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Quantifying the system-wide recovery potential of waste in the global paper life cycle

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ABSTRACT

Waste from the global paper life cycle can be a lost economic opportunity and a risk to the natural environment and human health. This study assesses the recovery potential of major waste flows in the global paper life cycle to support improvements in material use. The "recovery potential" indicator shows the technical possibility for extracting value from waste through recycling and other forms of recovery. The potential is identified through a review of recovery technologies that are currently applied or likely to be commercially available by the year 2050. The analysis compares current material use in the global paper life cycle with an ideal scenario in which the recovery potential of all major waste flows is fulfilled. In the ideal scenario, the Recycled Input Ratio (RIR) is increased from 38% to 67%–73% and the landfill intensity is reduced from 331–473 kg/t paper to 0–2.6 kg/t paper. The reduction in required landfill space is achieved mainly through increased consumer waste recycling. Better management of industrial waste from the paper sector has a rather limited impact on the RIR and landfill intensity. The conditions for successful recovery of waste are discussed separately. The analysis shows that the recovery potential indicator can be usefully applied to estimate potential improvements in complex material systems and the findings may inform policies for resource efficiency and the circular economy.

1. Introduction

Sustainable waste and resource management should aim to reduce resource consumption and protect the environment and human health. Waste reuse and recovery enables the substitution of secondary materials in place of primary material inputs, avoids the harmful impacts of virgin material extraction and processing, and reduces the volume of waste going to landfill. For example, the use of paper sludge in cement kilns can reduce fuel and limestone consumption, avoid emissions from cement production and the impacts of limestone mining, and lower the amount of sludge or sludge ash to landfill. Waste may be reused within a facility, or across companies and industries through "industrial symbiosis" (Chertow, 2000).

This study focuses on waste in the global paper life cycle. Paper is a key industrial sector in terms of energy consumption and environmental impacts. These impacts include forest degradation and deforestation, air emissions from power and heat generation, paper mill wastewater discharges, and emissions from landfill. In 2012, the consumption of paper products including newsprint, printing and writing paper, sanitary paper, and packaging was 399 Mt. The paper sector used approximately 347 Mt of virgin fibre in mechanical and chemical pulping and 215 Mt of discarded paper for recycling (Van Ewijk et al., 2016).

The global production and consumption of paper generate a large volume of solid waste including industrial waste (206 Mt) and end-of-life (E-o-L) discards (363 Mt) (Van Ewijk et al., 2016). The waste represents a lost economic opportunity and a risk to the natural environment and human health. Pulping and bleaching residues feature high pollutant loads (Kamali and Khodaparast, 2015). Some fractions of the waste are hazardous and waste treatment can lead to pollution of air, water, and soil (Suhr et al., 2015). For example, land application of paper sludge ash poses a significant risk to groundwater through leaching of metals (Environment Agency, 2015).

There are several reviews of waste generation and treatment in the pulp and paper sector. Bird and Talberth (2008) reviewed recovery options for various pulp and paper waste streams and examined waste treatment data for the United States. Monte et al. (2009) described waste management for pulp and paper in the European Union. Suhr et al. (2015) outlined best available techniques for the European pulp and paper sector, including ones for waste management. Finally,

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Bousios and Worrell (2017) reviewed alternative feedstocks and waste treatment options in the paper and board industry. However, none of these studies quantified the systemic benefits of using waste as a resource.

Park and Chertow (2014) introduced a "reuse potential" indicator, which specifies the extent to which a waste can be used as a resource through a set of technologically available options. The reuse potential represents the usefulness of a waste with a score between 0 (complete waste) and 1 (complete resource). For example, a score of 0.45 indicates that 45% of the waste can be reused. The reuse potential shows what is technically feasible before other factors such as market demand and government regulation are considered (Park and Chertow, 2014).

The present article adopts the logic of the "reuse potential" from Park and Chertow (2014) but uses the term "recovery potential" instead so as to be consistent with the definitions in the Waste Framework Directive (EC, 2008). The term "recovery" includes recycling (substituting the original material), non-energy recovery (substituting other materials), and energy recovery (substituting fuels); these three activities represent the most widely observed uses of waste in the paper life cycle. The "reuse" of paper waste – using products or components again for the same purpose – is not included in the analysis. Waste that is not recovered is either incinerated without energy recovery or disposed of in landfill.

This study aims to answer the following question: how would the complete realization of the recovery potential of major waste streams in the global paper life cycle contribute to a circular economy by reducing waste to landfill and virgin material demand? The article makes a theoretical contribution by providing a testing ground to further refine the method proposed by Park and Chertow (2014). This method has been applied only to the case of Coal Combustion By-products (CCBs) and deserves to be explored for other materials and complex material systems in particular. The final results are intended as a benchmark at the systems level and show what is possible at best. They also show what *cannot* be achieved even under the most optimistic assumptions. For example, there are limits to the avoidance of virgin inputs through increased recycling.

