Global Life Cycle Paper Flows, Recycling Metrics, and Material Efficiency

Stijn Van Ewijk,[1] Julia A. Stegemann,[2] and Paul Ekins[1]

[1] Institute for Sustainable Resources (ISR), University College London, London, United Kingdom
[2] Center for Resource Efficiency & the Environment (CREE), Department of Civil, Environmental & Geomatic Engineering, University College London, London, United Kingdom

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Summary

Despite major improvements in recycling over the last decades, the pulp and paper sector is a significant contributor to global greenhouse gas emissions and other environmental pressures. Further reduction of virgin material requirements and environmental impacts requires a detailed understanding of the global material flows in paper production and consumption. This study constructs a Sankey diagram of global material flows in the paper life cycle, from primary inputs to end-of-life waste treatment, based on a review of publicly available data. It then analyzes potential improvements in material flows and discusses recycling and material efficiency metrics. The article argues that the use of the collection rate as a recycling metric does not directly stimulate avoidance of virgin inputs and associated impacts. An alternative metric compares paper for recycling (recovered paper) with total fibrous inputs and indicates that the current rate is at just over half of the technical potential. Material efficiency metrics are found to be more useful if they relate to the reuse potential of wastes. The material balance developed in this research provides a solid basis for further study of global sustainable production and consumption of paper. The conclusions on recycling and efficiency should be considered for improving environmental assessment and stimulating a shift toward resource efficiency and the circular economy.

Introduction

High recycling rates are often cited as evidence for the environmental performance of the paper sector. The global paper system nevertheless contributes to numerous environmental problems, including climate change, water pollution, and air pollution. Allwood and colleagues (2010) show that, even under a highly optimistic business-as-usual scenario, carbon emissions from the paper sector in 2050 will far exceed the reduction target of 50%. The necessary impact reductions are unlikely to be met unless all potentials are explored. To discover these potentials, a detailed material flow analysis (MFA) of paper production, consumption, and waste treatment is needed. This article provides such an analysis for global paper flows from virgin inputs to end-of-life waste treatment.

The MFAs for paper and pulp in the existing literature are detailed at the national level (Hekkert et al. 2000; Cote et al. 2015; Hong et al. 2011; Sundin et al. 2001) or highly aggregated at the global level (Allwood et al. 2010). The aim of this study is to produce a detailed global material balance of paper flows like those published for steel (Cullen et al. 2012) and aluminum (Cullen and Allwood 2013; Liu et al. 2012). Such a material

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Address correspondence to: Stijn van Ewijk, Institute for Sustainable Resources (ISR), University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, United Kingdom. *Email*: stijn.ewijk.13@ucl.ac.uk

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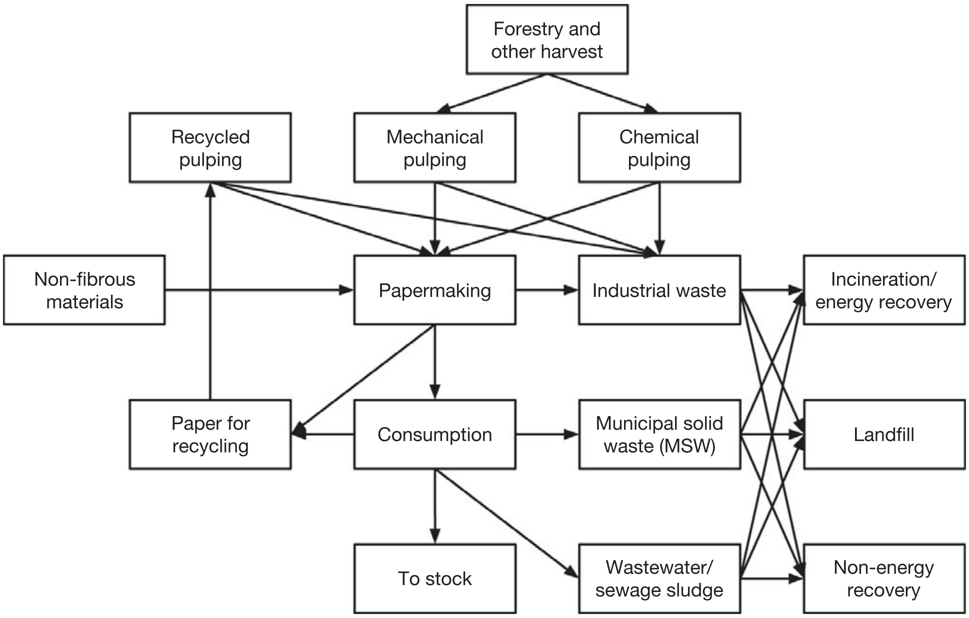

