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

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Highlights

- The recovery potential of waste flows in the global paper life cycle is estimated
- An ideal life cycle features complete fulfilment of the recovery potential of waste
- The Recycled Input Rate (RIR) is 38% in 2012 and 67-73% in the ideal life cycle
- The landfill intensity may be reduced from 331-473 kg/t paper to 0-2.6 kg/t paper
- The results reflect optimistic assumptions and maximum technical possibilities

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. 2017).

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. 2017). 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, 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.

62 Park and Chertow (2014) introduced a "reuse potential" indicator, which specifies the extent to

63 which a waste can be used as a resource through a set of technologically available options. The

64 reuse potential represents the usefulness of a waste with a score between 0 (complete waste) and 1

65 (complete resource). For example, a score of 0.45 indicates that 45% of the waste can be reused.

66 The reuse potential shows what is technically feasible before other factors such as market demand

67 and government regulation are considered (Park and Chertow 2014).

68 The present article adopts the logic of the "reuse potential" from Park and Chertow (2014) but uses

69 the term "recovery potential" instead so as to be consistent with the definitions in the Waste

70 Framework Directive (EC 2008). The term "recovery" includes recycling (substituting the original

71 material), non-energy recovery (substituting other materials), and energy recovery (substituting

72 fuels); these three activities represent the most widely observed uses of waste in the paper life cycle.

73 The "reuse" of paper waste – using products or components again for the same purpose – is not

74 included in the analysis. Waste that is not recovered is either incinerated without energy recovery or

75 disposed of in landfill.

76 This study aims to answer the following question: how would the complete realization of the

77 recovery potential of major waste streams in the global paper life cycle contribute to a circular

78 economy by reducing waste to landfill and virgin material demand? The article makes a theoretical

79 contribution by providing a testing ground to further refine the method proposed by Park & Chertow

80 (2014). This method has been applied only to the case of Coal Combustion By-products (CCBs) and

81 deserves to be explored for other materials and complex material systems in particular. The final

82 results are intended as a benchmark at the systems level and show what is possible at best. They

83 also show what *cannot* be achieved even under the most optimistic assumptions. For example, there

84 are limits to the avoidance of virgin inputs through increased recycling.

85 The article proceeds as follows. The next section discusses methods and data for calculating the

86 recovery potential. Section 3 presents the results and compares current material flows with ideal

87 material flows in two Sankey diagrams. Section 4 reflects on the limitations of the approach, the

88 conditions for recovery, and the policy implications of the findings.

89 **2   Methods and data**

90 **2.1   Recovery potential indicator**

91 Park & Chertow (2014) first suggested the reuse potential indicator and tested it for the case of coal

92 combustion by-products (CCBs). For each type of CCBs – fly ash, FGD (flue-gas desulfurization)

93 gypsum, bottom ash, and boiler slag – the authors estimated the amount that can be "technically"

94 reused and recovered based on a set of commercially available reuse technologies in the United

95 States. They showed that CCBs in the United States were 35-85% resource-like materials, depending

96 on which reuse options are considered in the calculation (e.g. a more conservative estimate

97 considered encapsulated uses of CCBs only while another considered all legally allowable uses).

98 This study takes a slightly different approach. It has a larger scope but less detail than Park &

99 Chertow (2014) and analyses all waste flows of the global paper life cycle. The assessment focuses

100 on 1) the types of waste and the variety of waste recovery options and 2) the system-wide changes

101 in material flows if the recovery possibilities are fully exploited. Two methods are used for assessing

102 the recovery potential: a review of technologies that are currently available or potentially available

103 by the year 2050 and an assessment of benchmark performance.

104 The review focuses on technologies and practices that may be commercially available by the year

105 2050, and which safely substitute a virgin alternative. Information regarding waste recovery options

106 is compiled from the academic and grey literature and includes technologies that are currently in the

107 research and development phase and those that are commercially applied. The recovery potential is

108 subsequently estimated based on an *if-then* statement. For example: *if* universal collection of end-

109 of-life discards were introduced, *then* 100% of waste paper from final consumption would be a

110 resource.

111 The benchmark values are derived from the best performance observed at the mill, company, or

112 country level. Such benchmark performance is often the result of the implementation of several

113 technologies. Cases of best performance and practices are published in national statistics (e.g. for

114 recycling) and company reports (e.g. industrial landfill rates). The following example describes a

115 recovery potential based on benchmark performance: *if* global recycling operates at South-Korean

116 standards, *then* 97% of end-of-life discards would be collected for recycling. Benchmark

117 performance is equal to or less than the technically possible level of recovery.

2.2 Current recovery in the paper life cycle

119 The identification of a recovery potential first requires all data regarding the type and quantity of

120 waste from the paper life cycle that is currently generated and recovered. Figure 1 displays the

121 materials (rectangular boxes) and processes (rounded boxes) in the global paper life cycle with a

122 detailed breakdown of solid waste generation and treatment. Waste (grey boxes) includes industrial

123 waste and two categories of consumer waste: end-of-life discards and paper in sewage. The

124 industrial waste is difficult to categorize because different data sources use different categories and

125   waste from different processes may be mixed during waste (water) treatment at the paper mill.

126   Waste is nevertheless aggregated in the following categories based on their properties and volume.

127   1. *End-of-life discards* cover all the solid paper waste discarded from residential and

128   commercial sectors, excluding the paper industry. It excludes net additions to stock and

129   toilet paper, which ends up in sewage. It is often recycled but may be contaminated.

130   2. *Paper in sewage* consists of toilet paper that ends up in the sewer system and is treated as

131   sewage. It is considered separately from end-of-life discards because the fibres are not

132   available for recycling.

133   3. *Black liquor* is produced during the chemical (Kraft) pulping process and contains the lignin

134   and hemicellulose separated from the cellulose for paper. It also contains inorganic

135   chemicals used for pulping but only the organic fraction is discussed in this article. Black

136   liquor has a high heating value and is virtually always used for on-site energy recovery (Naqvi

137   et al. 2010).

138   4. *Recycling sludge* is generated during pulping and deinking of paper for recycling. It contains

139   fibres, fillers, inks, adhesives, and inorganic materials. It is considered separately from other

140   sludge because it has higher levels of contamination. It has a low heating value (Makinen et

141   al. 2013; Monte et al. 2009).

142   5. *Papermaking waste* consists of losses from the conversion of pulp and non-fibrous material

143   into paper and the conversion of paper into paper products. It is a clean and convenient

144   source of paper for recycling (Stawicki and Read 2010).

145   6. *Sludge and rejects* cover the aggregate losses from chemical pulping (excluding black liquor

146   and by-products) and mechanical pulping. They are suspended in wastewater, have fibrous

147   content, and a low heating value (Suhr et al. 2015).

148   7. *Causticizing waste* consists of inorganic sludge generated in the chemical recovery cycle. It

149   includes green liquor dregs, lime mud, and slaker grits. This waste has high alkalinity and

150   may be contaminated (Bird and Talberth 2008).

151   8. *Boiler ash* results from organic waste combustion. The focus of this article is on wood and

152   sludge ash and it excludes mixed ash from co-firing of, for example, coal and wood. Boiler

153   ash has a high alkalinity and is cementitious (Bird and Talberth 2008).

154   The amount of waste generation and recovery are quantified based on a full material balance of the

155   global paper life cycle established by Van Ewijk et al. (2017). This material balance only includes

156   aggregate waste generation and treatment flows, which need to be separated into several smaller

157   flows.

158 -   For waste generation, the flows are disaggregated in the following categories: chemical
159   pulping by-products, sludge and rejects, causticizing waste, and boiler ash. The flows are
160   largely based on waste intensities published by Suhr et al. (2015). The detailed estimation of
161   waste generation is explained in Appendix A.
162 -   For waste recovery, the fractions of recycling, energy recovery and non-energy recovery are
163   estimated for each waste category. The data are drawn from a variety of sources covering
164   several countries including the United States, Finland, and Canada. The detailed estimation
165   of current recovery is explained in Appendix B.