The article proceeds as follows. The next section discusses methods and data for calculating the recovery potential. Section 3 presents the results and compares current material flows with ideal material flows in two Sankey diagrams. Section 4 reflects on the limitations of the approach, the conditions for recovery, and the policy implications of the findings.

2. Methods and data

2.1. Recovery potential indicator

Park and Chertow (2014) first suggested the reuse potential indicator and tested it for the case of coal combustion by-products (CCBs). For each type of CCBs – fly ash, FGD (flue-gas desulfurization) gypsum, bottom ash, and boiler slag – the authors estimated the amount that can be "technically" reused and recovered based on a set of commercially available reuse technologies in the United States. They showed that CCBs in the United States were 35–85% resource-like materials, depending on which reuse options are considered in the calculation (e.g. a more conservative estimate considered encapsulated uses of CCBs only while another considered all legally allowable uses).

This study takes a slightly different approach. It has a larger scope but less detail than Park and Chertow (2014) and analyses all waste flows of the global paper life cycle. The assessment focuses on 1) the types of waste and the variety of waste recovery options and 2) the system-wide changes in material flows if the recovery possibilities are fully exploited. Two methods are used for assessing the recovery potential: a review of technologies that are currently available or potentially available by the year 2050 and an assessment of benchmark performance.

The review focuses on technologies and practices that may be commercially available by the year 2050, and which safely substitute a virgin alternative. Information regarding waste recovery options is compiled from the academic and grey literature and includes technologies that are currently in the research and development phase and those that are commercially applied. The recovery potential is subsequently estimated based on an *if-then* statement. For example: *if* universal collection of end-of-life discards were introduced, *then* 100% of waste paper from final consumption would be a resource.

The benchmark values are derived from the best performance observed at the mill, company, or country level. Such benchmark performance is often the result of the implementation of several technologies. Cases of best performance and practices are published in national statistics (e.g. for recycling) and company reports (e.g. industrial landfill rates). The following example describes a recovery potential based on benchmark performance: *if* global recycling operates at South-Korean standards, *then* 97% of end-of-life discards would be collected for recycling. Benchmark performance is equal to or less than the technically possible level of recovery.

2.2. Current recovery in the paper life cycle

The identification of a recovery potential first requires all data regarding the type and quantity of waste from the paper life cycle that is currently generated and recovered. Fig. 1 displays the materials (rectangular boxes) and processes (rounded boxes) in the global paper life cycle with a detailed breakdown of solid waste generation and treatment. Waste (grey boxes) includes industrial waste and two categories of consumer waste: end-of-life discards and paper in sewage. The industrial waste is difficult to categorize because different data sources use different categories and waste from different processes may be mixed during waste (water) treatment at the paper mill. Waste is nevertheless aggregated in the following categories based on their properties and volume.

1. *End-of-life discards* cover all the solid paper waste discarded from residential and commercial sectors, excluding the paper industry. It excludes net additions to stock and toilet paper, which ends up in sewage. It is often recycled but may be contaminated.
2. *Paper in sewage* consists of toilet paper that ends up in the sewer system and is treated as sewage. It is considered separately from end-of-life discards because the fibres are not available for recycling.
3. *Black liquor* is produced during the chemical (Kraft) pulping process and contains the lignin and hemicellulose separated from the cellulose for paper. It also contains inorganic chemicals used for pulping but only the organic fraction is discussed in this article. Black liquor has a high heating value and is virtually always used for on-site energy recovery (Naqvi et al., 2010).
4. *Recycling sludge* is generated during pulping and deinking of paper for recycling. It contains fibres, fillers, inks, adhesives, and inorganic materials. It is considered separately from other sludge because it has higher levels of contamination. It has a low heating value (Makinen et al., 2013; Monte et al., 2009).
5. *Papermaking waste* consists of losses from the conversion of pulp and non-fibrous material into paper and the conversion of paper into paper products. It is a clean and convenient source of paper for recycling (Stawicki and Read, 2010).
6. *Sludge and rejects* cover the aggregate losses from chemical pulping (excluding black liquor and by-products) and mechanical pulping. They are suspended in wastewater, have fibrous content, and a low heating value (Suhr et al., 2015).
7. *Causticizing waste* consists of inorganic sludge generated in the chemical recovery cycle. It includes green liquor dregs, lime mud, and slaker grits. This waste has high alkalinity and may be contaminated (Bird and Talberth, 2008).
8. *Boiler ash* results from organic waste combustion. The focus of this