Figure 1 The paper system.

balance helps identify options for reducing virgin material inputs and associated environmental impacts. An analysis based on the mass balance principle can approximate important but ill-reported flows such as virgin wood inputs, non-fibrous inputs, and waste treatment flows.

The material balance is a useful contribution for two reasons. First, it is used in this article for comparing and analyzing mass-based performance metrics. Such mass-based metrics are used by governments around the globe to track environmental performance and therefore deserve critical analysis. This article shows the shortcomings of commonly used recycling and efficiency metrics and makes recommendations for improving them. The article also quantifies the technical recycling potential. Second, the material balance can serve as a basis for more advanced methods that may consider energy, water, emissions, land use, and other environmental impacts. Such life cycle assessments (LCAs) require a material balance to start with, and no such balance yet exists for the paper system.

The article is structured as follows. The next section explains the data sources, assumptions, and methods used for constructing the material balance. This is followed by the results, in the form of a Sankey diagram, and a discussion of recycling metrics, efficiency metrics, and appraisal of waste reuse. The article concludes by suggesting improvements in environmental performance metrics and indicating directions for future research.

Data and Methods

This study constructs a material balance to indicate the origin, destination, and size of global flows of wood, pulp, paper, and waste paper for 2012. The data are drawn from a variety of sources and the values are calculated using material-balance equations and matrix algebra. The assessment considers the dry masses of all flows—gases and water are not included. The consumption of five categories of paper, chemical pulp, mechanical pulp, and paper for recycling is based on the Food and Agriculture Organization of the United Nations (FAO) (FAO 2016). The flows in each life cycle stage are further specified using parameters from the literature and industry reports (see section SI-1 in the supporting information available on the Journal's website). Materials referred to as by-products or co-products in the literature are consistently referred to as wastes in this analysis and include black liquor, tall oil, and turpentine. Waste paper that is recycled, sometimes called recovered paper, is referred to as paper for recycling. Pulp from paper for recycling, sometimes called secondary pulp or recovered pulp, is referred to as recycled pulp. The fraction of postconsumer waste paper that is neither recycled nor ends up in the sewer is referred to as residual waste paper.

Figure 1 displays the main stages in the life cycle of paper from harvest to waste treatment. Paper is produced from wood, non-wood harvest, waste paper, and non-fibrous material. Wood is converted into mechanical, chemical, and semichemical wood pulp. Mechanical pulping consists of grinding wood and is highly energy intensive. Chemical pulping is used for higher-quality products since it removes undesirable lignin from wood. Semichemical pulping combines a grinding stage with chemical treatment, but is split into equal fractions of chemical and mechanical pulping in the further analysis. In addition to wood, a fraction of non-wood pulp from materials such as straw is used, mainly in China and India. Paper for recycling is pulped separately and often deinked. The different pulps, together with non-fibrous materials, are used in different combinations for papermaking of different grades (omitted in figure 1). After consumption, paper is either added to stock, recycled, or ends up in incineration (with or without energy

Table 1 Yield ratios for pulping and papermaking

Parameter	*Range*	*Reference*	*Value used*	*Notes*
Chemical pulping	0.40 to 0.55	(Martin et al. 2000)	0.48	Median value
Mechanical pulping	0.90 to 0.95	(Martin et al. 2000)	0.93	Median value
Recycled pulping	0.73 to 0.89	(Stawicki and Read 2010; FAO 2016)	0.81	See section S1-3 in the supporting information on the Web
Papermaking	—	(Eurostat 2016; FAO 2016)	0.95	—

Table 2 Fraction of inputs in five main grades of paper

	Outputs				
Inputs	*Newsprint*	*Printing + writing*	*Sanitary + household*	*Packaging*	*Other*
Recycled pulp	0.68	0.08	0.34	0.56	0.27
Chemical pulp	—	0.62	0.66	0.22	0.51
Mechanical pulp	0.22	—	—	0.11	—
Non-fibrous	0.10	0.30	—	0.10	0.23

recovery), landfill, or the sewer. The paper sector generates paper for recycling and industrial waste such as sludge, which is used for energy recovery, non-energy recovery, or landfilled.