166 The total quantity of mill waste used in this study is slightly different from Van Ewijk et al. (2017)
167 because by-products are subtracted from the total waste stream and lime makeup and boiler ash are
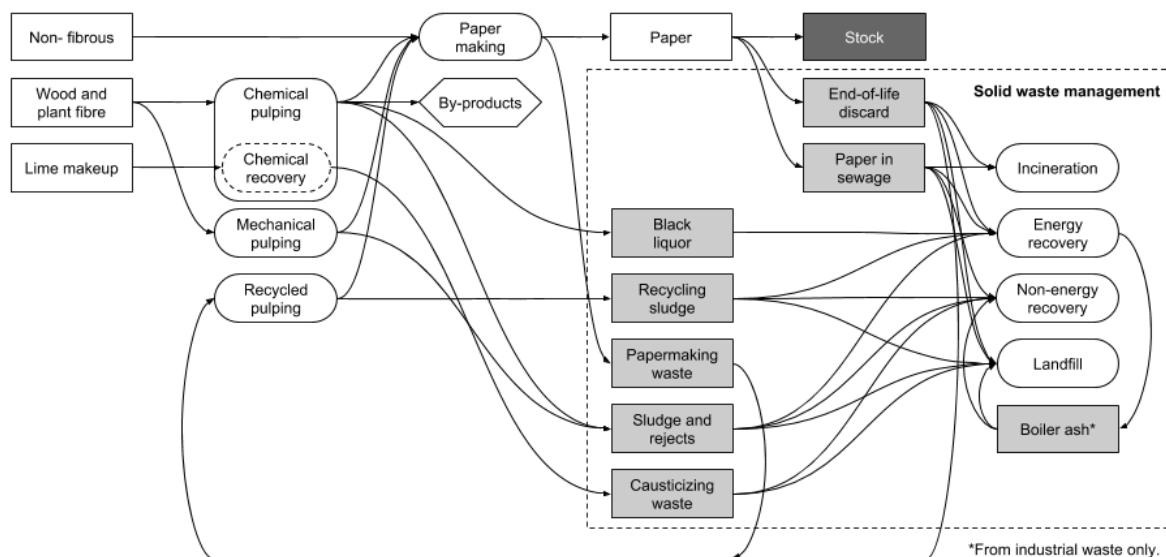168 added to the material balance.

Figure 1: Flows (rectangular boxes) and processes (rounded boxes) in the paper life cycle.

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170 A number of flows are not taken into account because they are very small, such as fly ash from the
171 recovery boiler (which is largely re-burned), minor lime residues, and salt cake from chlorine dioxide
172 production (Kinnarinen et al. 2016). Losses of pulping chemicals and ash from the combustion of
173 materials other than the aforementioned waste are also excluded, as well as any waste from
174 ancillary processes not described by Van Ewijk et al. (2017). Bark and other wood waste fall outside
175 the system boundary because they do not necessarily constitute process waste. When mills buy logs
176 including bark (instead of chips) specifically for energy recovery purposes, the bark may be
177 considered a fuel rather than an unintended process waste.

2.3 Waste recovery options

Waste recovery is categorized into recycling, non-energy recovery, and energy recovery. Table 1 lists recovery options for waste from the paper life cycle, based on a review of the literature. The table matches the types of waste with the recovery options. It also shows the relevant properties of the waste, the process outputs, the avoided virgin alternative, example applications, and the stage of technological development for each recovery option. Substitution ratios between secondary and virgin material are not included since they strongly depend on the quality of the waste and the exact type of application. The substitution ratio for the largest waste flow, end-of-life discards, ranges between 0.9 and 1.7 t/t of virgin fibre (Van Ewijk et al. 2017).

The status of technological development of the recovery options is indicated as follows: 1 = research and development, 2 = pilot and demonstration, 3 = full-scale implementation. Only technologies that are firmly established (e.g. black liquor combustion) are given score 3. Each combination of waste flow and recovery option is in a unique stage of technological development. For example, composting of recycling sludge faces different challenges from composting of sludge and rejects. However, non-energy recovery operations are assigned a joint technology status 1-3, as no more detailed data could be obtained. Apart from combustion, all of the energy recovery options are either in the research and development stage or in the pilot and demonstration stage, depending on the type of waste that is recovered.

The overview of recovery technologies does not include pre-treatment of the waste. Drying is required for many forms of recovery of wet waste. Alternatively, Hydrothermal Carbonization (HTC) renders drying unnecessary and yields hydrochar that can be used for various energy and non-energy recovery operations (Mäkelä et al. 2016; Alatalo et al. 2013; Kambo and Dutta 2015). Besides drying, several other pre-treatments may be needed to separate and purify the waste. The level of purification that can be achieved through pre-treatment technologies directly affects the recovery potential of the waste. For example, the separation and preparation of lime mud, green liquor dregs, and slaker grits may involve sedimentation, filtration, washing, dewatering, drying, and grinding. Technology choice affects waste properties such as pH, water content, and level of impurities (Kinnarinen et al. 2016).

Table 1: Waste recovery options for major waste flows in the global paper life cycle.

Type of recovery potential	Recovery option or application	End-of-life discards	Paper in sewage	Black liquor	Recycling sludge	Papermaking waste	Sludge and rejects	Causticizing waste	Boiler ash	Relevant property	Process outputs	Substitute	Concept or example	Technology status	References
Recycling	Recycling	x				x				Fibre content	N/A	Virgin fibre	Recycling of fibres into new paper products	3	N/A
Non-energy recovery	Soil improver						x	x		Particle sizes		Various organic materials	Road construction, erosion control	1-3	(Deviatkin et al. 2014; Bird and Talberth 2008; Kinnarinen et al. 2016; Fytili and Zabaniotou 2008)
	Compost		x		x		x	x	x	Organic content		Other green waste	Spreading on farmland		
	Fertilizer		x		x		x		x	Nutrients		Virgin N, P, K	Forest soil, agricultural land		
	Neutralizer							x	x	Alkalinity		Virgin minerals, mainly limestone	Acid Mine Drainage (AMD), wastewater treatment, soil liming		
	Aggregate				x		x	x	x	Particle size and shape		Virgin aggregate	Brick, road surface		
	Admixture		x		x			x	x	Cementitious properties		Portland cement	Cement production, concrete blocks		
	Filler				x		x			Fibre content		Virgin fibre	Fibreboard, particle boards		
	Adsorbent				x		x	x	x	Adsorption capacity		Virgin adsorbents from fossil carbon	Flue gas desulfurization, adsorption of odours and colours		
Energy recovery	Combustion		x	x	x		x			Water content, ash content, heating value	Direct heat, ash	Biomass or other fuels, minerals such as sand, other ash	Incineration with or without auxiliary fuels such as coal	3	(Ouadi et al. 2013; Naqvi et al. 2010; Ekstrand et al. 2013; Deviatkin et al. 2014; Stoica et al. 2009; Fytili and Zabaniotou 2008)
	Anaerobic digestion		x		x		x				Methane fuel gas, digestate	Natural gas, virgin fertilizer	Breakdown by microorganisms without oxygen	1-2	
	Gasification		x	x	x		x				Syngas, ash	Natural gas, minerals such as sand, other ash	High-temperature conversion with limited oxygen		
	Pyrolysis		x		x		x				Pyrolysis oil, chemicals, charcoal	Fossil fuels and virgin minerals	High-temperature decomposition without oxygen		

2.4 Recovery potential calculation

209 The calculation of the recovery potential of each waste flow is based on four main assumptions. First,

210 all known technologies and practices, listed in Table 1, are assumed to be further developed over the

211 next few decades and to become commercially available by 2050. Second, it is expected that

212 improved contamination control allows for functional and safe use of waste in non-energy recovery

213 and energy recovery applications. Significant efforts would be required to achieve this in practice,

214 including prevention (e.g. substituting chemicals or using alternative materials), removal (e.g. better

215 deinking technology), constraining (e.g. encapsulated use of waste), and destruction of

216 contaminants (e.g. thermal treatment). Third, for recycling, contamination is assumed to affect the

217 yield ratio of recycled pulping, because of the following issues.

