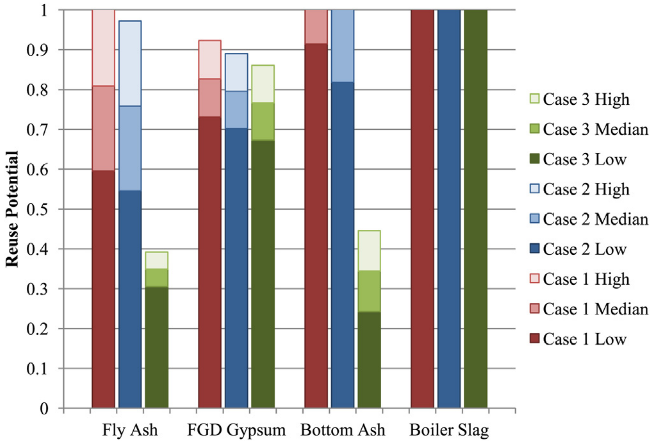

Fig. 4. Reuse potential values at three different levels (represented as dark, medium, and light colors) and under the three different cases (represented as red, blue, and green bars) for fly ash, FGD gypsum, bottom ash, and boiler slag generated in 2009 within the United States. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

all higher than 0.8, meaning that they are more than 80% resource-like. As supported by this high value of reuse potential, CCBs have already evolved into resources to a considerable extent with the development of reuse technologies available in the United States by 2009. Exclusion of a few reuse categories which are controversial for potential adverse impacts on human health and the environment (Case 2) did not change the reuse potential values much. The reuse potential values for fly ash showed between 2.8% and 8.3% reductions, and those of FGD gypsum showed 3.6–3.9% reductions. The bottom ash showed 10.4% reductions only in the lowest reuse potential value with no change occurring for the rest. In Case 3, however, the median reuse potential values for fly ash and bottom ash were significantly reduced to 0.35 and 0.34, respectively. Reuse categories including fills, road base and soil/waste stabilization represent a considerable portion of fly ash and bottom ash potential demand. In contrast, for all three cases, reuse potential values of boiler slag remained at 1 even with the most conservative assumptions. For FGD gypsum, the reuse potential consistently exceeded 0.7 in all three cases, reinforcing its strong resource-like nature.

Fig. 5 is a visual representation of further use potential and actual reuse in 2009 for all CCBs calculated for Case 1. Dark colors represent actual quantity of CCB use in year 2009 and lighter colors represent further use potential for CCBs. It shows that fly ash has an enormous potential to be reused in fills, embankments, and concrete products, but not much potential was found in the rest of reuse categories. To increase the quantity of fly ash reuse, it would be most technically feasible to target reuse applications such as fills, embankments and concrete products. In absolute terms, further use potential of fly ash was much larger than that of other types of CCBs, but fly ash had the lowest range of reuse potential values because of its massive annual generation. Bottom ash also had the largest potential to be reused in fills and embankments, while FGD gypsum had its single largest potential in gypsum panel products. The further use potential of FGD gypsum was highly concentrated on gypsum panel products instead of dispersing over a variety of reuse categories, so the potential to increase its reuse was relatively limited compared to fly ash or bottom ash. Even though boiler slag had a reuse potential value of 1, it still has more potential to be used in road base, sub-base, blasting grit, roofing granules, and aggregates.

4. Discussion

4.1. Management implications of reuse potential

The test run of the reuse potential indicator in the case of CCBs showed the utility of the indicator to quantify the usability of waste