Yield Ratios

The inputs to chemical and mechanical pulping can be calculated from reported global pulp production (FAO 2016) and the yield ratios for pulping (table 1). Martin and colleagues (2000) suggest ranges of yield ratios for pulp relative to the wood input for mechanical pulping and chemical pulping. This analysis uses the median values. Other references such as MacLeod (2007) and Briggs (1994) suggest similar values. The yield ratios for non-wood pulping are assumed similar to those for chemical wood pulping. The recycled pulping yield ratio is calculated by considering the use of paper for recycling per paper grade and the yield ratio per paper grade. The calculation uses the production matrix in table 2 and recycled pulping yield ratios from Stawicki and Read (2010). It assumes that between 0% and 50% of recycled inputs to packaging are deinked (see section SI-3 in the supporting information on the Web).

Yield ratios for papermaking are dependent on the paper grade that is being produced and can vary significantly per paper product. The papermaking yield ratio is therefore derived from aggregate waste paper losses and total paper production in the pulp, paper, and print sector in the European Union (EU) 28 (Eurostat 2016; FAO 2016). These losses are recycled and part of the total global paper for recycling quantity reported by the FAO. The resulting yield ratio is very close to the value in the International Energy Agency (IEA) (IEA 2007, 264) and used by Allwood and colleagues (2010). It should be noted that these wastes result mostly from paper converting and printing and do not constitute inefficiencies in paper mills. The quantity of non-fibrous filler materials is calculated from the final difference between pulp inputs, conversion losses, and paper outputs in papermaking and cross-checked with European data (CEPI 2012).

Production Matrix

Table 2 shows the fractions of pulp and non-fibrous material inputs in the five main paper grades. The total quantities of pulp, the four paper grades, and "other paper" are taken from the FAO (2016). The total pulp and filler requirement is adjusted for losses in papermaking. The values in table 2 are calculated in a three-step procedure. First, the fraction of recycled pulp in each grade is calculated from paper for recycling utilization reported by the Confederation of European Paper Industries (CEPI) (CEPI 2012) and the yield ratio for recycled pulping. Each fraction for recycled pulp is scaled downward based on the total global amount of recycled pulp, to correct for the difference between European and global recycling levels. Second, the fraction of non-fibrous material are approximations based on Cote and colleagues (2015). The fraction of non-fibrous materials in "other" is calculated from the final difference between the total non-fibrous material use and the use in all other paper grades. Last, in accord with Laurijssen and colleagues (2010), the further input to newsprint is assumed to be mechanical pulp, and for printing + writing and sanitary + household paper it is chemical pulp. The remaining quantity of mechanical pulp is allocated to packaging. The remainder of chemical pulp is allocated to "other."

Postconsumer Waste and Stock

Table 3 displays the relevant parameters for calculating postconsumer waste flows. Each year, consumers add some newly purchased paper to stock and dispose of some of their purchases or old stock. The net additions to stock are assessed in three ways. First, product lifetime distributions were used. The

Table 3 Parameters for waste treatment and net additions to stock

Parameter	*Value*	*Reference*
Net addition to stock	0.09 (0.06 to 0.12)	(Cote et al. 2015; IEA 2007; FAO 2010)
Fraction of consumption to sewage	0.03	(Cote et al. 2015)
Fraction of residual waste to energy recovery	0.12	(OECD 2015)
Fraction of residual waste to incineration	0.08	(OECD 2015)

distribution of product lifetimes can be flexibly captured using, among others, a Weibull distribution (Müller et al. 2014). This study uses a Weibull distribution of total annual waste paper outputs in Germany based on the parameters determined by Cote and colleagues (2015) and applies it to global paper and cardboard consumption. The second method follows the FAO (2010) and uses a decay model with a half-life of 2 years for all paper products. For both methods, the net addition to stock in a single year is highly sensitive to variations in annual consumption. To deal with this, the global paper and cardboard consumption time series (1961–2012) was approximated with a least squares quadratic regression function. The two methods result in fractions of net additions to stock of 0.06 and 0.09, respectively. A third estimate was taken from the IEA (2007, 264). This report suggests a value of 0.12 to 0.15, but because of the discrepancy with the results from the more advanced estimations, only the lower value of 0.12 is considered.

