Sustainable use of materials in the global paper life cycle

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Declaration

I, Stijn van Ewijk, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Human activity has greatly affected the natural environment. The production and consumption of materials and products have contributed to the destruction and degradation of ecosystems worldwide. Evidence suggests that we increasingly endanger the ability of the environment to support our way of life.

Efficient use of materials (e.g. waste prevention) and circulation of materials (e.g. recycling) are widely acknowledged means to reduce the impacts of production and consumption. However, for many reasons, the efficient and circular use of materials is not sufficient to meet targets for environmental sustainability.

To better understand this issue, the thesis explores the climate change mitigation benefits of changes in material use in the global paper life cycle. Efficient and circular use of materials is defined as the fulfilment of the potential of waste to be used as a resource and measured through a recovery potential indicator.

A quantitative model describes material flows, energy flows, and GHG emissions of the global paper life cycle from 2012 to 2050. The emissions are compared with targets based on the carbon budget for staying below 2 degrees average global warming. The model scenarios reflect varying degrees of use of waste as a resource.

The results show that full use of waste as a resource is not sufficient to meet the GHG targets for the paper life cycle but strong decarbonization of energy inputs is. In fact, increased recycling yields more emissions unless the decline in energy from combustible waste from virgin pulping is compensated for with low carbon fuels.

The thesis concludes that the recovery potential indicator is suitable for analysing large material systems and may be used in public policy. To address climate change, guiding principles for material use need to consider the energy and carbon intensity of material processing and should be constantly evaluated.

Contents

List of publications

Published

Van Ewijk, S. and J.A. Stegemann. 2016. Limitations of the waste hierarchy for achieving absolute reductions in material throughput. *Journal of Cleaner Production*.

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List of abbreviations

CEPI	Confederation of European Paper Industries
CH_4	Methane
CHP	Combined Heat and Power
CI	Carbon Intensity (kg CO_2/GJ)
CO_2	Carbon dioxide
CR	Collection Rate
DMC	Domestic Material Consumption
DOCf	Degradable Organic Carbon dissimilating fraction
DOCiw	Degradable Organic Carbon content industrial waste
DOCp	Degradable Organic Carbon content paper
E-o-L	End-of-Life
EKC	Environmental Kuznets Curve
EPR	Extended Producer Responsibility
EU	European Union
F	Share of methane in landfill gas
GHG	Greenhouse Gas
GJ	Gigajoule (10^9 Joule)
GWP	Global Warming Potential
IE	Increased Efforts (model scenario)
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCF	Methane Correction Factor
MFA	Material Flow Analysis

MSW	Municipal Solid Waste
Mt	Megatonne (10^6 tonnes)
N_2O	Nitrous oxide
NaS	Net addition to Stock
OECD	Organisation for Economic Co-operation and Development
OX	Oxidation factor
PJ	Petajoule (10^{15} Joule)
R	Rate of methane capture
RC	Recycled Content
REF	Reference (model scenario)
RIR	Recycled Input Rate
RP	Recovery Potential
SEC	Specific Energy Consumption (GJ/t)
W-a-R	Waste as a Resource (model scenario)
WFD	Waste Framework Directive
WTTP	Waste Water Treatment Plant

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1 Introduction

1.1 Motivation

Our epoch, the Anthropocene, is defined by man's impact on the natural environment. Population growth, land use change, urbanization, and industrialization have irreversibly changed ecosystems and the global climate. Industrial production and consumption has improved the lives of billions but also led to the destruction and degradation of the natural environment (Crutzen and Stoermer 2000; Steffen et al. 2007).

We depend on the world's ecosystems for clean air, water, food, shelter, and numerous daily conveniences. The environmental sustainability of our way of life hinges on the ability of the environment to sustain our activities; current trends suggest that we increasingly endanger that ability (Ekins 2000). Among the most important and best-understood environmental challenges is anthropogenic climate change (Steffen et al. 2015).

Responses to these challenges include *resource efficiency* and the *circular economy*. More efficient and circular use of materials is thought to lower the pressure on natural resources whilst stimulating economic growth. The two concepts have received much attention from academics and practitioners (Kirchherr et al. 2017; Bocken et al. 2017) and are promoted by the European Union (EU) (EC 2015) and the United Nations (UN) (UNEP 2017).

More efficient use of materials (e.g. higher yield ratios) and circulation of materials (e.g. recycling) are intuitively correct and widely acknowledged means to reduce the impacts of production and consumption. However, these strategies are inherently limited, and even very efficient and circular global material life cycles are unlikely to meet climate change mitigation targets (Allwood et al. 2010).

To address climate change, we need to know which material use strategies are *sufficient* to meet greenhouse gas (GHG) emission targets. The answer depends on the type of material, the production process, use patterns, and waste treatment. Industrial GHG emissions are dominated by the production of metals, plastics, cement, and paper. This thesis focuses on the global life cycle GHG emissions from the latter material.

1.2 Aim and objectives

The aim of the thesis is *to assess the climate change mitigation benefits of the efficient and circular use of materials in the global paper life cycle*. There are two objectives:

- To model material flows in the global paper life cycle and assess the potential for more efficient and circular flows.
- To model the impacts of efficiency and circularity on energy use and GHG emissions in the paper life cycle.

Chapters 5 to 8 focus directly on the thesis objectives. Chapters 2 to 4 review the literature, define concepts, and summarize the methodology.

1.3 Relevance and contribution

The analysis focuses on paper because it is one of the most important materials in our society. The material is used to generate and spread knowledge, to package and protect goods, and for many other sanitary, household, and specialty purposes. The latter includes applications like wallpaper, stamps, and air filters. Annual paper consumption is around 400 Megatonne (Mt) and the paper sector is one of the main material processing industries in terms of energy use and carbon emissions (IEA 2007a; Worrell et al. 2008).

Climate change is the main focus of the analysis (other environmental impacts of paper are discussed in Chapter 4 and 9). The Intergovernmental Panel on Climate Change (IPCC) has reviewed the scientific literature and states that anthropogenic GHGs are higher than ever; the increased concentration of GHGs in the atmosphere has "widespread impacts on human and natural systems". A further increase of emissions will make "severe, pervasive and irreversible impacts for people and ecosystems" more likely (IPCC 2014).

The thesis contributes to knowledge by clarifying and improving our understanding of strategies for the sustainable use of materials. First, it merges efficient and circular use of materials into a single and measurable potential-based concept of waste. Second, it adds rigour to the study of material use by estimating the potential use of multiple waste flows in a complex material system. Third, it provides detailed insight into the systemic interactions that affect the climate change impacts of the global paper life cycle.

The thesis makes a technical contribution by introducing a new quantitative model of the global paper life cycle which consistently combines a material balance, an energy balance, emissions factors, and organic matter decay functions. It includes carbon dioxide (CO_2) emissions from all life cycle stages and methane (CH_4) emissions from landfill. It also provides a detailed description of waste flows and the "reuse potential" (Park and Chertow 2014) of these waste flows. The model is used to run scenarios for material use, energy use, and landfill practices up to 2050.

The thesis findings are useful contributions that can form the basis of future research. First, the potential-based concept of waste can be used to analyse material systems other than the global paper life cycle. The thesis also outlines policy applications that merit further study. Second, the material balance of the global paper life cycle and the energy and emissions model can serve as the basis for assessment of environmental impacts other than climate change, and the development of environmental indicators.

The contributions are also relevant to practitioners and policymakers. The potential-based concept of waste provides a practical interpretation of the popular but vague adage that "waste is a resource". For decision makers in the paper life cycle, the thesis provides preliminary estimates of the recovery potential of relevant waste flows. For policymakers, there are recommendations for better interpretation and development of guiding principles for the sustainable use of materials.

1.4 Literature gap

The thesis responds to three distinct gaps in the literature. First, there is a gap in evidence for the environmental benefits of resource efficiency and the circular economy. In a recent special issue on the circular economy, Bocken et al. (2017) call for careful evaluation of the environmental benefits of circular economy activities. Cullen (2017) argues for a deeper understanding of material flows, energy flows, and the practical limitations of circularity. Korhonen et al. (2018) list "research themes" related to the circular economy and include the environmental impacts of material circularity. By scrutinizing the climate change mitigation benefits of the efficient and circular use of materials, the thesis responds to these calls for research.

Second, resource efficiency and the circular economy can be interpreted as the use of "waste as a resource". This idea needs to be substantiated by analysing the current regulatory concept of waste. However, the relevant literature tends to focus on the waste hierarchy (Van Ewijk and Stegemann 2016; Lèbre and Corder 2015; Gharfalkar et al. 2015), waste prevention (Corvellec 2016; Zorpas and Lasaridi 2013), and the legal detail of the definition of waste (Tromans 2001; Scotford 2007). The thesis addresses the gap with a conceptual analysis of the legal definition of waste in the European Union and its ability to promote the efficient use of resources. The analysis reveals several challenges with the legal definition and suggests to address these with a potential-based concept of waste.

Third, there have been several analyses of material flows, energy flows, or GHG emissions in the paper life cycle, but most studies lack a global perspective and very few studies include future emissions projections (a full list of studies is provided in Section 4.4). The most relevant study in terms of rationale and purpose is Allwood et al. (2010). However, this study is limited in detail and scope: it excludes organic carbon stocks and flows and does not disentangle the role of using waste as a resource in emission reduction scenarios. The thesis presents a more comprehensive model for the global paper life cycle that includes a detailed material balance, a separate energy balance, fossil carbon emissions, and organic carbon stocks and flows. An updated paper demand forecast is also included.

1.5 Thesis overview

The thesis proceeds as follows. The next two chapters focus on the literature and construct the theoretical framework. Chapter 2 reviews the literature on the sustainable use of materials. It identifies efficiency and circularity as dominant principles for material use and summarizes them as "the use of waste as a resource".

Chapter 3 analyses the regulatory concept of waste and its capacity to stimulate resource conservation. It finds that the legal definition of waste is inadequate and suggests to complement it with a potential-based concept of waste. The concept indicates the potential use of waste as a resource and may be measured with the "reuse potential indicator" developed by Park and Chertow (2014).

Chapter 4 introduces the empirical analysis of the global paper life cycle. It describes the history, properties, and problems of paper, reviews the relevant modelling literature, and summarizes the modelling approach. It explains the relevance of climate change and derives GHG emission targets for the global paper life cycle based on the carbon budget for staying below 2 degrees average global warming.

Chapters 5 – 8 contain a detailed description of the empirical analysis including methods and data, results, and discussion of the results.

- Chapter 5 presents an analysis of material flows in the global paper life cycle and shows how the potential use of waste should be considered in metrics.
- Chapter 6 estimates the recovery potential of waste flows in the global paper life cycle and discusses the system-wide impacts of using waste as a resource.
- Chapter 7 assesses GHG emissions from the global paper life cycle in 2012 by constructing an energy balance and analysing organic carbon stocks and flows.
- Chapter 8 estimates GHG emissions from paper up to 2050 based on a demand projection and scenarios for material use, energy use, and landfill practices.

Chapter 9 provides a general discussion of the most significant findings of Chapters 5 – 8. It describes discrepancies with other studies, the generalizability of the results, alternative approaches to carbon abatement, and implications of the findings.

Chapter 10 draws conclusions based on the findings in all the preceding chapters. It offers recommendations for improving guiding principles for the sustainable use of materials and provides suggestions for future work.

2 Sustainable use of materials

2.1 Introduction

It is hard to think of any activity that does not require, directly or indirectly, the production and consumption of materials. They provide us with food, transport, shelter, and communication. Materials may serve us briefly – such as fruits, petrol, or napkins – or for durations of years and decades – furniture, books, or electrical appliances. Some remain "in stock" in buildings and infrastructure and serve us for over a 100 years. Most importantly, we cannot sustain our way of life without, among many materials, metal, plastic, cement, glass, and paper.