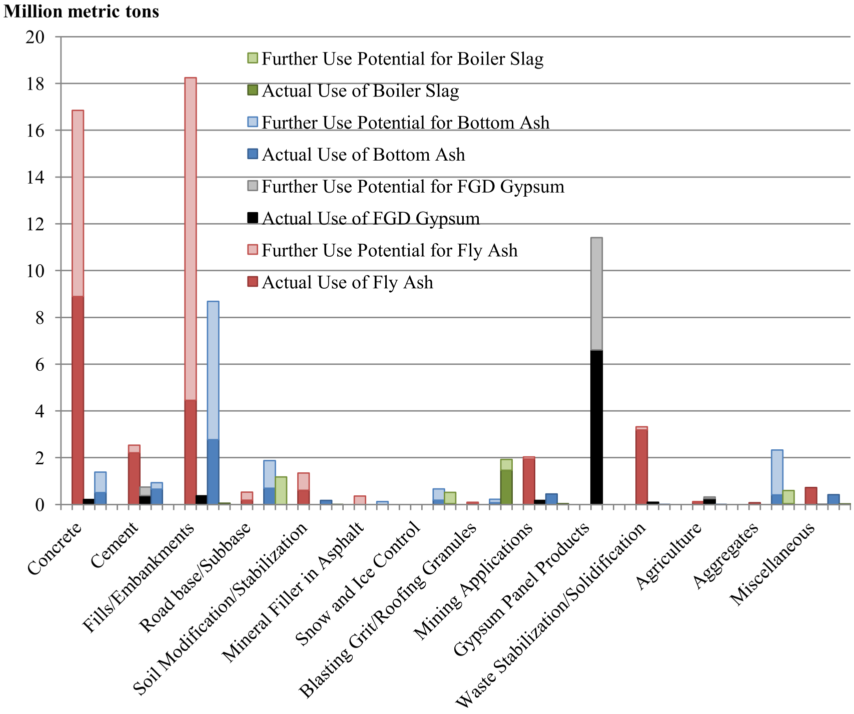

Fig. 5. Actual amount of reuse in 2009 and additional amounts that technically could have been used in 2009 for fly ash (the first red bars in each category), FGD gypsum (the second black bars in each category), bottom ash (the third blue bars in each category), and boiler slag (the fourth green bars in each category) calculated for Case 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

materials in terms of technology development. According to Fig. 4, the reuse potential values for bottom ash and boiler slag turned out to be higher than that of FGD gypsum or fly ash in Case 1 and 2. This was an unexpected result. FGD gypsum is mainly composed of high purity calcium sulfate and fly ash is known for its value as a pozzolanic/cementitious binder. On the contrary, bottom ash and boiler slag show higher heterogeneity in their compositions. From a material perspective, fly ash and FGD gypsum seem to be of higher quality than bottom ash or boiler slag. However, low-technology uses for bottom ash and boiler slag such as in road base, structural fill, and embankments were shown to have the potential to absorb a large quantity of bottom ash and boiler slag as demonstrated more specifically in Fig. 5.

These trial runs demonstrate that reuse potential does not assess physical or chemical characteristics *per se*, but examines material characteristics by their usefulness, showing how they can be benefited by technology. This illustrates a strength of the reuse potential indicator in contrast to previous quantitative approaches to waste that attempted to measure either the thermodynamic aspect only or the economic value only. Thus, the reuse potential indicator can be seen as an effective communication tool to share information about technical quality or maximum reusability of a waste material. Traditionally, information about waste processing and reuse technology has been available among experts and relevant industrial managers who handle waste, but could be more widely shared, even among consumers, through the reuse potential indicator. Just as the Material Safety Data Sheet (MSDS) systematically compiles information on material hazards, reuse potential can serve as a similar database but on the availability of technical reuse opportunities.

Once the reuse potential values for all waste materials are calculated, decision-makers have an information base from which to set priorities for reuse projects. When a material has a low reuse potential value, a longer-term solution such as incentivizing the development of reuse technologies may be necessary because a low reuse potential value implies either the lack of reuse technologies (technological barrier) or that the material itself contains a large portion of non-reusable elements (waste-like). When a material has a high reuse potential value, there is a higher probability of increasing its reuse because it implies the existence of technological solutions even though other barriers may still need to be addressed. In addition, the calculation of the reuse potential indicator can present a breakdown of further use potentials across reuse applications, as shown in Table 2 or Fig. 5, to guide reuse strategies and targets.