The quantities of residual waste paper per country are calculated from FAO (2016) and the parameters for additions to stock and losses to sewage. The parameter for sanitary paper to sewage is set based on the fraction of toilet paper reported for Germany (Cote et al. 2015). It was assumed that all residual waste paper ends up effectively treated as residual municipal solid waste (MSW). The rates of residual MSW going to energy recovery, incineration without energy recovery, and landfill (or other disposal) for 30 of 34 Organization for Economic and Cooperative Development (OECD) countries and China are taken from OECD (2015). Residual waste paper from the rest of the world is assumed to go to landfill. Paper in sewage sludge is assumed to receive the same treatment as residual waste paper with the difference that the non-burned fraction is divided equally between landfill and non-energy recovery such as land application.

Industrial Waste

The fate of industrial waste generated during pulping is extrapolated from industry sustainability reports and annual reports. Table 4 summarizes the data from four of the largest paper companies in the world, covering 11% of global paper and cardboard production. It shows total paper production per company and the reported amounts of waste landfilled or used for non-energy recovery. Some of these quantities were calculated from reported waste treatment per tonne of final product or treatment as a percentage of total waste generation. Non-energy recovery includes land application or composting of sludge. Waste used for energy recovery is not directly reported by most companies, but follows from the difference between pulping losses and the amounts of waste landfilled and used for non-energy recovery. Monte and colleagues (2009) list many pretreatments for energy recovery, but company reports tend not to differentiate such pretreatments.

The representativeness of the data is compromised by a selection bias—reporting is voluntary and the worst performers naturally stay silent—but the sample does feature good geographical coverage. Data reported by UPM, Stora Enso, Resolute FP, and SCA were excluded as these companies also produce significant amounts of timber. Small fractions of waste dealt with by third parties are allocated to non-energy recovery. Incineration without energy recovery is considered negligible. It is assumed that, on average, the companies produce as much pulp as needed for their own paper and cardboard production and thus reflect the global average for pulping waste per unit of final product. The figures reveal significant differences in performance between the different companies. On average, 0.06 (0.04 to 0.12) tonne/tonne of paper and cardboard production goes to non-energy recovery and 0.06 (0.04 to 0.11) tonne/tonne goes to landfill.

Table 4 Paper production and industrial waste flows as reported by major paper producers

			Industrial waste treatment (megatonnes)	
Company	*Country*	*Paper production (megatonnes)*	*Landfill*	*Non-energy recovery*
International Paper	United States	23.8	1.5	0.9
APP	Indonesia	8.3	0.3	0.7
Sappi	South Africa	5.4[a]	0.6	0.5
Kimberly Clark	United States	4.8	0.3	0.6
	Total	42.2	2.6	2.7

[a] Based on reported capacity and assumed 90% capacity utilization.