The focus of the thesis is on *materials*, which are a subset of *natural resources*, which include anything the environment has to offer such as clean air, land, oceans, and biodiversity. Materials consist of matter extracted from the natural environment and modified to serve economic and social purposes. They may be categorized as biomass (e.g. crops, wood, fish), fossil energy carriers (e.g. coal, oil, gas), ores and industrial minerals (e.g. iron, copper, bauxite), and construction minerals (e.g. stone, sand, gravel) (Krausmann et al. 2011).

Material use impacts the environment in numerous ways. The production and use of metal, plastic, cement, glass, and paper requires vast amounts of energy, water, and raw inputs, and generates harmful emissions to air, soil, and water. These environmental pressures affect the availability of natural resources and the quality of the natural environment and pose a risk to human health. A single material, such as paper, impacts the environment during every stage of the life cycle, which includes forestry, pulping, papermaking, printing, use, and waste management.

This chapter gives an overview of the most significant environmental aspects of material production and use. The next section looks at the links between materials, the environment, and society. Section 2.3 reviews sustainability targets and common methods for quantifying material use and its environmental impacts. Section 2.4 focuses on efficiency and circularity and lists limitations and challenges of these concepts. Section 2.5 discusses the findings and formulates a research agenda that serves as the foundation for the rest of the thesis.

2.2 The context of material use

2.2.1 A conceptual map of material use

Figure 2-1 depicts the material life cycle from the extraction of material resources to their final disposal. The life cycle is embedded in the natural environment from which the raw inputs are taken. These inputs are converted into materials and products and both production and consumption contribute to wealth and wellbeing. The main life cycle stages are raw material extraction, material processing, product manufacturing, and product use. At every stage, the conversion of material generates environmental pressures, such as air emissions, which impact the environment.

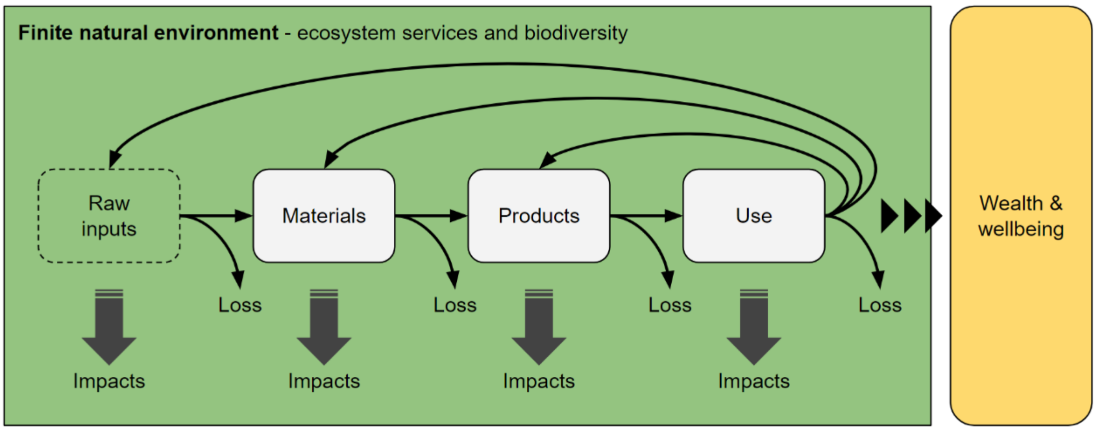

Figure 2-1. A conceptual map of material use.

Along the chain, materials are disposed and "lost", including End-of-Life (E-o-L) products. Some losses are prevented because materials and products are circulated to earlier stages of the life cycle: the loops indicate reuse, recycling, and recovery. Product life may be extended through reuse, repair, or remanufacturing. Organic materials may decompose and become raw inputs again; scrap metal and waste paper may be recycled into stainless steel and paper products. Loops in between the early stages in the life cycle (e.g. from products back to materials) are possible too but excluded from Figure 2-1 for legibility.

The environment is the provider of raw inputs to the production process and a sink for emissions and waste (losses). Raw inputs are obtained through forestry, fishing, hunting, agriculture, mining, dredging, quarrying, and oil and gas drilling. Losses include waste to landfill and the dispersion of materials in dissipative processes. Impacts from material processing include emissions to air, water, and soil. The environment is conceptualized as "ecosystem services and biodiversity", which is explained further in Section 2.2.3.

The benefits of production and use of materials, through employment and consumption, are expressed as a contribution to wealth and wellbeing. Income, as a contribution to wealth, is usually measured through Gross Domestic Product (GDP). For simplicity, the diagram shows a unidirectional relationship between material use and wealth, but wealth is also a driver of material use. The best conceptualization is probably mutual reinforcement: the production of materials involves labour and the payment of wages which in turn drives final demand. The drivers of material use are discussed further in the next section.

2.2.2 Drivers of material use

Material use has continuously increased over the past century. Figure 2-2 shows global consumption from 1900 to 2009 for major material categories. Total consumption grew rapidly after the Second World War, especially for construction minerals, ores and industrial minerals, and fossil energy carriers. This growth was driven by a fast increase in population and fast expansion of the economy. In 2009, the world population used around 68 Gt of materials, consisting of biomass (30%), fossil energy carriers (19%), ores and industrial minerals (10%), and construction minerals (42%) (Krausmann et al. 2011).

What drives material consumption? The influential book *A Theory of Human Need* by Doyal and Gough (1991) lists three basic needs: social participation, health, and autonomy. Similar categories are suggested by Nussbaum (2001) and Ryan and Deci (2001). These basic needs translate into needs for among others food, water, shelter, and transport. The provision of these products and services in turn requires production and consumption of materials to build houses, factories, hospitals, and infrastructure.

Needs, as defined by Doyal and Gough (1991), can be wholly fulfilled, which suggests consumption should ultimately plateau or decrease. However, *need satisfiers* are contextual and time-dependent. A century ago, social participation required less consumption, simply because modern communication technologies were not available. Technological change thus leads to a "lock-in" of consumption. In addition, consumption may be driven beyond the satisfaction of needs by "corporate shaping of demand", the discursive power of consumer sovereignty, and the economic growth imperative (Gough 2017).

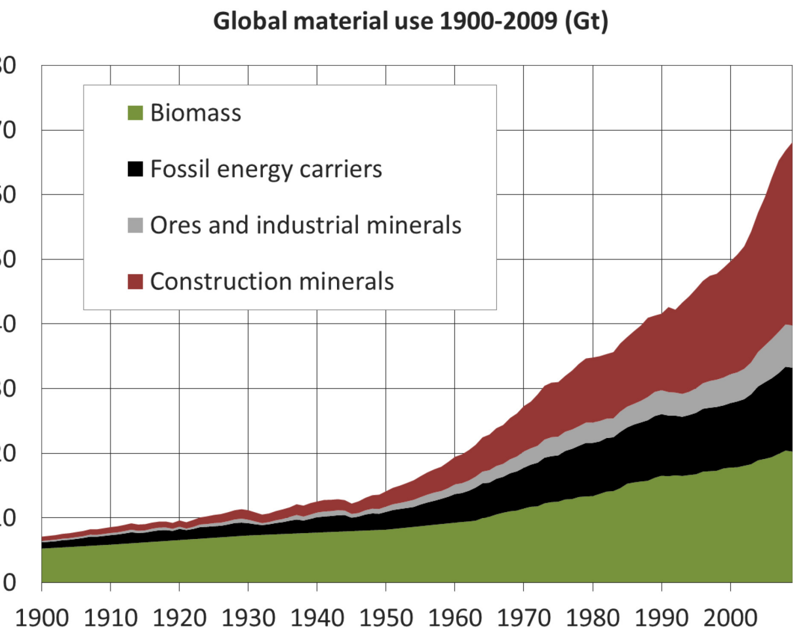

Figure 2-2. Global consumption of materials (Krausmann et al. 2011).

At the macro level, the drivers of resource use (and environmental impacts) are generally held to be population growth, increasing affluence, and technology (Ehrlich and Holdren 1971). These factors are mutually dependent: for example, population growth tends to slow down with increased income. Globally, material use has grown faster than the population but slower than the aggregate economic output. During the second half of the 20th century, material use grew by 244%, population grew by 140%, and GDP grew by 1285% (Krausmann et al. 2011; UN 2015a; Maddison 2007).

The role of economic growth in material consumption and environmental impacts is an area of intense debate. The *Environmental Kuznets Curve* (EKC) hypothesizes a decline in environmental impacts once countries pass a threshold of per capita income. The potential explanation is saturation of material demand and increased concerns about the environment. A recent review by Stern (2014) shows that this relationship has been observed for some pollutants only. The evidence suggests that the EKC does not generally hold across different pollutants and in different contexts.

Technology also has an ambiguous role in environmental impacts. The influential book *The closing circle* (Commoner 1972) described a rapid increase in environmental impacts after the Second World War and blamed it squarely on the "tendency of productive technology to pollute". Since then, views have largely shifted towards a belief in scientific advancement and technological change as the main strategy for reducing environmental impacts (Chertow

2000a). Population and wealth, on the other hand, are often considered beyond collective control. The belief in technology is at the heart of resource efficiency and the circular economy, which will be discussed in Section 2.4.1.

At the global level, more efficient resource use has decoupled wealth creation from material consumption. The material intensity (material use per unit of GDP) of the global economy has declined in the past century (Krausmann et al. 2009). Since absolute material use has continued to grow, this is called *relative decoupling*. To achieve *absolute decoupling*, material use (or environmental impacts) needs to decrease in absolute terms – not just grow at a slower rate than economic output. Decoupling is an important concept in sustainable resource management and may focus on material use or environmental impacts (UNEP 2011).

Globalization of production and consumption has made the measurement of decoupling at the national level very challenging. A commonly used metric for national material use is Domestic Material Consumption (DMC) but it excludes the materials associated with trade. For example, the materials used for producing goods in China that are consumed in the United Kingdom (UK) are largely excluded from the DMC of the UK. The "material footprint" of a country does include material consumption associated with trade and was calculated by Wiedmann et al. (2015). The authors show that many rich countries exhibit a decline in DMC but a close correlation between the material footprint and GDP.

2.2.3 Materials and the environment

Material use impacts the environment in many ways. An understanding of these impacts must start with a conceptualization of the natural environment. Figure 2-1 presented the natural environment as "ecosystem services and biodiversity". Ecosystem services are the benefits people obtain from ecosystems. The Millennium Ecosystem Assessment (2005) argues for the following broad categories of ecosystem services to be safeguarded: provisioning, regulation, cultural, and supporting functions. This categorization is based on earlier work on ecosystem services by Pearce & Turner (1990) and De Groot (1992).

- *Provisioning functions* cover the products that ecosystems supply which include materials, food, water, and fuels.
- *Regulating functions* relate to the processes that ensure among others a stable climate, water purification, flood regulation, and disease regulation.

- *Cultural functions* can be aesthetic, spiritual, or educational, and include recreational enjoyment of the environment.
- *Supporting functions* cover among others nutrient circulation, soil formation, and photosynthesis, and underpin the other functions.

Biodiversity – the richness and variation of species – is generally seen as separate from the ecosystem services listed above. It supports other ecosystem functions, such as provisioning of a resilient food production system. It also directly serves human beings in, for example, the case of bird watching or any other recreational activity in the natural environment. It should be noted that abiotic material flows are often ignored or represented inconsistently in ecosystem services classifications – there is an ongoing discussion on how to deal with this limitation (van der Meulen et al. 2016).