218 – Increased recycling implies the use of waste paper that is not currently recycled because of
219 its comparatively low quality.
220 – With increased recycling, contaminants may accumulate in the paper life cycle and reach
221 higher concentrations.
222 – A higher recycled content for all grades, including high-quality ones, leads to more strict
223 deinking requirements.

224 These issues may be partly addressed by introducing more separate collection of paper instead of

225 commingled collection (Miranda et al. 2013). However, increased recycling will inevitably require

226 more thorough deinking and cleaning of recycled pulp, which reduces the pulping yield. Based on

227 Van Ewijk et al. (2017), the recovery potential calculation applies a lower pulping yield (73% instead

228 81%) under complete fulfilment of the potential for recycling. Finally, the calculation excludes any

229 restrictions on demand for waste or waste-based products. In reality, demand may be limited

230 because of the limited number of recovery facilities, the transport costs of obtaining the waste, or

231 attitudes towards waste and waste-based products. These factors, as well as contamination issues,

232 are discussed further in Section 4.

233 **3 Results**

234 The results regarding the recovery of the individual waste flows are presented in table 2. It shows

235 the absolute quantities of waste generated in 2012 as well as the fractions (between 0 and 1) of

236 current recovery, benchmark recovery, and potential recovery. The benchmark recovery fraction and

237 the recovery potentials are derived from the literature, reports, and the information in table 1. They

238 are calculated based on the following assumptions.

1. *End-of-life discards* can be fully recycled but with aforementioned impacts on the recycled pulping yield. The benchmark collection rate was 91%, as reported in South Korea between 2012-2014 (FAO 2016)[1]. Using the global parameters for papermaking waste, net additions to stock, and paper in sewage, this implies a fraction of 0.97 of end-of-life discards to recycling (see Appendix C for the full calculation). The South-Korean performance is very close to the potential for recycling of 1.00 for end-of-life discards. At the same time, it is technically possible to use all paper waste for energy recovery. The combined potential is thus 1.00.

2. *Paper in sewage* may receive any treatment suitable for sewage sludge. This includes a large variety of non-energy recovery and energy recovery options. The role of agricultural use is limited: EU legislation prohibits deposition of untreated sludge on land and many countries banned sludge application altogether (Milieu Ltd. and WRc and RPA 2013). The recovery potential for non-energy recovery and energy recovery and the benchmark are 1.00 because various countries report zero sewage sludge to landfill (Milieu Ltd. and WRc and RPA 2013). It should be noted that energy outputs from energy recovery can be low due to the high energy demand for drying (Fytili and Zabaniotou 2008).

3. *Black liquor* is already always used to recover cooking chemicals, by-products, and energy. The recovery potential calculation for black liquor considers using it more efficiently through gasification. With this technology, black liquor is not burnt directly but converted to a fuel gas (BLG) that is burned in a gas turbine with combined cycle (BLGCC). Alternatively, the gas is turned into a motor fuel (BLGMF). BLG is likely to become a key technology and a competitive option in the future (IEA ETSAP 2015; Naqvi et al. 2010). Both BLGCC and BLGMF have been demonstrated in Sweden and the US (European Biofuels Technology Platform 2016; NETL 2016). The energy recovery potential for BLG is assumed to be 1.00.

4. *Recycling sludge* may be used for non-energy recovery and energy recovery. Data from individual mills show that zero landfill is achievable for deinking sludge (Deviatkin et al. 2014). Energy recovery options include combustion, anaerobic digestion (AD), gasification and pyrolysis. Full-scale facilities exist for anaerobic digestion of recycling sludge (Meyer and Edwards 2014) and there are pilot projects for gasification and pyrolysis of recycling sludge (Universiteit Twente 2015; Ouadi et al. 2012, 2013). Non-energy recovery technologies

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[1] Based on average collection and consumption in 2012-2014. Consumption was calculated as production + imports – exports. Singapore and Iceland had even higher collection rates but their volumes of collected paper are rounded estimates and therefore deemed less reliable. RISI, a major private sector data provider in the paper sector, is cited in several news outlets to calculate the South Korean collection rate at 92.1% in 2013.

269		suitable for recycling sludge include use as compost, fertilizer, aggregate, admixture, filler, or
270		adsorbent. The combined recovery potential is therefore 1.00.
271	5.	*Papermaking waste* is a clean and convenient source of recyclable material and can be fully
272		recycled according to Van Ewijk et al. (2017) and Stawicki and Read (2010). The current
273		recovery level and the benchmark therefore equate to a recovery potential of 1.00.
274	6.	*Sludge and rejects* can be used in a variety of ways but hardly any treatment data are
275		available for this mixed waste stream. The benchmark was assumed to equate best
276		performance for sewage sludge. Energy recovery options include combustion, anaerobic
277		digestion, gasification, and pyrolysis. Full-scale facilities exist for anaerobic digestion of
278		various types of paper mill sludge (Meyer and Edwards 2014). There are projects on
279		gasification and pyrolysis technologies that focus on virgin biomass and biowaste including
280		paper mill sludge (E4tech 2009; Meier et al. 2013). Non-energy recovery options include use
281		as soil improver, compost, fertilizer, aggregate, filler, and adsorbent. The combined recovery
282		potential is 1.00.
283	7.	*Causticizing waste* is often contaminated and among the most problematic waste in the
284		paper industry. Causticizing waste includes green liquor dregs, lime residues, and slaker grits.
285		Not all of these substances are equally suitable for recovery and they are often mixed to
286		improve the characteristics. When contamination issues are addressed, causticizing residuals
287		may be used as soil improver, compost, neutralizer, aggregate, admixture, and adsorbent.
288		Benchmark data are available only for fractions of causticizing waste. First, green liquor
289		dregs may be fully used in the cement industry (Mondi 2014). Second, Nurmesniemi et al.
290		(2007) show 46% recovery of lime mud and green liquor dregs combined. The recovery
291		potential is assumed to be in between these two (rounded) benchmark values: 0.50-1.00.
292		For the system-wide analysis a value of 0.75 is used. Better estimation of the recovery
293		potential requires further research on best practices.
294	8.	*Boiler ash* can be recovered as compost, fertilizer, neutralizer, aggregate, admixture, and
295		adsorbent. The benchmark at mill level is full utilization of boiler ash (Nurmesniemi et al.
296		2007; UPM 2015). The recovery options for coal ash or coal-wood ash are generally more
297		limited than for pure wood ash because of toxic elements (Park and Chertow 2014). The
298		non-energy recovery potential of 1.00 is therefore unlikely to be achieved if wood is co-fired
299		with other fuels.

300 Some waste can be used for both energy recovery and non-energy recovery. The assumed split

301 between the two options, shown in the last column of table 2, is necessary to establish a complete

302 material balance. For recycling sludge and sludge and rejects, the fraction for both treatments in

303 2050 is based on the relative sizes of the same fractions in 2012[2]. For end-of-life discards, recycling is

304 preferred over energy recovery. Based on Wiechmann et al. (2013), incineration with energy and

305 phosphorus recovery is considered to be most attractive for paper in sewage, and is categorized as

306 energy recovery.