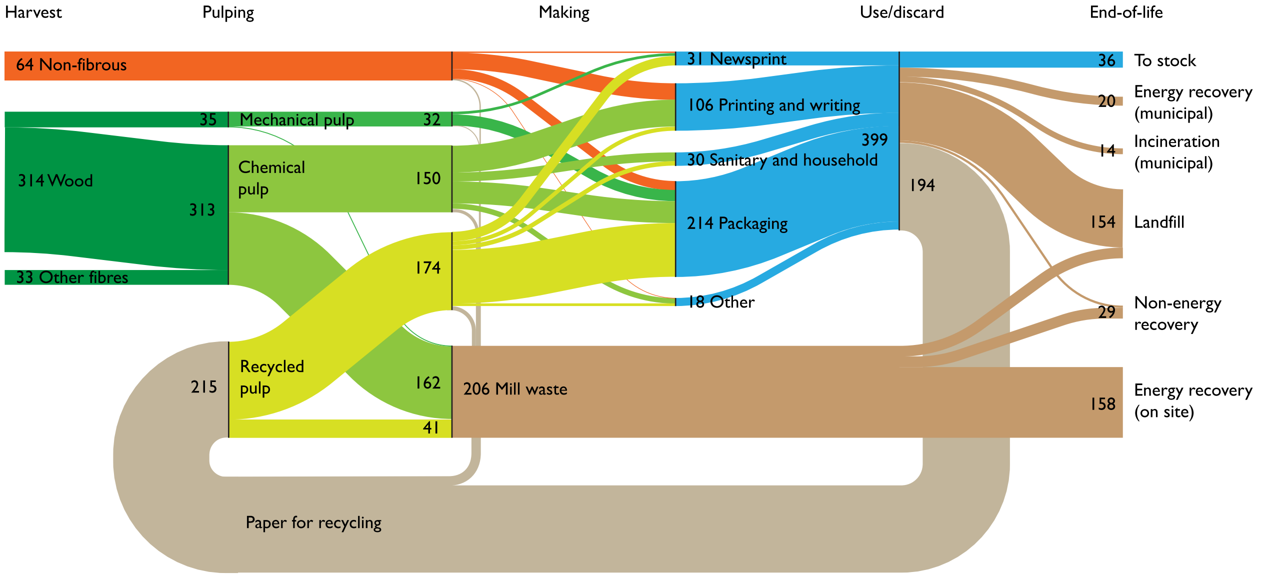

Figure 2 Global paper flows in 2012 in megatonnes.

Uncertainty

The data sources are sufficiently reliable to allow construction of a complete and consistent material balance. The apparent match between parameters and values from independent data sources reinforce the validity of the results. The following flows cannot be validated using the mass balance principle: non-fibrous input, virgin fibrous inputs, industrial waste generation, residual waste paper treatments, and industrial waste treatments. The amount of non-fibrous materials was calculated as a final difference. The non-fibrous content is 15.1% of final paper and cardboard production in 2012. Cross-checking reveals that this value is very close to the amount of non-fibrous materials (14.9%) used in a selection of European countries (CEPI 2012). The uncertainty of the other aforementioned flows is quantified through sensitivity analysis.

Sensitivity analysis shows the effect of parameter variation and is frequently applied to assess the robustness of material flow models (Laner et al. 2014). The approach in this article is to calculate a lower and upper bound for a flow based on the range of the relevant parameter. The parameter for the yield ratio of chemical and mechanical pulping affects virgin fibrous inputs and industrial waste generation, the parameter for net additions to stock affects the residual waste paper treatments, and the parameters for industrial waste treatment affect the total quantities going for non-energy recovery and landfill. The fraction of waste that is burned, but remains as ash, is included with non-energy recovery or landfill. All flows are reported to the nearest 1 megatonne.

Table 5 Material flows and their upper and lower bound

Material flow	*Lower bound (megatonnes)*	*Value used (megatonnes)*	*Upper bound (megatonnes)*
Virgin fibrous inputs	307	347	411
Net additions to stock	24	36	48
Postconsumer waste to energy recovery	19	20	22
Postconsumer waste to incineration	13	14	14
Postconsumer waste to landfill	116	130	145
Industrial waste to energy recovery	134	158	178
Industrial waste to non-energy recovery	16	24	48
Industrial waste to landfill	16	24	44

Results and Discussion

Figure 2 shows the Sankey diagram of global paper flows in 2012. The diagram displays the flow of materials from harvest (left) to end-of-life (right). The flow width reflects the quantity. Mill wastes indicate waste flows in the industry that are either used in on-site energy recovery, are non-energy recovered, or landfilled. On-site energy recovery by paper producers is displayed separately from incineration with and without energy recovery of paper in residual MSW. Waste paper from papermaking is visualized as separate fibrous and non-fibrous losses, and they enter the same recycling loop as postconsumer waste paper. The detailed results including equations are given in section SI-2 of the supporting information on the Web.

Table 5 shows the upper and lower bounds for several material flows based on the sensitivity analysis. The relative variation of the lower and upper bounds from the used value is largest for non-energy recovery and landfill of industrial waste. The ranges are skewed toward higher values because of the distribution of company performance. Despite the uncertainty, the material balance is useful for comparing the relative sizes of flows and analyzing potential improvements. Over time, the balance may be updated and improved with new data. The following sections discuss recycling and efficiency metrics and waste reuse appraisal based on the material balance.