Material use and ecosystem functioning are strongly interrelated. Ecosystems supply materials as part of their *provisioning function* but may become depleted or degraded through overexploitation. Material use also affects all other functions: the use of fossil fuels affects *regulating functions* by increasing the concentration of CO_2 in the atmosphere; uncontrolled extraction of construction minerals has huge impacts on landscapes and affects *cultural functions*; the material flows associated with agricultural production affect *supporting functions* like nitrogen and phosphorus circulation.

The ecosystem services approach reflects an anthropocentric and economic angle on the natural environment. It is the basis for monetary valuation of nature (Costanza et al. 1997) and natural capital accounting (Natural Capital Committee 2014). A more pluralistic approach is being developed by the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES). It recognizes the diversity in perceptions of nature and suggests a more deliberative approach to decision making. The approach includes the economic framing of the natural environment as one of many possible ways of conceptualizing the relationship between man and nature (Pascual et al. 2017).

2.3 Sustainability assessment

2.3.1 Sustainability targets

The dependence of the economy and society on ecosystem services and biodiversity implies that human activity should respect the limits of the natural environment. These limitations can be translated into basic principles for environmental sustainability. The following three principles of sound resource management have been broadly agreed in the literature (Ekins 2000; Daly 1990; Turner 1993).

- Renewable materials like wood, fish, and food crops should be used at a rate no faster than their reproduction rate. This principle is equally valid for the regeneration rates of ecosystems or the time that is needed for degraded land to be restored. It also applies to the assimilative capacity of the environment: the rate at which an ecosystem can neutralize emissions, such as CO_2, should not be exceeded by the rate at which they are introduced into the ecosystem.
- Non-renewable resources like fossil fuels and metals need to be substituted by renewable resources that supply the same functionality. Substitution of non-renewables by renewables can be postponed through higher efficiency or increased resource circulation. There is scope for substitution between non-renewable materials with different levels of scarcity but consumption must ultimately shift towards renewable materials and fuels that can be regenerated infinitely.
- Environmental impacts need to stay within the limits of the environment. Unfortunately, little is known about the precise limits of the environment. Natural systems often respond in non-linear ways to environmental pressures and may suddenly transition to an alternate stage. For example, continued logging may lead to soil erosion, loss of vegetation, and the collapse of a forest ecosystem. Since the natural development of soils and ecosystems occurs very slowly, reversing such a shift may be impossible (Filatova et al. 2016; Scheffer et al. 2001).

The three principles underpin the planetary boundaries framework, which provides targets related to a selection of global environmental problems. The framework, shown in Figure 2-3, was developed by Rockström et al. (2009) and updated by Steffen et al. (2015). It includes climate change, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows, freshwater use, land-system change, and biosphere integrity. The planetary boundary regarding, for example, climate change is a CO_2 concentration of 350 ppm based on the levels of radiative forcing, the associated response of natural systems, and the potentially disastrous consequences for society.

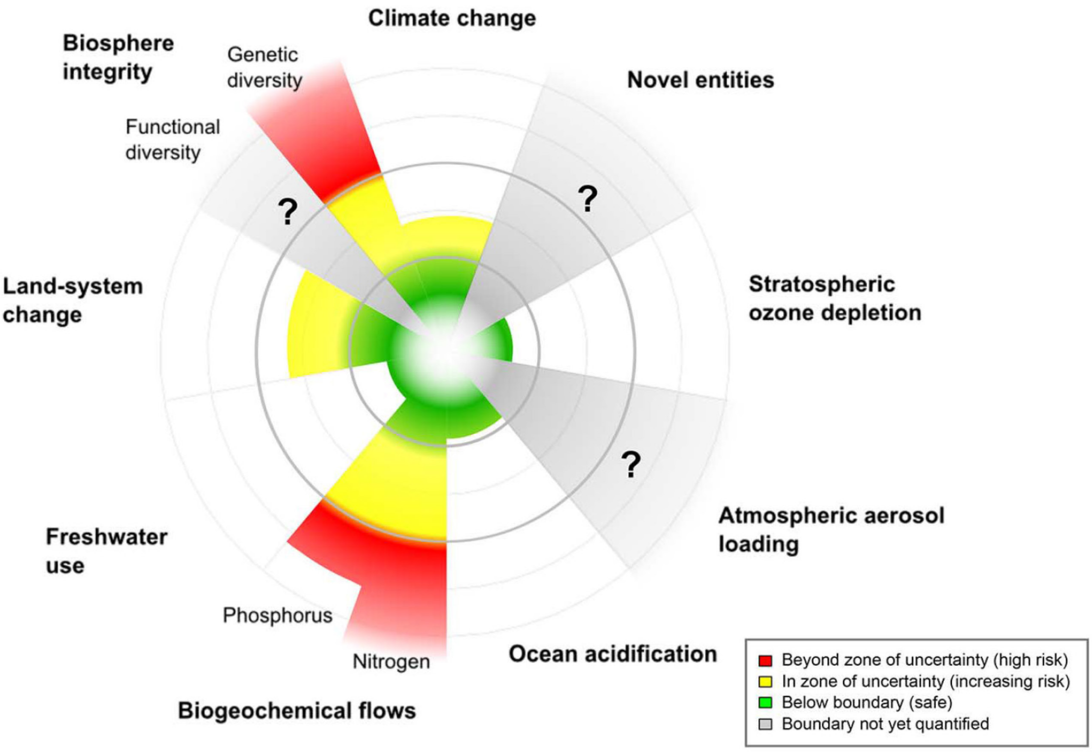

Figure 2-3. The planetary boundaries framework (Steffen et al. 2015).

The present framework does not define a planetary boundary for material extraction or material consumption. The impacts of material use, and the extent to which material use contributes to the exceedance of planetary boundaries, depends on the extraction methods, conversion processes, type of use, and E-o-L waste treatment. To set a target for material use, two main challenges need to be overcome.

- Targets for aggregate material use, such as DMC, are flawed because high impact materials are added up with low impact materials. A ton of gravel is not comparable to a ton of hazardous chemicals but both contribute equally to DMC.
- Mass-based targets for single materials, such as paper, have limited meaning because the associated environmental pressures depend on technology and energy choices. Pollution prevention techniques such as flue gas scrubbers can greatly reduce the impact of material processing.

The second challenge may be overcome for fossil fuels because they are virtually always combusted and contribute directly to climate change. Target setting for fossil fuels nevertheless needs to address possible substitution between more or less carbon-intensive fuels (e.g. coal and gas) and the possibility of Carbon Capture and Sequestration (CCS). A target for fossil fuel use, in relation to the planetary boundary for climate change, was estimated by McGlade and Ekins (2015). The authors address substitution through a cost optimization model (i.e. cheaper fuels are used first) and run scenarios with and without CCS. They show that a third of oil reserves, half of gas reserves and over 80 percent of coal reserves should be left unused until 2050.

Other targets have been formulated too but they inevitably lack robustness. For example, Stricks et al. (2015) set a boundary for Total Material Extraction (TMC). They identify 1970 as the most recent year in which environmental impacts were still acceptable, and choose the global material consumption at that time, of around 27 Gt/year[1], as a target. This target, combined with expected population growth, implies a per capita consumption target of 2.5-3.1 t/capita in 2050[2] – substantially lower than per capita consumption in 1970 (7.4 t/capita) or 2009 (10 t/capita). Unfortunately, this target completely ignores differences between materials and the role of technology choices in reducing the environmental impacts per unit of material.

2.3.2 Assessment methods

2.3.2.1 Material Flow Analysis

Target setting and performance assessment rely on several methods. The basic method for quantifying material production and consumption is Material Flow Analysis (MFA) and it will be applied in Chapter 5. MFA is defined as the "systematic assessment of the flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger 2004). It is used to help understand complex material systems, find inefficiencies, and optimize conversion processes. It can help anticipate future depletion and accumulation and assist in the design of efficient and compatible material flow systems such as waste management infrastructure.

The main principle behind MFA is conservation of mass. This principle was formulated centuries ago, most famously by the French chemist Lavoisier, and is commonly applied in chemical and process engineering. The application of modern MFA to environmental analysis of large systems, such as cities or industrial parks, took off in the 1970s. Economy-

[1] Stricks et al. (2015) report higher figures because they include unused material extraction in their calculation of the 2050 target.
[2] Based on a global population projection of 8.7 – 11 billion in 2050 (UN 2015a).

Wide MFA (EW-MFA) of the metabolism of countries was developed in the 1990s in Europe. In 2001, the EU Statistics Agency, Eurostat, published the first authoritative guide on EW-MFA (Moriguchi 2007; Eurostat 2001).

One of the main limitations of MFA is the use of materials as a proxy for environmental, economic, or social impacts. The concept of MFA, and the aggregation of different types of materials, could wrongly suggest that material flow indicators carry as much meaning as environmental impact indicators. MFA results should be interpreted carefully or used as a basis for further and deeper analysis. For example, an MFA may be extended by considering the energy or emissions associated with material flows. Another limitation of MFA is the lack of high-resolution data to meaningfully represent material grades or quality.

2.3.2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) goes beyond MFA by not only compiling the inputs and outputs of a process (life cycle inventory (LCI)) but also evaluating the associated environmental impacts (life cycle impact assessment (LCIA)). Elements of LCA will be applied in Chapter 7 and 8. LCA focuses on the impacts associated with the entire life cycle of a product and is used to analyse its comparative impacts, highlight the most harmful processes or material inputs, and the formulation of environmental indicators (ISO 2006). LCA studies may inform the design, purchase, and labelling of products, and support policy measures (de Bruijn et al. 2002; JRC/IES 2010).

The main purpose of a life cycle perspective is to avoid burden shifting by showing impacts in all life cycle stages. For example, a more fuel-efficient car may require more energy during manufacturing and only a life cycle perspective can reveal these trade-offs. In LCA, the focus is on a product system, which is the collection of unit processes and material flows. For example, the product system for a book includes fibres, ink and glue which are used for pulping, printing, and binding. Different product systems can be compared using a "functional unit" as a reference such as "one specific book bought and read by one person" (Moberg et al. 2011).

LCA is most useful for comparative analysis and less suited for calculating total impacts because the same impact may be allocated to various products in separate analyses. LCA may rely on standardized life cycle inventories such as Ecoinvent (Wernet et al. 2016) or dedicated inventories with inputs and outputs collated from the literature and technical reports. There is much room for improvement in data collection, quality, access, and transparency (Hellweg and Canals 2014). Other issues include parametric, model, and value choice uncertainty and variability across space, time, and between objects and sources (e.g. production facilities) (Huijbregts 1998).

2.3.2.3 Environmentally Extended Input-Output

A third method is Environmentally Extended Input-Output (EEIO) analysis. It will not be applied in the thesis but a brief introduction is required to support the methodological justification in Section 4.5. EEIO is used to evaluate the linkages between economic consumption activities and environmental impacts based on the interactions between different sectors in the economy. EEIO analysis is suitable for analysing the embodied impacts of downstream consumption or for calculating the embodied impacts of goods traded between nations. Embodied impacts are also called hidden or total impacts or "footprints" (Kitzes, 2013).

EEIO analysis was established by Leontief (1970) and builds on the monetary input-output tables of an economy and sectoral environmental accounts. The monetary data tables reveal which sectors contribute to a unit of final demand. For example, it will be found that agriculture, manufacturing, and services all contribute to potato production – farmers purchase machines from the manufacturing sector and the manufacturing sector hires consultants from the service sector. The sectoral environmental accounts, such as CO_2 emission tables, are used to translate the monetary flows into environmental flows and calculate the total environmental impact of satisfying a unit of final demand.