307 *Table 2: Waste recovery and recovery potential for major waste flows in the global paper life cycle.*

Waste flow	Quantity in 2012 (Mt)	Type of recovery	Current recovery	Benchmark	Recovery potential	Recovery in 2050
End-of-life discards	351	Recycling	0.55	0.97	1.00	1.00
		Energy recovery	0.12	N/A	1.00	0.00
Paper in sewage	12	Energy recovery	0.12	1.00	1.00	1.00
		Non-energy recovery	0.40			0.00
Black liquor	152	Energy recovery	1.00	1.00	1.00	N/A
Recycling sludge	41	Energy recovery	0.08	1.00	1.00	0.14
		Non-energy recovery	0.50			0.86
Papermaking waste	21	Recycling	1.00	1.00	1.00	N/A
Sludge and rejects	5.6	Energy recovery	0.25	1.00	1.00	0.50
		Non-energy recovery	0.25			0.50
Causticizing waste	4.5	Non-energy recovery	0.25	0.46*	0.75+-0.25	N/A
Boiler ash	0.4	Non-energy recovery	0.50	1.00	1.00	N/A

*For green liquor dregs and lime residues together (Nurmesniemi et al. 2007). Green liquor dregs may be fully recovered (Mondi 2016). No individual benchmark data are available for lime residues and slaker grits.

308

309 The overall changes in material flows under fulfilment of the recovery potential can be clarified with

310 Sankey diagrams. The first use of the Sankey diagram by its originator was to depict conventional

311 and ideal energy flows in a steam engine (Schmidt 2008; Sankey 1898). Figure 2 follows the same

312 logic and shows the material flow pattern in the global paper life cycle in 2012 and the potential flow

313 pattern based on fulfilment of the recovery potential. The demand for virgin materials is

314 recalculated by keeping the ratios between chemical and mechanical pulp and between non-fibrous

315 and fibrous inputs (pulp) constant. Because of the increase in recycled pulp, the fractions of both

316 mechanical and chemical pulp are approximately halved. The flows are normalized to 100 units of

317 consumption (for the base year 1 unit = 4 Mt). Appendix D provides detailed material balances and

318 specifies generation and treatment quantities for all eight waste flows. It should be noted that the

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[2] For recycling sludge, the fraction of energy recovery is 0.08 / (0.08 + 0.50) = 0.14. The fraction of non-energy recovery is 0.50 / (0.08 + 0.50) = 0.86.

319   total industrial waste flow in the ideal scenario is about a tenth smaller than in 2012 because

320   relatively high yield recycled pulping (73-89%) displaces low yield chemical pulping (40-55%). Boiler

321   ash generation is much higher because of increased levels of energy recovery.

322

Current (above):

Extraction | Pulping | Making | Disposal | Waste

16 Non-fibrous
87 Wood
1.1 Lime makeup
89 pulp
100 Paper
51 Mill waste
54 Recycling
0.4 Ash

9 Stock
33 Landfill
8 Incineration/Energy recovery
1.2 Non-energy recovery
6 Landfill
40 Energy recovery
6 Non-energy recovery

Ideal (below):

16 Non-fibrous
41 Wood
0.5 Lime makeup
89 pulp
100 Paper
44 Mill waste
93 Recycling
1.6 Ash

9 Stock
3 Incineration/Energy recovery
0.1 Landfill
21 Energy recovery
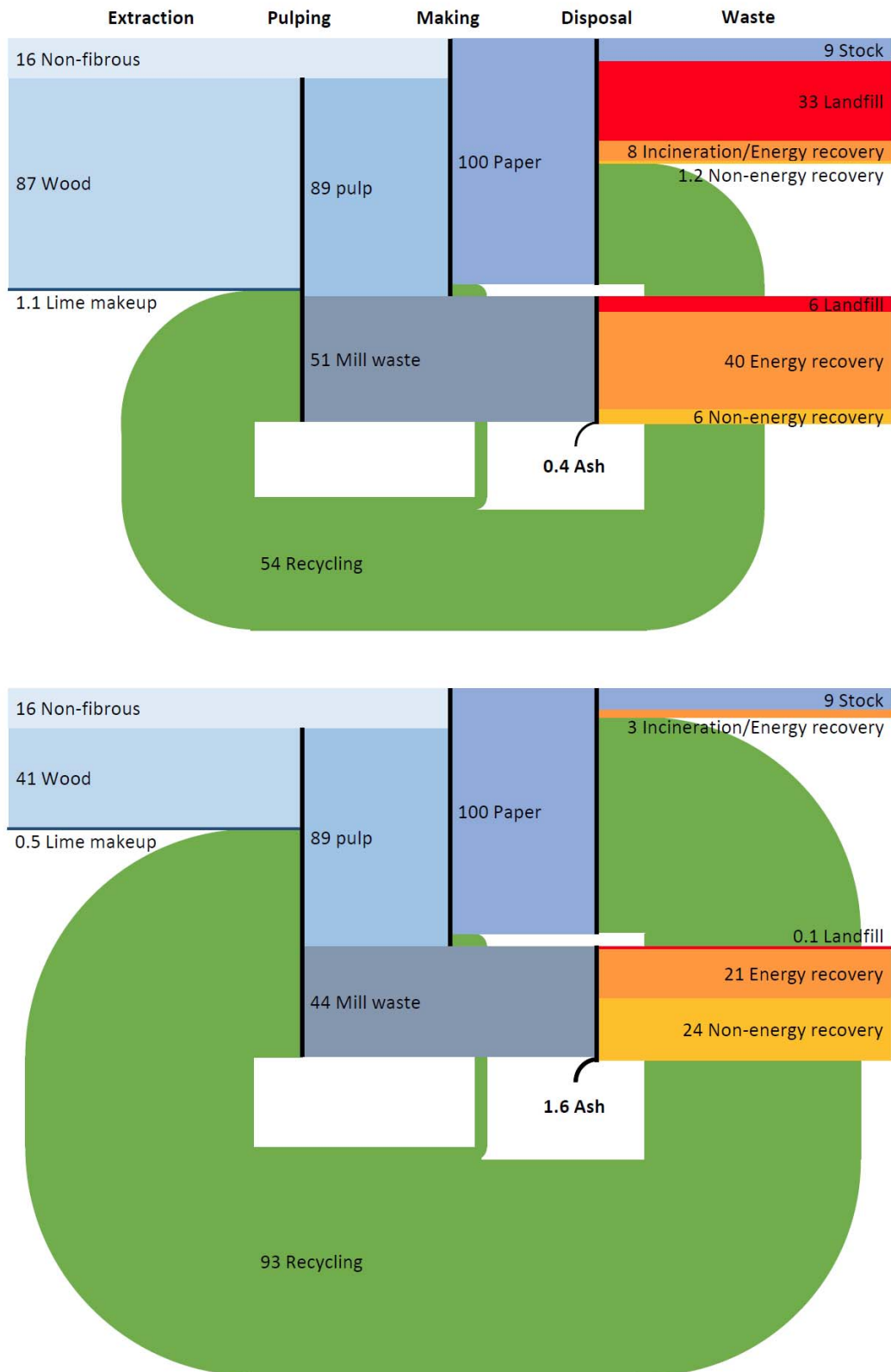24 Non-energy recovery

Figure 2: Current (above) and ideal (below) global paper life cycle. The flows are normalized to 100 units of consumption (for the base year 1 unit = 4 Mt).

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324   The ideal flow pattern improves performance in two ways. First, a large increase in recycling leads to

325   a large reduction in landfill. Recycling dominates the ideal scenario because end-of-life discards is

326   the largest waste flow in the system and almost all of it is recycled. Second, the demand for virgin

327   fibre is approximately halved which implies a proportional reduction of upstream environmental

328   impacts. The Recycled Input Rate (RIR), which measures the fraction of paper for recycling in the

329   total fibrous inputs, is almost doubled from 38% to 67-73%; the variation depends on the fraction of

330   addition to stock (0.06-0.12), which is not available for recycling (Van Ewijk et al. 2017). In the ideal

331   scenario, a significant amount of virgin materials is still required, mainly because fibres are lost in

332   the recycling process.

333   Wood is not the only virgin input that is avoided through waste recovery. The recovery of waste

334   other than end-of-life discards or papermaking waste substitutes for various raw materials including

335   virgin phosphorus, Portland cement, and fossil fuels. Recovery of industrial waste outside of the

336   system boundary is much higher in the ideal scenario. At the same time, increased recycling reduces

337   energy recovery of end-of-life discards in MSW incineration plants. The total impact of recovery of

338   waste outside of the global paper life cycle is a function of the substitution potential of the waste.