4.2. Environmental assumptions of reuse potential

The reuse potential indicator was devised to support management decisions to facilitate reuse of waste and resource conservation accordingly, but it should stand on the environmental assumption that reuse is done in a way not to harm public safety and environmental health. A reuse technology that processes waste materials into reusable forms should generate environmental harms within tolerable limits, and the recycled product must meet given environmental requirements. This necessitates the establishment and operation of appropriate regulations to manage the risk of final products containing waste materials and the associated processes in reusing waste materials.

The reuse potential calculation under three scenarios showed that different regulatory schemes based on different levels of environmental assumptions may significantly change the technical reusability of CCBs. According to current assumptions and calculations, restricting the use of CCBs in fills, road base, and soil/waste stabilization would significantly decrease the reuse potential value, particularly in the case of fly ash and bottom ash. To maintain the reuse potential provided by these reuse technologies that are already available, appropriate regulations that are based on comprehensive and thorough risk assessments should follow to ensure the final safety of these products containing CCBs. Some case studies on environmental performance of CCBs exist (EPRI, 1993; Hassett et al., 2001), but these analyses could be conducted in a more comprehensive way and expanded to diverse applications.

4.3. Limitations of reuse potential and next steps

The calculation of the reuse potential indicator requires a great deal of technical data which are often difficult to obtain, such as the quality of a material to be used in a specific application and substitution ratios. Lack of available data also increases uncertainty in assuming substitution ratios. In a few cases, CCB reuse categories including mining applications were excluded from the calculation due to lack of technical data. A wider application of the reuse potential thus calls for specific attention to data generation and collection about reuse.

In this paper, the calculation of the reuse potential was tested for CCBs generated in 2009 within the United States. More calculations can be done with CCBs generated earlier or later or within different geographical boundaries to understand how technology determines the resource-like nature of CCBs over time and space. Further application of the reuse potential indicator to different types of materials in various contexts would enable comparisons and provide opportunities to refine the calculation methodology.

In measuring the usefulness of waste materials, the reuse potential indicator considers some economic elements regarding technology commercialization, but it does not reflect all economic elements such as the fluctuating price of competing substitutes or transportation costs, all of which eventually determine the reuse rate of a material. The expression “potential” indicates the ideal maximum capacity for reusing a material primarily from a technological perspective. Reuse potential is thus always higher than the actual reuse rate that is eventually determined by market conditions. Therefore, the reuse potential should be considered a complementary tool to the reuse rate which, until now, has been used as the main tool when setting up policy targets. Updated market analyses would also be useful complements to the reuse potential indicator.

As a matter of policy, the choice of CCBs as a test case was revealing with respect to the difference between primary materials and secondary materials and their markets. Between 2001 and 2008, the average annual coal share of electricity generation in the United States ranged from 48% to 51%. According to the Energy Information Agency (U.S. Energy Information Administration, 2013), that generation number is expected to decline to 40% in 2013 and coal exports are increasing. A subsidiary result is decreasing generation of CCBs affecting those who had become accustomed to having CCBs available for reuse applications such as fly ash in cement. Further research could help explain how applications and markets for by-products are influenced when the use of the primary products from which they stem have significant changes in demand.

5. Conclusions

The motivation for defining and examining a “resource-based paradigm” was to support the notion that waste should be viewed as a potential resource until shown otherwise. A novel quantitative indicator, “reuse potential,” was developed to help both material and waste managers sort out decisions about technical feasibility of reusing discards in an informed way. The reuse potential indicator describes how resource-like a material is, capturing the variable quality of materials. Based on the idea that what determines the usefulness of a waste material is our knowledge of when and how to use it, the reuse potential quantifies the technical maximum reusability according to the technologies that are economically available to reuse the material in an environmentally sound way.