EEIO analysis is a powerful method for generating environmental data and the EEIO literature includes carbon, water, ecological, nitrogen, and biodiversity footprints. Hybrid LCA studies use data generated through EEIO to build life cycle inventories. However, the monetary flows that underpin EEIO analysis mostly reflect labour costs and the price of materials varies considerably by grade and quality – calculations based on average prices are therefore not very accurate. Moreover, use-phase emissions for LCA studies are hard to derive with EEIO analysis. Further limitations are low-resolution sectoral data and other data availability, consistency, and quality issues (Suh and Huppes 2002; Kitzes 2013).

2.4 Efficiency and circularity

2.4.1 Resource efficiency and the circular economy

What needs to be done about the environmental impacts of material use? The contemporary discussion about the problem emphasizes "resource efficiency" and the "circular economy". The UN defines resource efficiency as "producing more wellbeing with less material consumption (…) while respecting the ecological carrying capacity of the earth" (UN 2010). Resource efficiency is described by the European Commission as "improving economic performance while reducing pressure on natural resources through efficient use of them" (EC 2011a).

The International Resource Panel (IRP) identifies three key components of resource efficiency: economic value or output, resource use, and environmental impacts (UNEP 2017). These three components basically refer back to decoupling as described in Section 2.2.2. However, in the present context, "decoupling" is not descriptive but prescriptive: resource efficiency aims to decouple resource use and environmental impacts from economic output. It should be noted that decoupling does not describe what should actually be done – it merely suggests a desirable outcome at the aggregate economic level.

The circular economy is "restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times" (Ellen MacArthur Foundation 2016). It is opposed to the "linear economy" in which materials are quickly disposed. The EU *Circular Economy Action Plan* describes it as a system "where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimised" and which supports a "sustainable, low carbon, resource efficient and competitive economy" (EC 2015).

Perhaps worryingly, some uses of the term "circular economy" emphasize economic rather than environmental benefits. A recent review of definitions of the circular economy by Kirchherr et al. (2017) reveals that the practitioner literature, and the more recent peer-reviewed literature, tends to be more concerned with economic prosperity than environmental quality. Besides, the authors warn for "subverted definitions" that ignore waste reduction – if these definitions started dominating, the pursuit of the circular economy would lead to only incremental changes at best.

The circular economy is a more recent term than resource efficiency but has quickly gained traction mainly because of the advocacy work of the Ellen MacArthur Foundation. A Google Trends analysis shows that "circular economy" surpassed "resource efficiency" as a popular search query in 2013 and was about six times more frequent in the year 2016. In the academic literature, "resource efficiency" remains more widely used with around 27% more papers in 2016. About 8% of papers in 2016 on "resource efficiency" also use the term "circular economy".[3]

Both resource efficiency and the circular economy build on a long tradition of thinking about waste and resources. Circularity and the ecology metaphor – the idea that industrial systems should be modelled after regenerative natural systems – were popularized in publications like *Biomimicry* (Benyus 1997) and *Cradle to Cradle: Remaking the Way We Make Things* (McDonough and Braungart 2002). In 2010, the UK-based Ellen MacArthur Foundation started building a broad coalition of business, governments, NGOs, and universities around the concept of a circular economy (Ellen MacArthur Foundation 2012).

The idea of resource efficiency gained widespread attention in the 1990s with the book *Factor Four Doubling Wealth, Halving Resource Use* (Von Weizsäcker et al. 1997). The authors maintain that economic growth and a reduction in resource use are possible through a shift in focus from labour productivity to resource productivity. They envision an economy with less resource use, more employment, and more economic output. A similar point was made across the Atlantic in the book *Natural Capitalism* (Hawken et al. 1999) which emphasizes the critical importance of the natural environment as a factor of production.

Concepts like resource efficiency and the circular economy promise a win-win opportunity to increase economic growth and reduce pressures on the environment. Such optimistic thinking on the relationship between the economy and the environment is often labelled *Ecological Modernisation*. According to this school of thought, which originates in the 1980s, the economy benefits from greater environmental protection and resource conservation. This view broke with the past and put an end to the adversarial relationship between some environmentalists and the private sector (Revell 2005).

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[3] Based on Scopus queries for the terms in the title, abstract, and keywords: TITLE-ABS-KEY ("Resource efficiency"), TITLE-ABS-KEY ("circular economy"), and TITLE-ABS-KEY ("circular economy" AND "resource efficiency"). Queries were performed at 29-03-2017.

Contributions that precede ecological modernisation nevertheless remain relevant to the current debate. Key works that established the importance of materials and the potentially adverse effects of overexploitation include *The Tragedy of the Commons* (Hardin 1968) and Ayres & Kneese (1969), which established the importance of materials, waste, and pollution in economic thinking. The publication that firmly established the potential impacts of increased resource use was the Club of Rome report *Limits to Growth* which modelled the potentially disastrous impacts of exponential growth in population and consumption (Meadows et al. 1972).

2.4.2 Defining efficiency and circularity

Resource efficiency and the circular economy can be summarized as the minimization of material losses and the maximization of material circulation to achieve greater wealth and well-being whilst staying within the limits of the natural environment. The concepts thus prescribe the *efficient* and *circular* use of materials. *Efficiency* is about minimizing material losses during each material conversion by using as much material as possible for useful purposes. *Circularity* is about returning waste to an earlier stage in the same product life cycle or to another product life cycle through reuse, recycling, or recovery.

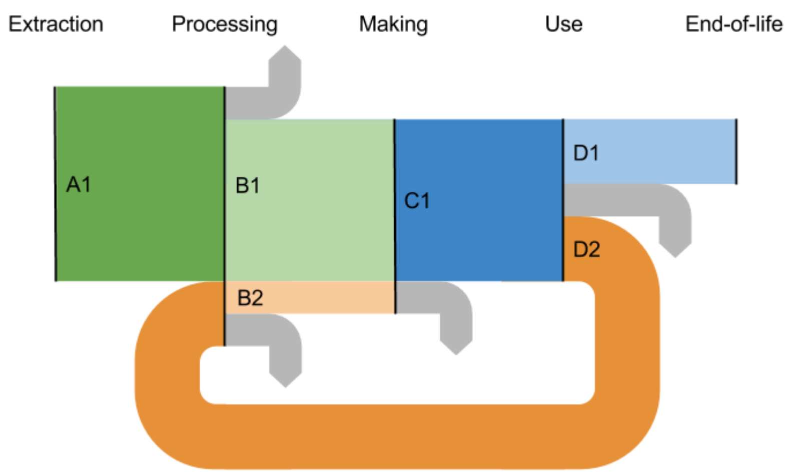

Figure 2-4. Sankey diagram of a simple material life cycle.

Efficient and circular use of materials can be explained further based on Figure 2-4. The figure describes a simple material system in which raw inputs (A1) are extracted, converted into materials (B1 and B2), made into products (C1), used and added to stock (D1), recycled (D2), or disposed. The *efficiency* of each conversion, and of the total system, can be expressed as the ratio between inputs and outputs of a material conversion. The standard metric for material efficiency (η_m), shown in Equation 2-1, is the ratio between material used in the product (M_p) and material supplied to it (M_s) (Lifset and Eckelman 2013).

Equation 2-1.

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

Measurement of *circularity* may focus on recycled inputs, recycled content, or the collection activity (Graedel et al. 2011; Hashimoto and Moriguchi 2004). In Equation 2-2, circularity (c_m) is expressed as the ratio between material that is part of a cycle (M_c) and the total amount of material that is supplied (M_s). The material that "circulates" could refer to the material that is collected, processed, or part of final products. The material that is supplied refers to the total inputs or the complete final product.

Equation 2-2.

$$c_m = \frac{M_c}{M_s}$$

Table 2-1 summarizes four efficiency metrics and three circularity metrics for the material system in Figure 2-4. The efficiency metrics focus on primary and secondary processing, making, and the total life cycle. The circularity metrics focus on material inputs, product content, and waste collection. There is no metric for "overall circularity" because the potential return of final products to the extraction phase is possible only for biotic materials and not included in Figure 2-4.

Table 2-1. Efficiency and circularity metrics in relation to Figure 2-4.

Category	Indicator	Equation
Efficiency	Primary processing efficiency	B1/A1
	Secondary processing efficiency	B2/D2
	Making efficiency	C1/(B1+B2)
	Overall efficiency	C1/(A1+D2)
Circularity	Recycled Input Rate (RIR)	D2/(A1+D2)
	Recycled Content (RC)	B2/(B1+B2)
	Collection Rate (CR)	D2/C1

Circularity and efficiency are complementary descriptions of a material system. Increased circulation of materials between the life cycle stages of extraction and E-o-L increases the overall efficiency of the material system because it reduces virgin input requirements. At the same time, increased efficiency of secondary processing, which is part of the circulation of materials, increases circularity. A comprehensive description of material flows in any given system therefore requires notions of both circulation and efficiency.

The suggested definitions of efficiency and circularity focus on products as useful outputs and can be used to measure the material requirements of supplying these products. A more comprehensive measurement of efficiency and circularity may focus on wealth (e.g. GDP), well-being (e.g. reported happiness), or material services (e.g. transport kilometres) as useful outputs and could be used to show which products and product designs can meet our needs at the lowest environmental impacts. The relationships between these output measures should be considered too (Allwood et al. 2013).

The metrics in Table 2-1 focus on quantitative losses only and ignore the loss of quality that occurs during the use and recycling of materials. For example, pulping of waste paper not only comes with material losses but also damages the fibres, and the use of various chemicals in production and use of paper, including inks and de-inking agents, affects fibre quality (Hubbe et al. 2007). Recycled products are therefore of lower quality than primary products. Efficiency and circularity indicators may capture qualitative losses by making a distinction between open-loop and closed-loop recycling (Haupt et al. 2016).

2.4.3 Limitations and challenges

Efficient and circular use of materials generally lowers environmental impacts. For example, recycling reduces energy requirements for material processing, reduces demand for virgin inputs, avoids the impacts of mining and primary processing, and limits waste to landfill (Geyer et al. 2016; IEA 2007a). However, there are at least five reasons why a perfectly efficient or circular economy (which would score 1.0 on all indicators in Table 2-1) is not possible or why efficiency and circularity alone are not sufficient for achieving environmental sustainability.

1) Material (re)cycling requires a reversal of the mixing and downgrading of materials and undoing these processes inevitably requires energy inputs. Recycling of most materials leads to energy savings compared to virgin material processing but nevertheless generates significant environmental impacts from electricity and heat generation. Recycling may also require the use of hazardous chemicals and generate contaminated wastes (IEA 2007a; Cullen 2017).

2) Materials in durable applications are not immediately available for recycling or reuse. A large fraction of raw materials accumulates in infrastructure, buildings, and equipment. These in-stock materials deliver important services to society and cannot be used in new products. Raw materials need to be extracted to satisfy the continuous demand for new products. Global material stocks have increased 23-fold over the period 1900-2010 with significant implications for global recycling (Krausmann et al. 2017).

3) Even if all materials only had short-term uses, demand cannot be met with recycled input only because of inherent quantitative and qualitative losses in the recycling process. Contamination issues may be addressed by preventing the introduction of contaminants, source separating recyclables, and improving contaminant removal techniques. However, improved removal of contaminants in, for example, paper may reduce the yield ratio of recycled pulping (Pivnenko et al. 2016).

4) Demand for materials is growing. Even if we could recycle or reuse all in-use products without any losses, it still would not be sufficient to meet tomorrow's demands for materials (Allwood 2014). Demand for steel, aluminium, plastic, cement, and paper is expected to increase by a factor 2 – 3 in 2050 from 2006 consumption levels (Allwood et al. 2010). The faster the demand growth, the harder it is to meet the new demand for material inputs through recycling.