339   The extent to which waste materials can substitute for virgin inputs depends among others on waste

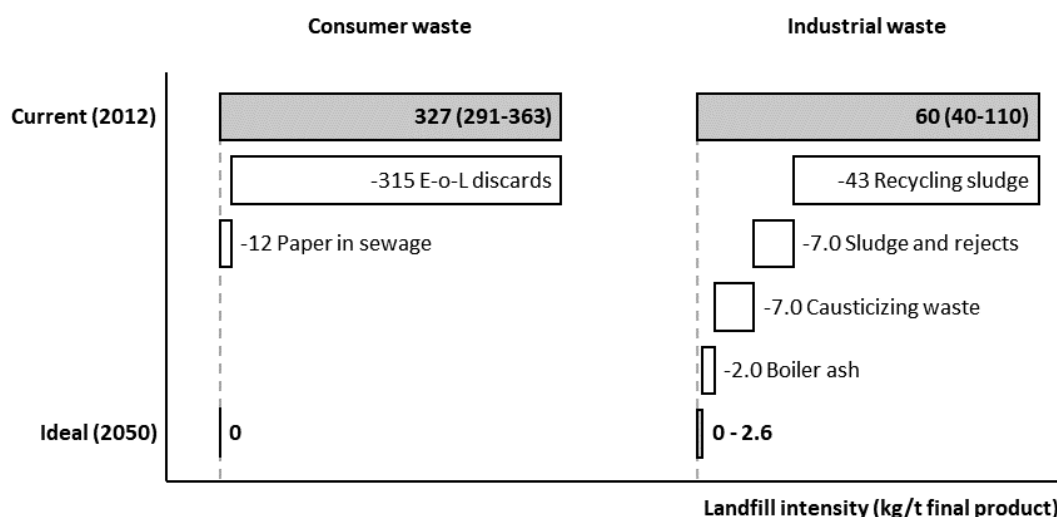340   properties, process efficiencies, and market conditions (Vadenbo et al. 2017).

341

342   *Figure 3: Contributions to a reduction in landfill intensity.*

343   Figure 3 shows the current and ideal landfill intensity of consumer waste (E-o-L discards and paper

344   to sewage) and industrial waste (all other waste streams). For consumer waste, the uncertainty

345   range for current performance is based on the extent of addition to stock; for industrial waste, the

346   uncertainty range is based on the differences in industrial waste generation data (Van Ewijk et al.

15

347 2017). The figure indicates to what extent diversion of individual waste flows contributes to the

348 overall reduction in landfill in the ideal scenario. The largest improvement is through diverting E-o-L

349 discards and recycling sludge from landfill. The overall landfill rate per tonne of final product

350 decreases dramatically to only 0-2.6 kg/t. In the ideal scenario, the waste to landfill consists of

351 causticizing residuals only. Near zero landfill may seem impracticable but a selection of paper mills in

352 Europe already claims landfill rates as low as 14 kg/t (CEPI 2013). UPM, a major paper producer,

353 aims for zero landfill status by 2030 and claims to have achieved this already for several mills (UPM

354 2016).

355 **4   Discussion**

356   **4.1   Limitations of the approach**

357 This study assessed the system-wide changes in material flows when fulfilling the recovery potential

358 of major waste streams in the global paper life cycle. In the "ideal" scenario, all recovery options

359 that are expected to be commercially available by 2050, are implemented. This was shown to reduce

360 virgin fibre requirements by approximately half and reduce waste to landfill to almost zero. However,

361 due to various limitations, it was not possible to provide precise estimates that could directly inform

362 decision-making. The lack of data on technology status and waste quality meant that only a single

363 optimistic scenario could be constructed. The present results are suitable for long-term scenario

364 analysis but do not directly indicate currently available opportunities.

365 More detailed data regarding the quantity and quality of waste, the status of the technologies, and

366 the waste properties required for successful recovery may be gathered for smaller spatial scales or a

367 more limited number of waste streams. The data collection process revealed that country data is

368 more widely available than global data; it should therefore be possible to formulate more precise

369 national recovery potentials. It should also be noted that in the present article, the extrapolation of

370 country data to the global level introduced bias. However, all national data are from countries with

371 large pulp and paper sectors that have a significant share in the global pulp and paper market

372 (Finland, United States, and Canada).

373 The optimization of the material flows did not consider the effect of waste generation and treatment

374 on supply and demand of electricity and heat. On-site energy recovery is an efficient and attractive

375 means of powering pulp and paper activities but the ideal paper life cycle features a much smaller

376 role for energy recovery. This outcome is generally consistent with the waste hierarchy but may not

377 actually be most beneficial for the case of the pulp and paper industry. It is also important to

378 account for the heating value of the waste; only black liquor has a significant heating value and

379 energy recovery from sludge makes a relatively small contribution to electricity and heat supply. At

380 the same time, a shift from virgin to recycled pulping lowers energy demand, though high deinking

381 requirements can reduce the energy savings of recycled pulping compared to chemical pulping.

382 Not all non-energy recovery options are unambiguously beneficial. Land application of sludge could

383 fertilize soils but may sometimes leave the soil quality unchanged. In the latter case, the waste is

384 diverted from landfill but the recovery operation does not replace virgin fertilizer. Worse even, the

385 sludge may contaminate and negatively affect the soil quality, which is why many countries

386 discourage or prohibit these activities (Milieu Ltd. and WRc and RPA 2013). Another concern is the

387 secondary waste resulting from waste recovery. For example, the use of waste as an adsorbent is a

388 low added value application, which generates an equal amount of waste after adsorption. This waste

389 then still needs to be dealt with and is probably incinerated. Ideally, the waste is recovered in such a

390 way that another use is still possible afterwards. In other words, recovery should try to avoid a "dead

391 end" at which only incineration or landfill remains.

392 The calculations were based on various optimistic assumptions and moving toward the ideal

393 scenario would require the right conditions to be realized. For example, the analysis assumed

394 universal collection for end-of-life discards, and hence fulfilling the recovery potential would first

395 require establishing the relevant infrastructure. An important barrier to recovery is a lack of

396 knowledge of recovery options and this article helps to overcome this barrier by presenting a

397 quantified recovery potential. Other conditions for recovery can be categorized as technological

398 (technological development), environmental (contamination and toxicity), economic (supply,

399 demand and transport), and social (social and cultural context). Due to a lack of data, these

400 conditions could not be incorporated in the quantitative analysis, but their relevance is further

401 explained in the next section.

402 **4.2 The conditions for recovery**

403 *4.2.1 Technological development*

404 The assessment focuses on technologies that are likely to be available by 2050. Technological

405 development is particularly important for advanced energy recovery technologies. Gasification (of

406 black liquor or sludge) and pyrolysis (of sludge) are not currently commercially applied. These

407 technologies are potentially more energy-efficient than combustion but require further

408 development for large-scale applications. Moreover, energy recovery technologies are capital

409 intensive. The shift from combustion to gasification of black liquor needs to fit the investment cycle.

410 Worldwide, many recovery boilers will become obsolete in the next 15 years. As gasification is

411   considered a promising technology, these old boilers may be replaced with gasification units (Naqvi
412   et al. 2010).

413   Energy recovery of waste flows other than black liquor is challenging, because of their high water
414   content, high ash content, and low heating values. Older combustion methods require co-firing with
415   other fuels but more efficient fluidized bed boilers do not require co-firing. For gasification or
416   pyrolysis, the sludge first needs drying, which partly offsets the gains from a more efficient energy
417   recovery process (Stoica et al. 2009). In all cases, the remaining ash should be recovered to reduce
418   the overall impacts of energy recovery of waste. Fulfilment of the recovery potential will require
419   further development and combined use of the suggested technologies.