To test and verify the utility of the reuse potential indicator, CCBs were chosen as a case study because of their common identification as both wastes and resources. Calculation of the reuse potential for CCBs showed that industry's long efforts to find innovative uses resulted in CCBs generated within the United States having more than 80% reuse potential in 2009 under current regulation in the United States. According to a breakdown of the further use potential by reuse categories, significant potential was found especially in fills and embankments. This provides specific guidance regarding which reuse options have the largest potential to increase CCB reuse. In a scenario assuming stricter regulations, the reuse potential values were reduced to 30% in the case of fly ash and bottom ash. Maintaining a certain level of CCB reuse should be accompanied by the establishment and operation of appropriate regulations that ensure the safe reuse of CCBs. This study shows the significant role that technological innovation can play in the broader establishment of the resource-based paradigm and, therefore, the importance of including wastes as resources as part of technology development efforts.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.11.053

References

ACAA, 2010. Comments to Hazardous and Solid Waste Management System: Identification and Listing of Special Waste; Disposal of Coal Combustion Residuals from Electric Utilities. American Coal Ash Association.

ACAA, 2011. 2009 Coal Combustion Product (CCP) Production and Use Survey Report. American Coal Ash Association.

Ayres, R.U., Ayres, L.W., Martinás, K., 1998. Exergy, waste accounting, and life-cycle analysis. Energy 23, 355–363.

Bain, A., Shenoy, M., Ashton, W., Chertow, M., 2010. Industrial symbiosis and waste recovery in an Indian industrial area. Resour. Conserv. Recyl. 54, 1278–1287.

Barr, S., 2007. Factors influencing environmental attitudes and behaviors: a U.K. case study of household waste management. Environ. Behav. 39, 435–473.

Baumgärtner, S., 2004. Price ambivalence of secondary resources: joint production, limits to substitution, and costly disposal. Resour. Conserv. Recyl. 43, 95–117.

Baumgärtner, S., Arons, J.D.S., 2003. Necessity and inefficiency in the generation of waste. J. Ind. Ecol. 7, 113–123.

Baumgärtner, S., Winkler, R., 2003. Markets, technology and environmental regulation: price ambivalence of waste paper in Germany. Ecol. Econ. 47, 183–195.

Bisson, K., Proops, J., 2002. An introduction to waste. In: Bisson, K., Proops, J. (Eds.), Waste in Ecological Economics. Edward Elgar Publishing, Inc, Northampton, pp. 1–10.

Bontoux, L., Leone, F., 1997. The Legal Definition of Waste and its Impact on Waste Management in Europe. European Commission Joint Research Centre.

Chalmin, P., Gaillochet, C., 2009. From Waste to Resource: an Abstract of World Waste Survey. Veolia Environmental Services and CyclOpe, Paris.

Chen, L., Dick, W.A., 2011. Gypsum as an Agricultural Amendment: General Use Guidelines. The Ohio State University.

Chertow, M., 2002. Pursuing sustainable solid waste management. Envtl. L. Rep. News Anal. 32, 10812–10821.

Chertow, M., 2009. Municipal solid waste: building stronger connections to jobs and the economy. In: Dernbach, J.C. (Ed.), Agenda for a Sustainable America, first ed. Environmental Law Institute.

Chertow, M.R., 1998. Waste, industrial ecology, and sustainability. Soc. Res. 65, 31–53.

Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energ. Env. 25, 313–337.

Cheung, S.F., Chan, D.K.-S., Wong, Z.S.-Y., 1999. Reexamining the theory of planned behavior in understanding wastepaper recycling. Environ. Behav. 31, 587–612.

Chu, P.-Y., Chiu, J.-F., 2003. Factors influencing household waste recycling behavior: test of an integrated model. J. Appl. Soc. Psychol. 33, 604–626.

Connelly, L., Koshland, C.P., 1997. Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology. Resour. Conserv. Recyl. 19, 199–217.

Connelly, L., Koshland, C.P., 2001. Exergy and industrial ecology. Part 2: a non-dimensional analysis of means to reduce resource depletion. Exerg. Int. J. 1, 234–255.

Dahmus, J.B., Gutowski, T.G., 2007. What gets recycled: an information theory based model for product recycling. Environ. Sci. Technol. 41, 7543–7550.

Delgado, L., Catarino, A.S., Eder, P., Litten, D., Luo, Z., Villanueva, A., 2009. End-of-Waste Criteria, JRC Scientific and Technical Reports. EU Joint Research Centre, Luxembourg.

Dernbach, J.C., 1993. The Other Ninety-six Percent. The Environmental Forum. Environmental Law Institute, pp. 10–15.