5) Consumer preferences and product development may shift towards new materials or products that are not available by reusing or recycling the existent stock (Allwood 2014). A shift in preferences is particularly relevant for reuse: products that are not broken or spent may be rejected still because they have become inferior, unsuitable, or worthless due to changes in circumstances. Such changes include fashion, new legislation, and technological development (Cooper et al. 2014).

Given the above limitations, it is very important to know *to what extent* the efficient and circular use of materials actually contributes to a better environment. The five limitations of efficiency and circularity therefore shape the research agenda for the study of the sustainable use of materials. This research agenda – as well as the research objectives for the thesis – is discussed in the next section.

2.5 Discussion: a research agenda

This chapter has reviewed the sustainable use of materials and highlights three important findings from the literature. First, there are clear principles for environmental sustainability but they cannot be applied directly to material use. Second, the current pursuit of sustainability is through more efficient and circular use of materials. Third, because of the five limitations listed in Section 2.4.3, the potential reduction in environmental impacts through the efficient and circular use of materials is inherently limited.

The three findings shape the agenda for research on the sustainable use of materials: it is necessary to test to what extent the efficient and circular use can reduce environmental impacts and help achieve environmental sustainability. This requires a measurable concept of the efficient and circular use of materials. It also requires the identification of environmental targets in relation to material use and a method for assessing the environmental impacts of more efficient and more circular use of materials.

The efficiency and circularity of material use may be captured through the material flow indicators listed in Table 2-1. However, these indicators ignore one or more of the five limitations inherent to the efficient and circular use of materials. For example, recycling is generally measured as a collection rate (CR), which ignores losses during secondary material processing. The CR only accounts for collected materials but not for actual avoidance of virgin inputs and is of limited use for measuring circularity.

Metrics for efficiency generally focus on the ratio between useful outputs and total inputs. Such metrics overlook some of the "losses" or "waste" that can be beneficially used. For example, the primary processing efficiency in the paper industry is measured as the ratio of pulp outputs over fibrous inputs. In practice, a large fraction of "waste" is used for energy recovery and provides a clean source of electricity and heat for paper mill operations. The "efficiency" of a process therefore needs to consider the (potential) use of waste.

An obvious starting point for testing circularity and efficiency is to first improve the aforementioned indicators. It is possible to modify current metrics to include losses during recycling or to account for the energy requirements or emissions. Composite indicators are discussed by, for example, Cullen (2017), who suggests including energy demand in metrics for secondary material processing. Metrics will be discussed further in Chapter 5 based on a material balance of the global paper life cycle.

Efficiency and circulation may also be captured *simultaneously* by focusing on the difference between *waste* and *resource.* Both efficient and circular use of materials boils down to using as much material as possible for useful purposes: the total fraction of *waste* is minimized whereas the fraction of *resources* is maximized. If the waste-resource distinction can be operationalized, it can be used to cover both efficient and circular use of materials. When quantified, it can be used as an alternative to efficiency and circularity metrics.

The latter approach is a core element of the thesis. A measure of waste used as a resource is a much needed quantification of the popular adage that "waste is a resource". Current legislation tends to define more rather than less material as waste in order to protect human health and the environment. However, depending on circumstances, some waste can be used as a resource and it is useful to know to what extent and how this is possible. This idea is further developed in Chapter 3 and applied to the global paper life cycle in Chapter 6.

Finally, this chapter showed that target setting for individual sectors, industries, materials, or products should consider the pitfalls of aggregate material use indicators. It should also consider that environmental impacts are not inherent to material use but a function of extraction, processing, and use practices. The life cycle impacts of efficiency and circularity should be compared against sustainability targets that reflect the finite character of the natural environment – such an analysis will be conducted in Chapters 7 and 8 regarding GHG emissions from the global paper life cycle.

2.6 Conclusions

This chapter reviewed drivers of material use, linkages between material use and the environment, methods for assessment of material flows and environmental impacts, and the main strategies for reducing these impacts. The discussion synthesized three findings that provide the foundation for the rest of the thesis.

- Efficient and circular use of materials, and the associated impact reductions, are inherently limited. The thesis aims to estimate the extent to which efficiency and circularity reduce GHG emissions from the global paper life cycle.
- The distinction between waste and resources is a fruitful starting point for measuring the efficient and circular use of materials. This notion is elaborated in Chapter 3 and used in the MFA in Chapters 5 and 6, to meet the first thesis objective.

- Environmental assessment of global material use requires a life cycle perspective and consideration of planetary boundaries. Such an assessment fulfils the second objective of the thesis and is presented in Chapters 7 and 8.

This chapter discussed a variety of materials and environmental problems. The next chapters focus on paper and climate change but Chapter 9 will return to the big picture and reflect on the implications of the findings for other materials and other planetary boundaries.

3 Waste as a potential resource

3.1 Introduction

Over the past few decades, waste has been regulated foremost as an inevitable and harmful residue of production and consumption. Most waste management practices are designed to protect the environment and human health from the impacts of waste through universal collection and safe disposal. More recently, attention has shifted towards the efficient use of resources and a reduction of wastage (Tromans 2001; UNEP/ISWA 2015).

Waste represents a two-fold challenge. First, it causes impacts on the environment and human health through littering, dumping, treatment, and disposal. Second, it implies environmental losses through the wastage of scarce and valuable resources. In other words, waste is both the consequence of a problem (the result of inefficiency) as well as the cause of a problem (the source of impacts on the environment and human health).

Chapter 2 showed that the circular economy and resource efficiency imply the efficient and circular use of materials, which can be summarized as "using waste a resource". The adage that "waste is a resource" and its variants[4] are widely used but hardly ever substantiated. In spite of decades of legislative progress, the definition of waste and its use as a resource remain contentious. The definition and identification of waste is a globally "unresolved challenge" and improvement is urgently needed (Butti 2012).

This chapter shows how a potential-based concept of waste may address several shortcomings in the legal definition of waste in the European Union (EU). A potential-based concept of waste indicates the extent to which the waste can be used as a resource through reuse, recycling, or recovery. It should also indicate under what conditions use as a resource is possible. The use of waste to its full potential as a resource can play an important role in pursuing resource efficiency and the circular economy.

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[4] Examples include: "Plastic waste is a resource" (PlasticsEurope 2015), "Trash to treasure" (US Chamber of Commerce Foundation 2016), "Rubbish or Resources" (Li and Khraisheh 2008) and "Waste: a problem or a resource" (EEA 2014).

Most critiques of European waste legislation and its ability to promote the efficient use of resources focus on the waste hierarchy (Van Ewijk and Stegemann 2016; Lèbre and Corder 2015; Gharfalkar et al. 2015) and waste prevention (Corvellec 2016; Zorpas and Lasaridi 2013). This chapter focuses on the legal definition of waste and develops a potential-based concept of waste to help address its shortcomings. The potential-based concept of waste *complements* the legal definition and is not intended as a replacement.

It should be noted that the use of waste as a resource requires the generation of waste in the first place. A more comprehensive concept of efficient and circular use of materials must also include *waste prevention* through better design of products and services. Waste prevention is not covered by the idea of using waste as a resource – this limitation will be discussed further in Section 3.4.1. The focus of the thesis is on the use of currently known waste as a resource rather than the prevention of these waste streams.

This chapter intends to clarify and operationalize the use of waste as a resource. The starting point is the regulatory concept of waste but the results will be applied in the environmental (not regulatory) analysis in Chapter 6. The next section dissects the regulatory concept of waste in the EU and Section 3.3 synthesizes three shortcomings of the legal definition of waste. Section 3.4 suggests to address these shortcomings with a potential-based concept of waste and Section 3.5 reflects on its use in policy and environmental assessment.

3.2 Regulatory concept of waste

3.2.1 Overview of three elements

The regulatory concept of waste comprises its legal definition, the associated guiding principles, and their implementation in policy. Figure 3-1 summarizes the three elements and the relationship between them. The legal definition includes the definition of waste ("waste is…") and the exceptions described by the criteria for end-of-waste status and by-product status. However, the legal definition of waste affects waste holders and users mostly through guiding principles and policy implementation.

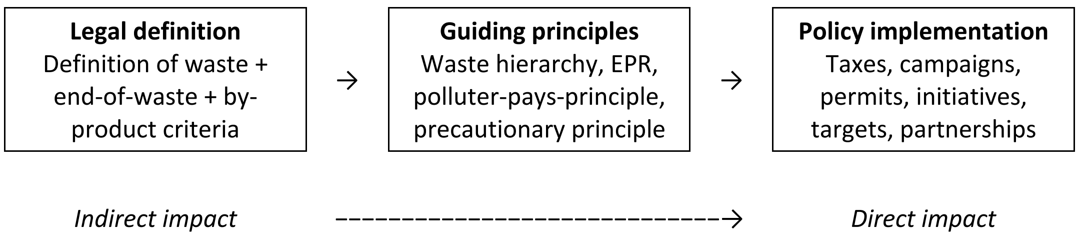

Figure 3-1. The three elements of the regulatory concept of waste.

The guiding principles include among others the waste hierarchy, the polluter-pays-principle, the precautionary principle, and Extended Producer Responsibility (EPR). These principles shape the organization and regulation of waste management and inform public policies like taxes, permits, and campaigns that are intended to improve waste generation and treatment practices to meet relevant government ambitions. The next three sections discuss the three elements of the regulatory concept of waste in detail.

3.2.2 The legal definition

The EU Waste Framework Directive (WFD) (EC 2008) defines waste as "any substance or object which the holder discards or intends or is required to discard". Legal definitions of waste in other jurisdictions also suggest that "anything discarded is waste" but phrase this in slightly different ways[5]. In the EU, the first exception to the legal definition consists of waste that ceases to be waste ("end-of-waste criteria"). The WFD states that a substance or object is no longer waste when it meets the following criteria:

- It has undergone a recovery operation;
- It is commonly used for specific purposes;
- There is an existing market or demand.

The end-of-waste criteria have been further specified under specific regulations for iron, steel, aluminium, and copper scrap and glass cullet (EC 2011b, 2012a, 2013). The second

[5] For example, the US Solid Waste Disposal Act defines solid waste as "*any garbage, refuse, sludge* from a waste treatment plant, water supply treatment plant, or air pollution control facility *and other discarded material*, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities . . ." (emphasis added) (US Congress 2016).

exception to the legal definition constitutes by-product streams. In the WFD, a substance or object qualifies as a by-product when it meets the following criteria:

- Further use of it is certain;
- It does not need further processing before further use;
- It is an integral part of a production process.

In addition, as for any product, the use of by-products or waste that is no longer waste must be lawful (regarding existing regulations such as product standards) and should not lead to overall adverse environmental or human health impacts (EC 2008). Some substances or objects are not excluded from the definition of waste but rather from the scope of the WFD. These substances or objects are either covered under other directives or simply not regulated as waste and include unexcavated but contaminated soil, excavated but uncontaminated soil, and non-hazardous agricultural or forestry material (EC 2008).

The criteria for defining waste, the end-of-waste criteria, and the criteria for by-products can be sorted into four categories of criteria that relate to discarding, impact, recovery, and use. The criteria that pertain to each category are explained below, with the relation to the WFD shown in parentheses.

- *Discarding*. The holder discards, intends to discard, or is required to discard the substance or object (waste definition).
- *Impact*. The use of the substance or object does not adversely impact the environment or human health (by-products and end-of-waste).
- *Recovery*. The substance or object has been recovered (end-of-waste) or does not require a recovery operation (by-product).
- *Use*. The substance or object is commonly used, there is market demand for it (end-of-waste), or further use of it is certain (by-product).

These criteria define the scope of waste legislation and provide a basic framework for its design. Waste legislation and policy builds on the definition of waste through a number of guiding principles, which are discussed in the next section.