420   Several factors influence the rate of environmental innovation. Park (2014a, 2014b) examined the
421   market and regulatory factors that affect the pattern of technological innovation for waste recovery.
422   For the paper life cycle, relevant market factors include the relative prices and quality of waste
423   materials and their substitutes. Regulatory factors include policies and legislation for waste
424   collection and management. Governments may mandate minimum recycling requirements or affect
425   prices through taxation. Another barrier to technological innovation may be limited demand growth
426   due to the recent collapse in newsprint sales and the drop in paper demand during the financial
427   crisis (FAO 2016). Since hardly any additional production capacity is required, technological
428   innovation may have been limited to the renewal of installed capacity.

429   *4.2.2 Contamination and toxicity*

430   Contamination control is essential for safe and functional recycling and non-energy recovery.
431   Regarding recycling, Pivnenko et al. (2016a) suggested the following hierarchy of priorities. Ideally,
432   contamination is prevented. For example, certain inks should not be introduced into the paper life
433   cycle and biomass waste should not be co-fired with coal to prevent ash contamination. When
434   contamination is not prevented, it should at least be constrained, by excluding certain waste from
435   certain uses and avoiding mixing of waste. Separate collection is a key step in constraining
436   contamination and leads to lower levels of rejects and higher final quality (Miranda et al. 2013). A
437   third option is to remove contaminants during deinking but this will also remove some fibres, leading
438   to lower pulping yields (Pivnenko et al. 2016; Stawicki and Read 2010).

439   Toxicity can be a problem with non-energy recovery because sludge and rejects, ash, and causticizing
440   waste can contain high levels of hazardous trace elements. This is most problematic when
441   contaminants get dispersed into the natural environment through composting and use as fertilizer.
442   Landspreading of contaminated paper sludge ash may affect soil quality, water quality, human

443 health, and livestock. There may also be physical contaminants such as plastics and metals

444 (Environment Agency 2015). The recovery options for mixed ash are more limited since there may be

445 more contaminants in coal-wood ash including arsenic and lead (Park and Chertow 2014). For

446 causticizing residuals, hazardous trace elements and residual alkali constitute barriers to recovery

447 (Kinnarinen et al. 2016; Bird and Talberth 2008).

448 Energy recovery of waste generates flue gases, which may contain SO2, NOx, dust, dioxins, furans,

449 PAHs, and heavy metals. Good design of the combustion process can reduce the generation of

450 pollutants. The main process variables are time, temperature, and mixing, and these should be

451 manipulated to minimize (but rarely to fully eliminate) harmful emissions. Dioxins in flue gases, for

452 example, can be destroyed and removed through thermal treatment and adsorption, but partly end

453 up in the remaining ash (Lam et al. 2010). The use of appropriate chemicals for printing, coating, and

454 bleaching as well as flue gas cleaning technologies such as electrostatic precipitators (to remove

455 dust) also help minimize the impacts of energy recovery from waste (Suhr et al. 2015).

456 *4.2.3 Supply, demand, and transport*

457 Demand for waste from the paper industry is limited. There is a finite capacity for using waste in

458 cement for example, because as a low quality contaminated resource, it cannot fully substitute for

459 virgin inputs. In addition, the paper industry sometimes has to compete with other waste suppliers.

460 The inelasticity of supply of waste can complicate recovery: the quantity, quality, and time of

461 generation of waste may not respond to the preferences of the user. For example, deinking sludge

462 generation, as a joint product of paper production, follows the market demand for paper, not for

463 sludge (Deviatkin et al. 2014; Baumgärtner 2004). Sludge also varies in quality between mills and

464 over time for the same mill. Recovery facilities must therefore operate with flexible quality

465 standards and the quality must be measured more frequently than for regular products.

466 Supply of high-quality paper for recycling is dependent on separate collection efforts because it

467 avoids contamination with other waste (Miranda et al. 2013). The South Korean benchmark provides

468 a successful example of a recycling infrastructure. The opportunity to recycle is provided through

469 universal collection infrastructure and motivated through a Volume-based Waste Fee (VWF)

470 introduced in 1995. Waste must be discarded in standardized plastics bags in order to be picked up.

471 The bags can be purchased from local government. Recyclables are exempt from the fee and are

472 source separated and collected from public bins at no charge. The fee on non-recyclables is

473 supposed to incentivize consumers to shift as many recyclables as possible towards the recycling bin

474 (Park and Lah 2015; Lee and Paik 2011). Fulfilment of the recovery potential of end-of-life discards

475 requires such a system, or an equally effective one, to be implemented globally.

476 Waste materials often have relatively low value and transport costs can be prohibitive. Transport is
477 not normally considered in the waste hierarchy but plays an important role in assessing the practical
478 and economic feasibility of waste recovery. One of the keys to industrial symbiosis is geographic
479 proximity (Chertow 2000). Jensen et al. (2011) show that waste exchanges under the National
480 Industrial Symbiosis Program (NISP) in the United Kingdom are skewed towards shorter distances.
481 Half of exchanges of paper and cardboard, compost and soils, minerals, wood products, ashes and
482 slags, and aqueous sludge are within distances of 11-108 km. Paper mills that use recycled fibre are
483 more likely to be located close to other industrial facilities and near urban areas and have many
484 opportunities for industrial symbiosis. Paper mills that rely on virgin fibre may be located in remote
485 forests where few other industries are located. In the latter case, options such as land application
486 may be more attractive than for example recovery in the construction industry.

487 ### 4.2.4 Social and cultural context

488 Waste is generally perceived negatively, reflecting deeply held cultural norms regarding products,
489 materials, and their context. The environmental hazard from waste partly stems from the disinterest
490 of the waste holder and the prevailing culture of throwing waste away carelessly (Cheyne 2002).
491 Waste is therefore sometimes littered, discarded in the wrong bins, or tipped. In particular, complex
492 products that need careful handling to make sure they retain their value may be dumped in bins or
493 left on the kerbside rather than brought to dedicated collection points. It is therefore necessary to
494 push for careful discarding by the waste holder. The "stigmatization" of waste may be reduced by
495 relabelling waste and specifying its value in terms of the reuse (or recovery) potential (Park 2012).

496 In contrast to waste, waste-based products are perceived rather positively and consumers are
497 sometimes willing to pay more for such products than for products from virgin materials. A study of
498 paper products by Mobley et al. (1995) suggested positive consumer attitudes towards recycled
499 content based on an appreciation of the environmentally friendly character. The effect was only
500 observed for paper of a well-known brand and not for paper of an unknown (fictitious) brand.
501 Hamzaoui-Essoussi and Linton (2010) showed that willingness to pay for waste-based products
502 decreases with perceived functional risk. An example of a product with high functional risk is food
503 packaging because of the possibility of food contamination (Suciu et al. 2013).

504 Social proximity – such as friendly or professional relationships – may be just as important as
505 geographical proximity to facilitate the use of waste as a resource between companies and
506 industries (Velenturf and Jensen 2016). A much-cited and related social factor is trust (Gibbs 2003;
507 Ashton 2008). The use of waste as a resource requires information sharing and investment in specific
508 technologies and infrastructures. Trust enables firms to engage in such transactions with high asset

509   specificity (Boons et al. 2017). Contingency plans and back-up contracts help companies deal with a

510   defaulting supplier. The coordination of the exchange of waste as a resource should consider the

511   embeddedness of decision making in social relationships and seek to build trust among the

512   participants (Doménech and Davies 2011).

513   **4.3   Policy implications and further research**

514   The aforementioned barriers to waste recovery could not be incorporated in the analysis, but our

515   results provide insights into the possibilities for the long term and exemplify a methodology that

516   may be applied at smaller spatial scales. With better (local) data, more precise results may be

517   calculated and used for regulatory purposes. In the EU, the Industrial Emissions Directive (IED) (EC

518   2010) lays down the rules for permitting industrial facilities based on Best Available Techniques

519   (BATs). For example, the BAT for the pulp and paper industry suggests using waste as an industrial

520   feedstock, for land spreading, or in construction materials (Suhr et al. 2015). There are, however, no

521   quantitative estimates of the potential for using waste from the pulp and paper sector as a resource.