Recycling Metrics

Current recycling metrics provide only a distorted image of the paper system. Recycling is commonly calculated by dividing paper for recycling by total production of paper and cardboard (Ervasti et al. 2015). For the global paper system, this results in a collection rate of 54%. However, this metric is both inconsistent and lacks meaning. It is inconsistent because it compares a quantity from the pulping stage (paper for recycling inputs) with a quantity from the papermaking phase (total production or consumption). The metric omits the losses that occur in between the two stages and ignores that not all paper is discarded and therefore not available for recycling. The metric also lacks meaning because its value does not reflect the purpose of recycling. The main goal of recycling is the reduction of impacts by displacing virgin production (Geyer et al. 2016). A recycling metric can only reflect the avoidance of virgin inputs by focusing directly on the harvest stage of the life cycle. A recycling metric that is both consistent and meaningful should compare waste paper inputs (paper for recycling) with total inputs (paper for recycling plus virgin fibrous harvest). Such a metric was discussed by Graedel and colleagues (2011) and named the *recycled input rate* (RIR).

The value of the RIR is 38% while the collection rate is 54%. The difference reflects the relatively high yield ratio of recycled pulping compared to chemical pulping. In other words, an increase in paper for recycling inputs does not imply a proportional decrease in virgin input requirements. Due to the differences in pulping efficiencies, 1 mass unit of paper for recycling may either displace 0.9 units of wood for mechanical pulping or 1.7 units of wood for chemical pulping. When paper for recycling substitutes virgin inputs without affecting the ratio between mechanical and chemical pulp inputs, the average global substitution rate is around 1.5. In practice, it depends on the desired properties of the final product whether recycled pulp will substitute mostly mechanical or chemical pulp. The RIR should be used with care because it can be inflated through inefficient use of secondary material (Chen 2013). The metric is also sensitive to the fraction of non-fibrous inputs since these could also substitute virgin pulp. It is beyond the scope of this article to discuss desirable levels of substitution of fibers by non-fibrous material.

Recycling metrics expressed as percentages may create the false impression that 100% recycled paper is technically possible. It is therefore important to report the technically achievable maximum performance alongside actual performance. At 2012 consumption levels, 351 tonnes (± 12 tonnes) of paper for recycling can be collected. The rest of consumption is irretrievably lost in the sewer or added to stock. The lower and upper bound is based on variability in additions to stock. In addition, papermaking generates 21 tonnes of paper for recycling. The total potential quantity of paper for recycling implies a collection rate of 90% to 96%. This large supply of paper for recycling can only be used with improved control of contamination. Pivnenko and colleagues (2015) show that 51 contaminants currently found in paper can pose challenges for recycling. Contamination may exclude certain uses of paper for recycling or lead to lower pulping yields. The most effective measure is not source separation or removal, but to phase out the use of chemicals altogether (Pivnenko et al. 2016).

The maximum value of the more desirable RIR can be calculated assuming a fixed non-fibrous content fraction and a fixed ratio between mechanical and chemical pulp for virgin fibrous inputs. The calculation assumes the lower recycled pulping yield ratio of 0.73 to reflect the increased need for deinking. Under these assumptions, the technical limit of the RIR is 67% to 73% (see section SI-4 in the supporting information on the Web). In other words, only 67% to 73% of fibrous inputs can be supplied by waste paper, the rest needs to be virgin fibers. The current performance for the metric is 38%, which is just over half of the technical potential. The inclusion of a technical potential in the reporting of recycling metrics can support better decision making. It would be useful for policy makers and industry to know how much more recycling is possible. An LCA would be required to assess the environmental merit of maximizing recycling.

Material Efficiency Metrics

Another way to improve paper production is by increasing the material efficiency of conversion processes since it reduces input requirements. The overall material efficiency (or yield ratio) of paper production strongly depends on the paper grade and required pulp inputs. For example, mechanical pulping has a much higher yield (0.90 to 0.95) than chemical pulping (0.40 to 0.55). However, the wastes from chemical pulping are used for energy recovery and can be sufficient to meet the energy demand of the mill. Low yield in chemical pulping therefore does not necessarily represent an undesirable inefficiency. The beneficial use of waste materials needs to be captured when discussing material efficiency.