3.2.3 Guiding principles

The guiding principles in the WFD are mainly the waste hierarchy, the polluter pays principle, the precautionary principle, and EPR. The waste hierarchy is at the core of the

WFD and among the foundations of waste management in developed countries (Dijkgraaf and Vollebergh 2004). It is a priority order for waste management options and usually covers three to five options. The hierarchy in the WFD states that waste prevention is most desirable, followed by reuse[6], recycling, other recovery, and disposal (EC 2008). A shorter version is widely known as the 3Rs: Reduce, Reuse, Recycle (Sakai et al. 2011).

The polluter pays principle is a guiding principle of EU and international environmental law. It states that the cost of pollution or its management should be borne by the polluter. Adherence to the principle should lead to more efficient and effective waste prevention and corresponds to a general idea of fairness. It may be applied by including the cost of pollution in the prices of goods and services. The principle was first suggested by the Organisation for Economic Co-operation and Development (OECD) in 1972 and taken up in legislation in many countries (Nash 2000; OECD Council 1972).

The precautionary principle requires that activities that present a risk of serious environmental impacts should be prevented even if conclusive evidence for these impacts is presently absent. The principle emerged in Germany and spread to European environmental policy in the 1970s. The UN Rio Declaration on Environment and Development in 1992 firmly established the principle at the global level. Application of the principle is challenging since risk is inherent to technological progress (Foster et al. 2000; Cameron and Abouchar 1991; EEA 2001).

Finally, EPR is meant to integrate environmental concerns into product design. Under EPR, manufacturers bear the cost of the end-of-life waste treatment of their products and are expected to minimize these costs. The EPR principle is consistent with the polluter pays principle as it allocates the costs of pollution with the producer and its customers. It was first suggested in 1990 and pioneered in Sweden and Germany in the early 1990s (Lifset and Lindhqvist 2008; Lindhqvist 2000; Lifset et al. 2013).

3.2.4 Policy implementation

The definition of waste and the guiding principles are the same for every EU member state. However, the transposition into national law and the subsequent policy implementation is done in different ways. Member states are allowed to decide on the details of waste

[6] The WFD actually defines “preparing for reuse” instead of “reuse”. This serves the purpose of regulating “checking, cleaning or repairing, recovery operations” (EC 2008).

management at the national, regional, or local level (Nash 2008). The national context, including government budgets, bureaucratic capacity, political trends, lobbying, and the inherited policy landscape, leads to distinct waste regimes.

The following categories of public policies may be implemented, in accordance with the guiding principles laid down by the WFD (UNEP 2015; OECD 2007).

- Information instruments: campaigns, training, education, and product labelling to inform and equip individuals and organizations; guidance documents to help businesses comply with waste regulation and legislation.
- Economic instruments: taxes and charges that reflect environmental burdens; subsidies, loans, and tax reductions for environmentally friendly technologies; tradable permit schemes; deposit-refund schemes for packaging.
- Regulatory instruments: bans or restrictions on particular uses or export of waste; environmental quality standards regarding air, water, and soil; technical standards for industrial facilities.
- Voluntary agreements: agreements or partnerships between governments, the private sector, and tertiary sector, which may be completely voluntary or include legally binding elements.

In addition to the above, governments may choose to support innovation and technological development through a variety of measures including public funding of research, development, and demonstration (RD&D) activities.

Each guiding principle can be implemented in various ways. For example, Reichenbach (2008) reviews pay-as-you-throw (PAYT) schemes in EU member states that were developed partly to comply with the WFD and notes a variety of mechanisms including user or bin identification, volume or weight-based billing, and the use of individual or collective bins. Cahill et al. (2011) find that member states' EPR systems for Waste Electrical and Electronic Equipment (WEEE) vary in terms of pre-existing policies and systems, methods for achieving compliance, fee structure, targets, waste streams, and the role of local authorities.

3.3 Shortcomings of the legal definition

3.3.1 Context of waste

The regulatory concept of waste should support the reduction of impacts from waste on the environment and human health and contribute to resource conservation. However, the legal definition is tailored towards the former and tends to ignore the latter. As a result, waste management is not fit for resource efficiency and the circular economy. This section and the next two sections describe three interrelated shortcomings of the legal definition of waste, which are not currently compensated for through guiding principles or their policy implementation.

To start with, what is waste depends on the context, but the legal definition largely ignores this. The literature shows that waste can be defined in terms of economic value (McCormick 1986), technical necessity and efficiency (Baumgärtner and Arons 2003), environmental hazard and pollution (Cheyne 2002), or interpreted as a social construct (Reno 2014). Economic, technical, environmental, and cultural factors are spatially and temporally distinct and "waste" is therefore "transient" (Thompson 1979), a "temporary attribute" (Dijkema et al. 2000) and "not static" (Kronenberg and Winkler 2009).

By implication, "non-waste" is also contextual; substances or objects have a functional, physical, technological, economic, social, and legal product lifespan (Woodward 1997; RICS 2016). Once any of these lifespans has been exceeded, the owner may wish to discard the substance or object, upon which it is legally defined as waste. Unfortunately, the legal definition fails to highlight that a product that is discarded because of, for example, social reasons (fashion) can still be a "non-waste" based on functional, physical, technological, economic, and legal criteria.

The legal definition includes the economic aspects to some extent in the end-of-waste and by-product criteria. At the same time, it accepts any discarded or intended to be discarded substance or object as waste and therefore fails to stimulate the extended or repeated use of them. If instead individuals or organizations were presented with options for improving this context, or moving waste into such a context, they could render the object or substance useful again. Examples are reuse of components in a different product or repurposing a technically inferior device for less demanding tasks.

3.3.2 Waste users

Waste may be seen as a resource by a third party, but the definition of waste ignores this because it only represents the intention of the waste holder ("intends to discard or discards") and possible obligations to dispose ("required to discard"). The legal definition does not suggest there is a category of waste that should not be discarded for the sake of a waste user. In fact, the WFD only defines the "waste producer", "waste holder", "dealer", and "broker" but not the final "user" or "reuser".

As a result, the waste user has to actively prove that the waste is in fact a resource, whereas the waste holder is allowed to freely discard any potentially valuable wastes. Preventing "unjustified" discarding requires a reversal of the current system: the waste holder would have to actively prove that the discarded material is a waste. But faced with a barrier to discard, the waste holder may resort to fly-tipping instead; it is the cost of legal waste management that drives waste trafficking and illegal disposal (Europol 2011).

EPR schemes partly address this issue by putting the responsibility for waste with the manufacturers, who are dependent on consumers for the correct return of their products. By financing waste collection and treatment, manufacturers help consumers discard their waste more cheaply (assuming the consumer would pay higher waste management charges otherwise), which reduces illegal disposal or incorrect sorting (Dubois 2012). Of course, subsidization of waste management does not ensure all waste is correctly discarded – cost is just one determinant of behaviour (Heller and Vatn 2017; Czajkowski et al. 2017).

3.3.3 Carelessness

Careless discarding – without considering its necessity or the possibility of another user – may be compounded by negative perceptions of waste. Besides having no further use to its holder, waste is "out of place", and the holder may wish to be as far as possible from it. Waste is a social categorization that evokes a repulsion that is not necessarily explained by the inherent properties of the material (Reno 2014; Douglas 1966); the emotive character of waste and the public resistance to waste facilities are among the main factors that complicate waste law (Tromans 2001).

Informed by the precautionary principle, the regulatory concept of waste aims to strictly control the impact of all discarding rather than to avoid careless discarding. It includes more rather than less waste to make sure all waste is subject to the same strict regulation and to reduce the threat of pollution (Bontoux and Leone 1997). Conventional chemicals or hazardous substances regulations are considered inadequate for waste because such regulations focus on useful products with an intended use and commercial value and do not factor in that the owner may not care about the destination of the substance.

The current approach is necessary for environmental protection but leaves little room for discouraging the waste holder from careless discarding and encourage *careful* discarding. Carelessness may be avoided only through a change in perceptions of waste. If waste were seen as an object one merely has no use for, but which requires care, discarding may be less hazardous, and support recycling and recovery activities. This would demand an awareness among waste holders of the value of recovery and recycling of waste upon correct sorting and discarding and the arbitrariness of negative perceptions of some waste.

3.4 A potential-based concept of waste

3.4.1 Purpose and benefits of the concept

The shortcomings of the legal definition may be addressed through the development and application of a potential-based concept of waste, which indicates the extent to which and how waste can be used as a resource. Importantly, the potential-based concept of waste is not an alternative to the current legal definition, which appropriately protects the environment and human health, but an additional guiding principle to stimulate resource conservation. Making the potential of waste known to waste holders responds to all three challenges identified in the preceding section.

1. It emphasizes the importance of context by highlighting the possibilities for utilization. Ideally, the waste holder is prompted to seek other options than discarding the material. The waste holder may be confronted with economic, technical, environmental, and cultural criteria that lead to a different or more nuanced evaluation of the waste status of a substance or object.
2. It compensates for the asymmetry between the waste holder and the waste user in the legal definition. A potential-based concept of waste reflects the judgement of the waste user, not the waste holder. It may stop the waste holder from conducting a self-centred evaluation of the usefulness of an object or substance and help the waste holder identify a third party for whom the waste constitutes a resource.

3. It can reduce the likelihood of careless discarding. Waste is found useless by the waste holder and the negative connotation of the cultural category "waste" obstructs any further engagement with the fate of the material. Reframing waste as a substance or object with a potential use, irrespective of who the next user is, may stimulate more careful and correct discarding.

The potential-based concept of waste focuses squarely on the potential use of the waste rather than any of the four categories covered by the legal definition (discarding, impacts, recovery, and use, see Section 3.2.2). The criterion of *potential use* is different from the criterion of *use* because the use criteria are limited to *common* or *certain* further use or existent market demand. The *potential use* covers a much wider set of possibilities and is limited only by the knowledge of options for using waste as a resource.

Table 3-1 shows the relationship between the EU waste hierarchy, the legal definition of waste, and the potential-based concept of waste. The potential-based concept of waste logically only relates to legally defined "waste". The table shows that "waste" may be reused, recycled, recovered, or disposed. The scope of the potential-based concept of waste is limited to reuse, recycling, and recovery; disposal should happen only if the substance has no potential at all for being used as a resource.

Table 3-1. Linkages between the regulatory and potential-based concept of waste.

	Status of substance or object	
EU Waste hierarchy	**Legal definition**	**Potential-based concept**
Prevention	Non-waste	-
Preparing for reuse	Waste	Potential resource
Recycling		
Other recovery		
Disposal		-

The category "preparing for reuse" relates to waste because "preparation" refers to a waste recovery operation. In addition, reuse may relate to products that one may "intend to discard" (but never does) and these products are waste according to the legal definition too. The potential-based concept does not target waste prevention because the WFD strictly defines it as "measures taken before a substance, material or product has become waste" (EC 2008) and thus relates to "non-waste" (Gharfalkar et al. 2015).

The potential of waste may be expressed by showing to what extent and how a waste can be used as a resource. The "how" can be detailed by referring to the main categories of reuse, recycling, recycling, and recovery. Recovery may be subdivided into energy recovery (substituting fuels) and non-energy recovery (substituting other materials). These categories can be subdivided again. Energy recovery, for example, can be further specified as combustion, anaerobic digestion, pyrolysis, or gasification.

The conditions for successful use need to be expressed because they specify what contextual factors need to be manipulated in order to overcome the barriers to using waste as a resource. For example, a certain material may be recycled *if* separate collection infrastructure is put in place, or a material may be recovered *if* the relevant technology is further developed and commercialized. Further specification may focus on the spatial and temporal scale of the assessment and the assumptions regarding the economic, technical, environmental, and social conditions.