522   When data allows, the BATs could be presented more usefully with the reuse or recovery potential

523   indicator.

524   This study has highlighted the options for waste recovery in the global paper life cycle but without

525   prioritizing among all options. What should decision-makers in the paper sector pursue? The waste

526   hierarchy can provide some guidance for choosing between recycling, non-energy recovery and

527   energy recovery but does not necessarily stimulate system-wide reductions of material use, nor does

528   it consistently indicate lowest environmental impacts (Van Ewijk and Stegemann 2016). To choose

529   between the different options, one might use the following performance criteria, in order of

530   increasing difficulty of their assessment: diversion from landfill, substitution of virgin materials,

531   reduction of individual environmental impacts, and reduction of systemic environmental impacts.

532   The analysis in this article considered only the first two criteria based on a material flow analysis.

533   Assessing the latter two criteria would require a life cycle assessment and is the subject of future

534   research.

535   Regulation can stimulate or deter recovery. Recovery occurs more likely under flexible waste

536   management regulation, which focuses on environmental standards instead of prescribing

537   treatments, and strict discouragement of the lower options of the waste hierarchy (Costa et al.

538   2010). Waste exchange through direct government intervention has proved largely unsuccessful.

539   Instead, "kernels" of symbiosis should be "uncovered" and supported (Chertow 2007). A case study

540   of waste exchanges with a Finnish paper mill concluded that public policy should focus on providing

541   the right conditions for industrial symbiosis, through the provision of knowledge and data and the

542   implementation of appropriate spatial planning and land-use policies (Lehtoranta et al. 2011).

543   Regulation also has a role to play in fulfilling a variety of conditions for recovery: technological

544   development, contamination and toxicity, supply, demand, and transport, and social and cultural

545   context.

546   Future research may overcome the limitations of this study. Better data regarding current and

547   potential recovery options may be obtained through industry collaboration. The calculated recovery

548   potentials only reflect what is likely to be technically possible in 2050. Besides, the analysis has not

549   shown the potential benefits of waste recovery beyond the confines of the paper industry. Paper

550   waste recovery in agriculture has implications for this sector too, as well as for sectors that supply

551   the agricultural sector. Furthermore, the analysis focused on final waste treatments within the paper

552   life cycle and ignored the potential benefits of cascading biomass use across different sectors. For

553   example, fibres could be used in timber, for paper, and as a fuel successively. There is also a

554   potential to shift towards plants and agricultural residues as feedstocks (Bousios and Worrell 2017).

555   Exploring all these possibilities requires a much wider system boundary and is left for future

556   research. Finally, the approach demonstrated in this article may be applied to other material life

557   cycles and sectors, primarily those that feature large waste streams and good data availability.

558   **5   Conclusions**

559   This analysis uniquely combined the concept of a "recovery potential" with a full material balance of

560   the global paper life cycle. The results show what the "ideal" paper life cycle would look like if known

561   technologies and best practices were further developed and implemented globally. The analysis

562   distinguished end-of-life discards, paper in sewage and the following industrial wastes: black liquor,

563   recycling sludge, papermaking waste, sludge and rejects, causticizing waste, and boiler ash. The

564   recovery options were categorized as recycling, non-energy recovery, and energy recovery.

565   The results show current (2012) material flows and ideal material flows for the global paper life cycle.

566   The ideal system represents a probable technical potential in 2050. The fulfilment of the recovery

567   potential of all waste flows significantly improves the system performance. The Recycled Input Rate

568   (RIR) rises from 38% to 67-73% and the landfill intensity decreases from 331-473 kg/t paper to 0-2.6

569   kg/t paper. Fulfilment of the recovery potential requires meeting the technical, environmental,

570   economic, and social conditions relevant to waste recovery.

571   The analysis supports the recovery of waste as a resource by giving a global overview of the recovery

572   potential of major waste flows in the global paper life cycle. The results can also be used for an

573   assessment of environmental impact reductions. Further research should seek to overcome the

574   limitations of this study. It may consider local technical and non-technical constraints and formulate

575   a more precise potential for waste recovery. The analysis may also be improved by considering the

576   cascaded use of materials and the linkages between sectors and material life cycles.

577   **6   Acknowledgements**

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734

735 **8 Appendices**

736 **A. Waste generation**

737 The figures for waste generation are calculated in four steps. First, the following flows are taken

738 from Van Ewijk et al. (2017): *end-of-life discards* and *papermaking waste.* Second, the waste from

739 chemical pulping and the waste from mechanical pulping are further detailed and combined in the

740 following flows:

741   - *Black liquor* is the proportion of chemical pulping waste that is not a by-product or part of
742   sludge and rejects.
743   - *By-products* are mainly tall oil and turpentine. By-products are produced at 10-75 (50
744   typical) kg/t pulp (Suhr et al. 2015, p. 204).
745   - *Sludge and rejects* consist of two fractions of chemical pulping waste and all of the
746   mechanical pulping waste. The two fractions of chemical pulping waste are Waste Water
747   Treatment Plant (WWTP) residuals, produced at a rate of 10 kg/t pulp (Suhr et al. 2015, p.
748   250), and screening rejects, produced at a rate of 2-20 (used value 11) kg/t pulp (Suhr et al.
749   2015, p. 251).

750 Third, causticizing waste consists of losses from the chemical recovery cycle and is compensated for

751 with lime-make up. This flow is included as both an input and an output and leads to a larger overall

752 waste generation than in Van Ewijk et al. (2017). It is not part of chemical pulping waste because it

753 results from a separate process. Causticizing waste is produced at an average rate of 30 kg/t pulp

754 and varies between 10 and 60 kg/t pulp (Suhr et al. 2015, p. 251).

755 Last, ash is included as a secondary waste from waste combustion and included as both an input and

756 an output in the material balance. The quantity of boiler ash follows from the ash content of waste

757 used for energy recovery, based on the following assumptions.

758   - Sludge and rejects: 10% ash content. This is a rough approximation based on the ash content
759   of mechanical pulping sludge (2% based on wood), Kraft screening rejects (10%), and WWTP
760   solids (20%) (Gavrilescu 2008; Suhr et al. 2015).
761   - Recycling sludge: 45% ash content (Suhr et al. 2015).

762 The resulting waste flows are detailed in Appendix D.

763 **B. Waste treatments**

764 The treatment of end-of-life discards, papermaking waste, and paper in sewage is discussed in Van

765 Ewijk et al. (2017). The waste treatment of the other waste flows is calculated using the following

766 procedure.

767   1. Taking the total waste treatment intensities in kg/t paper for non-energy recovery and

768   landfill from Van Ewijk et al. (2017).

769   2. Estimating the fractions of non-energy recovery, energy recovery, and landfill for sludge and

770   rejects, causticizing waste, and boiler ash based on the literature.

771   3. Calculating the quantities of boiler ash based on ash content of the relevant waste and the

772   fraction of industrial waste to energy recovery.

773   4. Calculating the treatment fractions for recycling sludge by balancing waste treatment of all

774   other flows, ash generation, and total waste treatment.

775 Because the data are very uncertain, the waste treatment fractions are rounded to quarters, except

776 for the case of recycling sludge, since this is calculated from final differences. Below, the individual

777 waste flows are discussed (step 2 and 4).

778 *Sludge and rejects*

779 Sludge and rejects cover mechanical pulping losses, Kraft rejects, and Kraft WWTP residuals. These

780 waste streams can also be categorized as WWTP residuals because they are suspended solids that

781 first go through wastewater treatment. Bird and Talberth (2008) present data for WWTP residuals

782 from a 2002 study by the American Paper and Forestry Association which suggests that 52% of the

783 waste is landfilled, 22% is used for energy recovery, and 26% is applied to land or used for other

784 non-energy recovery operations. It is assumed that globally one quarter is used for energy recovery

785 and one quarter is used for non-energy recovery.