Dewan, S., 2009. Hundreds of coal ash dumps lack regulation. N. Y. Times (accessed 01. 14.10.). http://www.nytimes.com/2009/01/07/us/07sludge.html.

Dick, W.A., Kost, D., 2006. A review of agricultural and other land application uses of flue Gas desulfurization products. In: Ladwig, K. (Ed.). The Ohio State University, Palo Alto, California.

Dijkema, G.P.J., Reuter, M.A., Verhoef, E.V., 2000. A new paradigm for waste management. Waste Manage. 20, 633–638.

EPRI, 1993. Environmental Performance Assessment of Coal Ash Use Sites. Technical Brief. Electric Power Research Institute, Palo Alto, California.

EPRI, 2008. Mercury Release from Concretes Containing Fly Ash and Powdered Activated Carbon Sorbents. Technical Resource – Coal Combustion Product Use. Electric Power Research Institute.

EPRI, 2009a. Coal Ash: Characteristics, Management and Environmental Issues. Technical Update – Coal Combustion Products – Environmental Issues. Electric Power Research Institute, Palo Alto, California.

EPRI, 2009b. Human Health Risks from Mercury in Concrete and Wallboard Containing Coal Combustion Products. Technical Brief. Electric Power Research Institute.

European Coal Combustion Products Association, 2008. Production and Utilisation of CCPs in 2007 in Europe (EU15) (accessed 01.19.10.). http://www.ecoba.com/ecobaccpprod.html.

FHWA, 2011. User Guidelines for Waste and Byproduct Materials in Pavement Construction. Federal Highway Administration, United States Department of Transportation.

Frosch, R.A., 1996. Toward the end of waste: reflections on a new ecology of Industry. Daedalus 125, 199–212.

Gaba, J.M., 1989. Solid waste and recycled materials under RCRA: separating chaff from wheat. Ecol. L. Q. 16, 623–666.

Gaudreau, K., Fraser, R., Murphy, S., 2009. The tenuous use of exergy as a measure of resource value or waste impact. Sustainability 1, 1444–1463.

Gille, Z., 2007. Toward a social theory of waste. In: Gille, Z. (Ed.), From the Cult of Waste to the Trash Heap of History: the Politics of Waste in Socialist and Postsocialist Hungary. Indiana University Press, Indianapolis, IN, pp. 11–40.

Graedel, T.E., Allenby, B.R., 2002. Industrial Ecology, second ed. Prentice Hall.

Guerin, D., Crete, J., Mercier, J., 2001. A multilevel analysis of the determinants of recycling behavior in the European countries. Soc. Sci. Res. 30, 195–218.

Gutowski, T.G., 2008. Thermodynamics and recycling: a review. In: Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment. IEEE Computer Society.

Gutowski, T.G., Wolf, M.I., Dahmus, J.B., Albino, D.K., 2008. Analysis of Recycling Systems. In: CMMI Research and Innovation Conference. NSF.

Hassett, D., Heebink, L.V., Bloom, P., Gustin, F., 2001. In: Golden, D. (Ed.), Environmental Evaluation for Utilization of Ash in Soil Stabilization Applications. Electric Power Research Institute and the United State Department of Energy, Palo Alto, California.

Hosoda, E., 2000. Material cycle, waste disposal, and recycling in a Leontief–Sraffa–von Neumann economy. J. Mater. Cycles Waste 2, 1–9.

JCOAL, 2009. Utilization of Coal Ash (accessed 15.09.09.). http://www.jcoal.or.jp/coaltech_en/coalash/ash02e.html.

Kelly, T.D., Sullivan, D.E., 2006. Coal Combustion Products Statistics. The United States Geological Survey.

Lombardi, K., 2010. "Beneficial Use" of Coal Ash in Question as EPA Mulls Regulation. iWatch (accessed 24.11.11.). http://www.iwatchnews.org/2010/11/24/2291/beneficial-use-coal-ash-question-epa-mulls-regulation.