3.4.2 Potential-based waste metrics

The potential of waste to be used as a resource may be expressed in several ways, which could focus on technical, economic, environmental, and social aspects. There is a wealth of studies on waste-related metrics but they do not list metrics that emphasize the *potential* of waste (Fischer-Kowalski et al. 2011; Moriguchi 2007). Most metrics capture the extent to which waste is generated and the fraction of waste that is already used as a resource. They do not directly indicate limitations or possibilities for the use of waste as a resource.

To the author's knowledge, the only exception is Park and Chertow (2014), who present an indicator which emphasizes the technical possibilities for using waste as a resource. The "reuse potential indicator" shows the extent to which a waste is "resource-like", on a scale from 0 to 1. A reuse potential of 0.45, for example, shows that 45% of a certain waste can be used as a resource. The reuse or recovery potential indicator signifies the technically available options for reuse or recovery before consideration of economic and regulatory barriers.

The formulation of the potential of waste as a resource may follow common classifications for the availability of fossil and mineral resources. Park (2012) applies the McKelvey classification to secondary materials and Winterstetter et al. (2016) applies the UNFC-2009 primary resource classification framework (UNECE 2010) to "anthropogenic resources". Winterstetter et al. (2016) present three dimensions for classifying the resource-like nature of waste.

- General economic viability as evidenced by current and expected market conditions.
- The feasibility of extraction as evidenced by (preliminary) studies of current and potential projects or operations.
- The knowledge and confidence associated with the composition and extractable material content.

Some of the above criteria, especially for the first dimension, are similar to the end-of-waste criteria. However, they can be applied more flexibly. The potential-based concept of waste, after all, is not intended to mark a strict regulatory line between waste and resources. Instead, it indicates to what extent and how a waste could be used as a resource, based on the particular properties of the object or substance and its context, to inform and motivate waste holders.

Metrics can be used to indicate the reuse or recovery potential of waste under different economic, technical, or regulatory scenarios with distinct spatial and temporal boundaries. For example, Park and Chertow (2014) consider three cases for the reuse of Coal Combustion By-products (CCBs) in the United States: 1) all legally allowable uses, 2) all legally allowable uses except controversial land applications, and 3) only encapsulated use. The results ranged from a high reuse potential of 85% in the first case to a low reuse potential of 35% in the third case.

3.5 Discussion: application of the concept

3.5.1 Industrial waste management

The potential-based concept of waste may be used for policy formulation and environmental assessment. In terms of industrial waste policy, the performance of facilities in the European Union is regulated through the Industrial Emissions Directive (IED) (EC 2010). The Directive lays down the rules for permitting industrial facilities based on Best Available Techniques (BATs). In short, facilities must comply with environmental standards based on BAT reference documents which list techniques that yield the lowest emissions including waste generation.

The BAT reference documentation considers the efficient use of materials and the use of waste both within and outside of the facility. For example, the BAT reference document for the pulp and paper industry suggests using waste as an industrial feedstock, for land spreading, or in construction materials (Suhr et al. 2015). There are, however, no quantitative estimates of the potential for using waste from the pulp and paper sector as a resource. The BATs could be presented more usefully as a conditional potential using the aforementioned reuse or recovery potential indicator.

The recovery potential of industrial and consumer waste in the global paper life cycle will be quantified in Chapter 6, based on benchmark performance and a review of waste recovery options in the literature. A more detailed and locally specified assessment of the same waste flows could inform the BATs for the pulp and paper industry in the European Union. Additional data would be needed to indicate benchmark performance in the European context, which may be gathered through case studies or industry surveys.

3.5.2 Consumer waste management

Just like businesses, households and individuals may be confronted with the potential use of their waste as a resource. Information regarding the potential may be supplied as part of the waste infrastructure, on product packaging, and through general media channels. The potential-based concept of waste relates to some of the determinants of behavioural change: by showing to what extent and how waste can be used as a resource it contributes to consumer knowledge and may slowly change social norms.

A review by Cox et al. (2010) concludes that the most significant barrier to waste prevention by consumers is a lack of understanding of “waste prevention”, the associated actions, and the difference between waste reduction and recycling. In other words, consumers lack an understanding of the use of waste as a resource and the conditions under which this can happen. A potential-based concept of waste would help consumers imagine waste as a potential resource which, through their own actions, can be used longer or again.

Other barriers to prevention found by Cox et al. (2010) are apathy, inconvenience, a sense of powerlessness, not feeling responsible, and social norms. Viewing waste as a potential resource could help overcome the latter two barriers. The concept of waste as a potential resource could show individual responsibility by indicating which action is required by whom. It could also change social norms in the long term by blurring the lines between waste and resource and removing some of the stigma associated with anything discarded.

Finally, the EU currently sets targets for the recovery and recycling of several waste streams, and these could be contextualized with the recovery potential of waste. For example, the WFD demands a minimum of 50% recycling of at least paper, metals, plastic, and glass. Such a target may be contrasted with *how much* can be recycled and *under what conditions*. This would make a better benchmark than the implied maximum of "100% recycling". This argument is explored further in the discussion section of Chapter 5.

3.5.3 Environmental assessment

The waste-specific reuse or recovery potential indicator, together with current and desired performance, provides an insightful measure of the environmental performance of products, systems, or policies. An example for evaluation of public policy is given in Figure 3-2. The figure shows what is currently achieved, what is demanded by regulation, and what could be done at best under various assumptions (scenarios). Such an approach does not show what is environmentally desirable or sufficient but at least shows how current performance and desired performance relate to what is possible. The performance gap may inform and stimulate improvement.

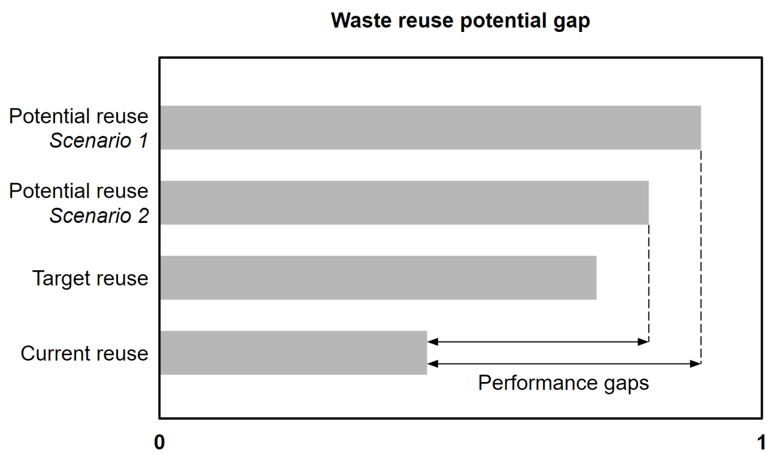

Figure 3-2. Example of reuse potential, target performance, and current reuse.

Environmental assessment may guide product and system design. For product designers, the potential-based concept of waste expresses the likelihood of end-of-life products being used as a resource, conditional upon its properties and context. The eco-design directive (EC 2009a) lists some relevant properties: the diversity of materials and components, ease of disassembly and access to materials, level of standardization and coding, and technical recyclability.

At the systems level, the fulfilment of the potential of waste equates the efficient and circular use of materials. A system-wide analysis can indicate the impact of using waste streams as a resource and provide insight into the benefits of a resource efficient circular economy. As a start, Chapter 6 will show to what extent complete fulfilment of the recovery potential of waste in the global paper life cycle can reduce virgin inputs requirements and waste to landfill. Similar analyses may be conducted for other materials.

Chapter 6 will also show that the success of the potential-based concept of waste depends on data availability regarding waste generation, waste properties, and recovery options. Significant data collection efforts are necessary to gather this information. It depends on the applications how precise such information needs to be. Whatever the data quality, it is important to specify the assumptions and uncertainties regarding a particular expression of the potential of waste to be used as a resource.

3.6 Conclusions

The regulatory concept of waste is suitable for protecting human health and the natural environment but does not adequately address conservation of natural resources. The following three conclusions can be drawn from the analysis.

- The legal definition of waste ignores the context of waste and fails to consider the interests of the waste user as opposed to the waste holder. It aims to control the impacts of careless discarding rather than stimulating careful discarding.
- These issues may be resolved through a potential-based concept of waste which indicates the extent to which and how a material can be used as a resource. The potential-based concept of waste is complementary to the legal definition.
- The concept may be quantified for policy and environmental assessment with the reuse (or recovery) potential indicator (Park and Chertow 2014) which expresses the extent to which waste can be used as a resource with a score between 0 and 1.

Further research may further develop the concept by applying it to various waste materials and exploring policy applications. The thesis uses a recovery potential indicator to analyse to what extent and how efficiency and circularity can help reduce GHG emissions in the global paper life cycle. The next chapter will describe the global paper life cycle, climate change, and the modelling methods.

4 Methods and context

4.1 Introduction

The preceding chapters have shown the relevance of the research aim and explained the benefits of measuring the efficient and circular use of materials through a potential-based concept of waste. The subsequent chapters focus on the thesis objectives: modelling of material flows, assessment of the potential for efficiency and circularity, and modelling of energy use and GHG emissions in the paper life cycle. The present chapter describes the global paper life cycle, climate change, and the modelling approach.

The next section explains the history of paper and the main features and environmental problems of modern paper production. Climate change is discussed separately from other environmental issues in Section 4.3. Section 4.4 describes the gap in the literature and Section 4.5 summarizes the modelling of material flows, energy flows, and emissions. Section 4.6 describes how a GHG target for the global paper life cycle is estimated based on the global carbon budget for staying below 2 degrees average global warming.

4.2 The paper life cycle

4.2.1 History and context

Paper has been around for more than two thousand years but two aspects have hardly changed. First, the basic technique for making paper is still the same: in any papermaking process, fibres are dissolved into a watery pulp and the pulp is put over a screen and drained, pressed, and dried. Second, waste has always been an important feedstock, and was not limited to waste paper but also included rags from clothing.

The Chinese court official Cai Lun is generally credited as the inventor of paper in the second century AD. Archaeological findings suggest the first occurrence of paper to be much earlier, in the last centuries BC in China. The technique spread to Korea, reached Japan in the seventh century AD, and spread via the Arab world to Medieval Europe in the 11th century AD. Paper was adopted as a better alternative to precursors like tapa (bark cloth), felt, papyrus, and parchment (Tschudin 2006; Goedvriend 1988).

The mechanization of papermaking started in the late 17th century in Europe with the "Hollander beater", which could produce pulp more efficiently. By 1799 the first (manually driven) paper machine had been invented by the Frenchman Robert. Further development led to the invention of the Fourdrinier machine, which used a belt instead of a static screen to enable continuous production, a technology that is still found in modern papermaking machines (Tschudin 2006; Goedvriend 1988).

A major breakthrough for fibre supply was the invention of modern mechanical and chemical wood pulping techniques. The stone ground wood process was invented in 1843 and the soda, sulphate, and sulphite pulping processes originate between 1851 and 1866. The introduction of the steam engine initially made little difference to paper production because of constraints related to heat and power transmission. Better steel and the introduction of the electric motor enabled much larger machines (Tschudin 2006).

Papermaking has a rich history of scarcity issues, raw material substitution, and use of secondary materials. Over the centuries, a large number of alternative feedstocks have been explored. Goedvriend (1988) lists several types of rags, straw, bark, bast, and leaves that were used from the 16th century onwards. In the UK, paper was made from rags, which were scarce – several laws introduced in 1666-1680 required the dead to be buried in wool only, which protected both the paper and wool industry (Basbanes 2013, p. 63).