786 *Causticizing waste*

787 Bird and Talberth (2008) present US data gathered by NCASI for 1995 which shows 70% of lime mud,

788 95% of dregs, and 91% of grits go to landfill (or lagoon). Overall, 81% of these materials were

789 landfilled. Data from the Finnish Forest Industries collated by Kinnarinen et al. (2016) suggest that

790 71% of dregs were landfilled in Finland in 2012. If the landfill rates of lime mud and grits have

791 similarly improved, total causticizing waste landfill rates would be 61% in 2012 (71/95*81=61).

792 However, the Finnish data most certainly represent an above average performance. It is assumed

793 that approximately three quarters of global causticizing waste are landfilled.

794   *Boiler ash*

795   The American Forestry and Paper Association (AF&PA) presented a report in 2002 which shows that

796   about one third of boiler ash is recovered (Bird and Talberth 2008). In Canada, in 2002, about 80% of

797   ash from pulp and paper mills was landfilled (Elliott and Mahmood 2006). In 2003, over half of wood

798   ash from the pulp and paper industry in Finland was utilised (Emilsson 2006). Finland probably

799   performs well above the global average, partly because of very little mixing of wood ash with coal

800   ash. It is assumed that approximately half of wood and sludge ash from pulp and paper mills is used

801   in non-energy recovery in 2012.

802   *Recycling sludge*

803   Recycling sludge is the largest industrial waste fraction after black liquor from chemical pulping. The

804   treatment fractions are based on the differences between final treatments of the total industrial

805   waste flow based on the overall waste treatment intensities in Van Ewijk et al. (2017) and the waste

806   treatment of causticizing waste, boiler ash, and sludge rejects as described above. The calculation

807   includes secondary waste in the form of ash from energy recovery. This implies that any increase in

808   energy recovery entails an increase in the amount of waste that needs final treatment. The resulting

809   fractions are 8% energy recovery and 50% non-energy recovery.

810 **C. Recycling rate and recovery potential**

811 The recovery potential (RP) for recycling is not calculated as a recycling rate (RR) because it needs to
812 consider inevitable losses due to additions to stock and paper in sewage. The RP also distinguishes
813 between papermaking waste and end-of-life discards. The description of the RR and RP are as
814 follows:

815 - The RR divides total paper for recycling collection by total consumption. It includes paper for
816 recycling from the pulp, paper, and print industry (papermaking waste) and from consumers.
817 - The fulfilment of the RP for end-of-life discards indicates the fraction of potentially
818 recyclable end-of-life discards that is recycled. End-of-life discards consist of total
819 consumption minus net additions to stock and paper in sewage.
820 - The fulfilment of the RP for papermaking waste indicates the fraction of papermaking waste
821 that is recycled. Papermaking waste is calculated based on the yield ratio of papermaking.

822 The fulfilment of the potential for recycling of end-of-life discards can be calculated from the
823 recycling rate based on the flow quantities detailed in Appendix D. The RR can be calculated as
824 follows:

825 $$RR = \frac{F25 + F15 + F17 + F19 + F21}{F22 + F23 + F24} \qquad \text{(C.1)}$$

826 The RP for end-of-life discards and papermaking waste is 1.00. The actual quantity of recycling under
827 fulfilment of the RP can be calculated with the following two equations.

828 $$RP_{EoL\ discard} = F24 * 1.00 \qquad \text{(C.2)}$$

829 $$RP_{papermaking\ waste} = (F15 + F17 + F19 + F21) * 1.00 \qquad \text{(C.3)}$$

830 The current performance for recycling of end-of-life discards is lower than the potential. The
831 fulfilment of the potential can be calculated as follows.

832 $$RP_{EoL\ discard_{fulfilled}} = F25/F24 \qquad \text{(C.4)}$$

833 Based on the above, an RR of 0.91, as for South-Korea, can be converted to a figure for the RP
834 fulfilment. Consumption is assumed to be a 100 units. The calculation starts with distinguishing the
835 papermaking waste (PMW) based on the yield ratio of papermaking of 0.95 (Van Ewijk et al. 2017).

836 $$PMW = \frac{100}{0.95} - 100 = 5.3 \qquad \text{(C.5)}$$

837 Now the amount of end-of-life discard that is recycled can be calculated, assuming PMW is fully
838 recycled.

839 $$EoL_{recycling} = 0.91 * 100 - 5.3 = 86 \qquad \text{(C.6)}$$

840 Availability of end-of-life discards follows from net additions to stock and losses of toilet paper in

841 sewage (TP) of 0.09 and 0.03 respectively (Van Ewijk et al. 2017).

842 $$EoL_{discard} = 100 * (1 - NaS - TP) = 88 \qquad \text{(C.7)}$$

843 $$RP_{EoLdiscard_{fulfilled}} = \frac{86}{88} = 0.97 \qquad \text{(C.8)}$$

844 In conclusion, the benchmark for fulfilment of the recovery potential for recycling of end-of-life

845 discards is 0.97.

D. Material balances

847   *Table D.1: Detailed normalized current and ideal flows (for the base year 1 unit = 4 Mt).*

Flow	Input	Output	Current	Ideal
F1	Virgin fibre	Mechanical pulping	8.7	4.1
F2	Virgin fibre	Chemical pulping	78.3	36.4
F3	Paper for recycling (in)	Recycled pulping	53.9	93.3
F4	Mechanical pulping	Mechanical pulp	8.1	3.8
F5	Mechanical pulping	Sludge and rejects	0.6	0.3
F6	Chemical pulping	Chemical pulp	37.6	17.5
F7	Chemical pulping	Black liquor	38.0	17.7
F8	Chemical pulping	By-products	1.9	0.9
F9	Chemical pulping	Sludge and rejects	0.8	0.4
F10	Lime makeup	Recovery cycle	1.1	0.5
F11	Recovery cycle	Causticizing waste	1.1	0.5
F12	Recycled pulping	Recycled pulp	43.7	68.1
F13	Recycled pulping	Recycling sludge	10.2	25.2
F14	Recycled pulp	Consumption	41.5	64.7
F15	Recycled pulp	Papermaking waste	2.2	3.4
F16	Chemical pulp	Consumption	35.7	16.6
F17	Chemical pulp	Papermaking waste	1.9	0.9
F18	Mechanical pulp	Consumption	7.7	3.6
F19	Mechanical pulp	Papermaking waste	0.4	0.2
F20	Non-fibrous	Consumption	15.1	15.1
F21	Non-fibrous	Papermaking waste	0.8	0.8
F22	Consumption	Stock	9.0	9.0
F23	Consumption	Paper in sewage	3.0	3.0
F24	Consumption	End-of-life discards	88.0	88.0
F25	End-of-life discards	Recycling	48.6	88.0
F26	End-of-life discards	Energy recovery	4.7	0.0
F27	End-of-life discards	Incineration	3.1	0.0
F28	End-of-life discards	Landfill	31.5	0.0
F29	Paper in sewage	Non-energy recovery	1.2	0.0
F30	Paper in sewage	Energy recovery	0.4	3.0
F31	Paper in sewage	Incineration	0.2	0.0
F32	Paper in sewage	Landfill	1.2	0.0
F33	Black liquor	Energy recovery	38.0	17.7
F34	Recycling sludge	Non-energy recovery	5.2	21.7
F35	Recycling sludge	Energy recovery	0.8	3.5
F36	Recycling sludge	Landfill	4.3	0.0
F37	Papermaking waste	Paper for recycling (out)	5.3	5.3
F38	Sludge and rejects	Non-energy recovery	0.3	0.3
F39	Sludge and rejects	Energy recovery	0.3	0.3
F40	Sludge and rejects	Landfill	0.7	0.0
F41	Causticizing waste	Non-energy recovery	0.3	0.4
F42	Causticizing waste	Landfill	0.8	0.1
F43	Secondary	Boiler ash	0.4	1.6
F44	Boiler ash	Non-energy recovery	0.2	1.6
F45	Boiler ash	Landfill	0.2	0.0

848