Martin, M., Williams, I.D., Clark, M., 2006. Social, cultural and structural influences on household waste recycling: a case study. Resour. Conserv. Recyl. 48, 357–395.

Moriguchi, Y., 2007. Material flow indicators to measure progress toward a sound material-cycle society. J. Mater. Cycles Waste 9, 112–120.

Nash, H.A., 2009. The revised directive on waste: resolving legislative tensions in waste management? J. Environ. Law 21, 139–149.
NETL, 2006. Clean Coal Technology: Coal Utilization By-products. Topical Report. National Energy Technology Laboratory.
Northern Ireland Environment Agency, 2010. Quality Protocol: Pulverized Fuel Ash. Northern Irland Environment Agency, Oxon, UK.
Park, J., 2013. Wastes as Resources: the Case of Coal Combustion By-products in the United States. School of Forestry and Environmental Studies. Yale University.
Ramme, B.W., Tharaniyil, M.P., 2004. Coal Combustion Products Utilization Handbook, second ed. We Energies.
Rosen, M.A., Dincer, I., 1997. On exergy and environmental impact. Int. J. Energy Res. 21, 643–654.
The Environment Agency, 2008. Waste Protocols Project: Pulverised Fuel Ash and Furnace Bottom Ash. The Environment Agency, Oxon, UK.
Tonglet, M., Phillips, P.S., Bates, M.P., 2004. Determining the drivers for householder pro-environmental behaviour: waste minimisation compared to recycling. Resour. Conserv. Recyl. 42, 27–48.
Tromans, S., 2001. EC waste law: a complete mess? J. Environ. Law 13, 133–156.
U.S. Congress, 1992. Managing Industrial Solid Wastes from Manufacturing, Mining, Oil and Gas Production, and Utility Coal Combustion. Background Paper. Office of Technology Assessment, Washington, D.C.
U.S. Energy Information Administration, 2013. Coal Regains Some Electric Generation Market Share from Natural Gas (accessed 10.08.13.). http://www.eia.gov/todayinenergy/detail.cfm?id=11391.
USEPA, 1988. Report to Congress: Wastes from the Combustion of Coal by Electric Utility Power Plants. United States Environmental Protection Agency, Washington, DC.
USEPA, 1989. The Solid Waste Dilemma: an Agenda for Action, Final Report of the Municipal Solid Waste Task Force. United States Environmental Protection Agency.
USEPA, 2003. Beyond RCRA: Waste and Materials Management in the Year 2020, the RCRA Vision Paper. United States Environmental Protection Agency, Washington DC, p. 25.
USEPA, 2007a. Coal Combustion Waste Damage Case Assessment. United States Environmental Protection Agency.
USEPA, 2007b. Human and Ecological Risk Assessment of Coal Combustion Wastes. United States Environmental Protection Agency, Research Triangle Park.
USEPA, 2009. Sustainable Materials Management: the Road Ahead. United States Environmental Protection Agency.
USEPA, 2010a. Hazardous and Solid Waste Management System; Identification and Listing of Special Wastes, 40 CFR Parts 257, 261, 264 et al. In: Disposal of Coal Combustion Residues from Electric Utilities; Proposed Rule, vol. 75 (118). United States Environmental Protection Agency. Federal Register.
USEPA, 2010b. Human and Ecological Risk Assessment of Coal Combustion Wastes (Draft). United States Environmental Protection Agency.
USEPA, 2011. Material Characterization Paper in Support of the Final Rulemaking: Coal Combustion Residuals. United States Environmental Protection Agency.
Ward, J., 2010. The Value of Coal Combustion Products: an Economic Assessment of CCP Utilization for the U.S. Economy. American Coal Council, Washington DC.
Wilkinson, D., 1999. Time to discard the concept of waste? Env. L. Rev. 1, 172–195.
Wilkinson, D., 2002. Waste law. In: Bisson, K., Proops, J. (Eds.), Waste in Ecological Economics. Edward Elgar Publishing, Inc, Northampton, pp. 101–113.
Yuan, Z., Bi, J., Moriguichi, Y., 2006. The circular economy: a new development strategy in China. J. Ind. Ecol. 10, 4–8.