Basic material efficiency calculations ignore the role of waste reuse. The standard metric for material efficiency is the ratio between material used in the product (M_p) and material supplied to it (M_s) (Lifset and Eckelman 2013).

$$\eta_m = \frac{M_p}{M_s}$$

Allwood and colleagues (2011) show how energy use and carbon emissions associated with conversion processes can be included in this equation. However, the example of the paper industry shows that energy needs can also be met by energy recovery from wastes from the same conversion process. In addition, wastes can be used for non-energy recovery. Material efficiency metrics would be more useful if they counted in all these types of waste reuse. The term reuse is defined here as any further use of wastes including recycling, energy recovery, and non-energy recovery—all the uses that potentially substitute virgin inputs and contribute to the overall resource efficiency of production and consumption.

The reuse of wastes can be included in efficiency metrics by considering the *reuse potential* of waste flows. The concept of a reuse potential has been suggested and explored by Park and Chertow (2014) for coal-combustion by-products. The waste reuse potential depends on the material properties and contextual factors and may change over time. A major challenge is data availability, especially since materials can have multiple uses. The reuse potential is operationalized as a value between 0 (no reuse possible) and 1 (full reuse possible) (Park and Chertow 2014). In part, standards for waste utilization are already found in documentation on best available techniques (Suhr et al. 2015). The reuse potential could be included numerically in material efficiency calculations. In addition, for complex material systems, such as analyzed in this article, the ideal total flow pattern could be assessed by assuming the full exploitation of the reuse potential of each flow. A Sankey diagram could serve to display both actual flows (as in this article) and ideal flows based on maximum waste reuse. The latter idea coincides with one of the first uses of the Sankey diagram by its namesake. In 1898, Sankey used two diagrams to compare actual and ideal flows of energy flows in a steam engine (Schmidt 2008; Sankey 1898)—the same could be done for material flows.

The assessments of recycling rates and material efficiency are closely related since both rely on the identification of a potential. For postconsumer waste, the reuse potential can be more precisely specified as a *technical recycling potential* and concerns the amount of wastes actually available to be collected as resources for reprocessing. For material efficiency, the reuse potential of a number of process wastes should be considered. In other words: The performance of a system of production and consumption ought to be judged by the extent to which wastes that can be used as resources are actually used as resources. Importantly, a waste qualifies as a resource if it can (beneficially) substitute virgin inputs. This rule holds both for postconsumer waste and for industrial waste. The technical recycling potential of waste paper was already calculated in this article. The calculation of the reuse potential of industrial wastes requires detailed knowledge of the relevant flows and the establishment of standards for waste reuse and is left for further study, as is the challenge of prioritizing between different types of waste reuse.

Conclusions

This study calculated detailed global paper flows and critically discussed recycling and material efficiency metrics. The material balance was presented as a Sankey diagram and displays, for the first time, material flows in all stages of the global paper life cycle from virgin inputs to end-of-life waste treatment. The discussion of environmental performance metrics led to three distinct conclusions.

1. The currently common recycling metric divides paper for recycling by total paper production. This metric does not directly stimulate avoidance of virgin inputs and associated impacts. A better indicator is the RIR, which divides paper for recycling by total fibrous inputs.
2. Recycling metrics are more meaningful if the achievable potential is known. The *technical recycling potential* is constrained by additions to stock and losses to sewage. Assuming effective control of contamination, the fraction of paper for recycling in total fibrous inputs can still be almost doubled.
3. Material efficiency should consider both final products and reused wastes as outputs of a process. The reuse of wastes can be contrasted with the *reuse potential*, which depends on material properties and contextual factors. The fulfillment of the reuse potential may be included in material efficiency metrics.

Further research should build on the above three conclusions. This study provided a start by mapping the global flows of paper. Future work could assess the reuse potential of the different waste flows and their fulfillment in a circular economy. In addition, the material balance can be used as the basis for a variety of environmental assessments.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information contains: (1) the model parameters; (2) the material balance equations and flow quantities; (3) the recycled pulping yield ratio calculation; and (4) the technical recycling potential calculation.