The use of waste paper as an input is recorded as early as 1031 when the Japanese sought to substitute mulberry, gampi, and hemp. The Japanese most likely copied this practice from the Chinese (Hunter 1978). Large-scale recycling of waste paper probably started with modern paper production. Recycling has increased considerably over the past half a century with the recycling rate growing from around 20% in 1962 to 54% in 2012. At the same time, paper demand quintupled (FAO 2016).

The rise of electronic media has cast doubt on the future of paper. In the 1980s, there were great expectations of the "paperless office" but almost 40 years later remarkably little has changed (Hetemäki et al. 2005). Paper demand growth slowed down and slumped during the financial crisis of 2008 – 2012 and newsprint sales have declined in many countries. However, the age of paper is by no means over. Some new technologies, like office printers, stimulate rather than reduce paper demand and the increase in electronic devices calls for ever more paper packaging.

4.2.2 Modern paper life cycle

The modern paper production process is displayed in Figure 4-1. There are five main stages of the paper life cycle: forestry, pulping, papermaking, use, and E-o-L waste management. Additional steps include bleaching and printing. The main inputs are wood (56%), paper for recycling (34%), and non-fibrous material such as fillers and additives (10%). The main outputs are packaging (54%), printing + writing paper (26%), newsprint (8%), and sanitary + household (8%) (based on the figures in Chapter 5).

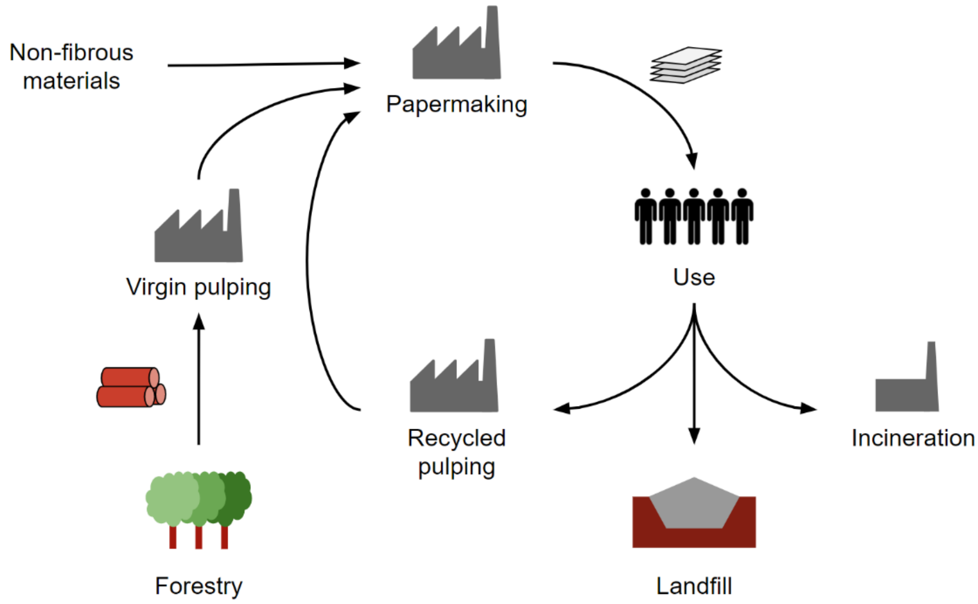

Figure 4-1. The production and consumption of paper.

Wood and *paper for recycling* are used for pulp. Wood fibre is supplied as logs or woodchips. Logs still need to be debarked and chipped at the paper mill. Wood chips are screened to remove contaminants. The paper for recycling feedstock comes from waste paper collection including waste material from the papermaking process. Paper for recycling may be retrieved from separate collection or mixed recyclables collection. The material may be sorted into different paper grades (Kramer et al. 2009; Miranda et al. 2013).

Virgin pulping may be mechanical, chemical, or semi-chemical. Mechanical pulping consists of grinding wood to weaken and separate the fibres. The process has a high yield but produces low-quality fibres with a high lignin content. The dominant chemical pulping process is sulphate (Kraft) pulping and applies a solution of sodium sulphide and sodium hydroxide (white liquor) to separate lignin and hemicellulose from cellulose. Semi-chemical pulp mills integrate mechanical and chemical pulping (Kramer et al. 2009).

Chemical recovery in the chemical pulping process ensures the reuse of pulping chemicals and generates energy from the lignin residues. Figure 4-2 shows the Kraft pulping process and the recovery cycle. After pulping, chemicals including lignin residues, called black liquor, are fed to a recovery boiler and burned. The reaction products are flue gases and green liquor. The green liquor is fed to a causticizing plant where, with the use of lime, it is converted back into white liquor for pulping. Lime mud ($CaCO_3$) is recovered in the lime kiln (Suhr et al. 2015).

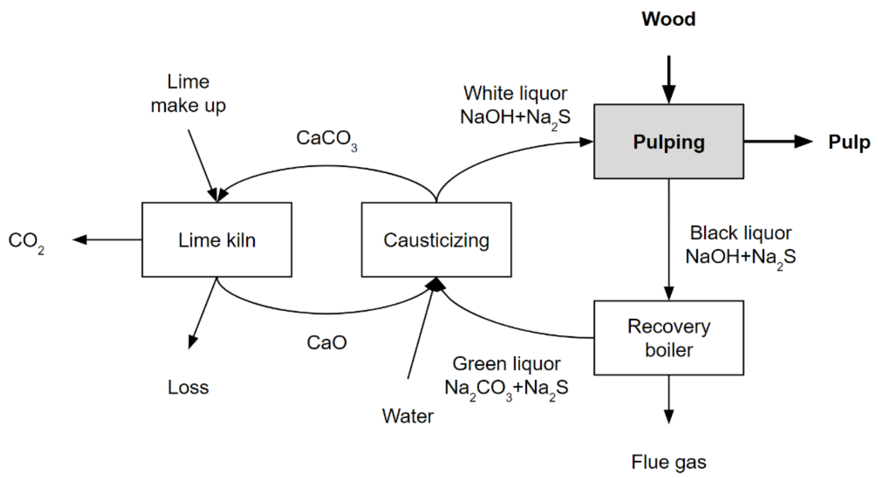

Figure 4-2. The chemical recovery cycle (adapted from Suhr et al. (2015)).

Recycled pulping consists of dissolving waste paper in water and removing contaminants through screening, a ragger mechanism, and the use of surfactants. The latter is used to remove inks and other contaminants from waste paper. Recycled fibre is of a lower quality than virgin fibre and contains more contaminants. Some of the contaminants can be harmful and restrict the use in for example food packaging. Increased levels of contaminant removal tend to reduce the process yield (Kramer et al. 2009; Pivnenko et al. 2016).

Bleaching of pulp helps obtain a bright white colour. Unbleached pulp is used for grey and brown paper and cardboard products. In the past, bleaching agents contained harmful elemental chlorine but this has almost been phased out. Bleaching agents are now either Elemental Chlorine Free (ECF) or Totally Chlorine Free (TCF). Common bleaching agents in the paper industry are chlorine dioxide, ozone, hypochlorite, sodium hydroxide, oxygen, and hydrogen peroxide (Kramer et al. 2009).

Papermaking consists of stock preparation, sheet formation, and drying. In the first stage, pulp is homogenized, dispersed in water, and screened to remove contaminants. The slurry is deposited onto fabric, the water is removed, and the sheet of paper is pressed. The sheet is then dried using heated rollers. The paper goes through a series of precisely spaced rollers to control thickness and smoothness (calendering). It is then wound on a reel (Kramer et al. 2009).

Non-fibrous materials are added to the paper during stock preparation and sheet formation to improve the properties of the final product and reduce the raw material cost. Non-fibrous materials are used as fillers or coatings to improve opacity, brightness, smoothness, and the absorbency of ink and other liquids. They may also be used to dye the pulp. Commonly used non-fibrous inputs are clays, calcium carbonate, and starch (CEPI 2014a, 2013a).

Printing happens after reels of paper are cut to size. The main printing technologies are relief, offset, and gravure. All technologies use plates, cylinders, or stencils which combine an ink-accepting surface with a non-ink surface. Offset printing is the most common technology and uses a rubber sheet to transfer ink from the image carrier to the paper. Digital printing is used for small volumes only and in households and offices (EC 2007).

Waste management of paper is required after use and disposal of paper products. The main options for paper include recycling, energy recovery, and incineration (without energy recovery). Industrial waste may be used in a variety of ways including recycling and recovery. Chapter 6 provides a detailed description of waste generation and management in the global paper life cycle and reviews the maximum technical possibilities for increased recovery of the waste.

4.2.3 Paper and the environment

4.2.3.1 Land-use change

Demand for pulpwood to produce paper products is among the many factors that exert pressure on forests. Tropical forests are of particular concern because of their role in biodiversity and global carbon stocks. Other contributors to deforestation and degradation, besides logging, include infrastructure extension and agricultural expansion. The relative importance of logging depends on the country and region. Commercial logging is a strong driver for forest degradation in Asia (Geist and Lambin 2002).

Pulpwood is sometimes obtained through illegal and selective logging which can trigger further conversion of tropical forests. The presence of roads for selective logging makes it easier to clear the land for agricultural purposes. The initial revenue gained from selling (illegally) logged wood is sometimes used to further convert the land (Boucher et al. 2011; Kissinger et al. 2012).

4.2.3.2 Air emissions

Fuel and waste combustion in paper mills leads to air emissions. These emissions include nitrogen oxides, sulphur dioxide, dust and particulate matter, heavy metals, carbon monoxide, hydrochloric acid, hydrogen fluoride, ammonia, Volatile Organic Compounds (VOCs), Persistent Organic Pollutants (POPs), Polycyclic Aromatic Hydrocarbons (PAHs), and dioxins and furans (EC 2006a, 2006b).

Prominent sources of emissions at paper mills are the recovery boiler (where black liquor is burned), the power boiler (where other waste and fuels are burned), and the lime kiln (where lime is burned). Municipal Solid Waste (MSW) incineration plants burn waste paper that is not collected for recycling. The printing sector is a major source of VOCs because of the use of organic solvents in the printing process (EC 2007).

4.2.3.3 Water pollution

Paper mills use large amounts of water for pulping and papermaking and produce vast quantities of wastewater. The most problematic substances in wastewater discharges are poorly degradable organic substances, chemical agents, nitrogen and phosphorus, chlorinated organics, and suspended solids (Suhr et al. 2015). Wastewater treatment generates wastewater treatment sludge which, in this thesis, is included in the analysis of solid waste.

There are several other processes in the paper life cycle, besides pulping and papermaking, which generate wastewater or water pollution. Fuel and waste combustion involves water flows for cooling and quenching of ashes. Landfill of paper waste contributes to the forming of leachates which may directly or indirectly pollute groundwater and water bodies. Some sanitary and household paper residues end up in sewage sludge and contribute to water pollution caused by sewage sludge treatment.

4.2.3.4 Odour and noise

Odour issues are commonly reported for pulp and paper mills that use the Kraft pulping process. The odour stems from reduced sulphur compounds indicated as total reduced sulphur (TRS). Some compounds are formed during the pulping process and others result from downstream processes. Odour is reduced by converting the compounds through thermal oxidation or adsorption with scrubbing technologies (Suhr et al. 2015).

Noise may be produced at any stage of the life cycle of paper. It can be an issue with paper mills, forestry activities, and wood processing facilities. The noisiest equipment includes grinders, cutters, pipelines and conveyor belts, fans, motors, and compressors. They are used in sawmills and paper mills. Sporadically occurring activities like steam venting or cleaning also cause noise as do the transport of raw materials and paper (Suhr et al. 2015).

4.2.3.5 Solid waste

Waste from the paper life cycle is discussed in depth in the thesis. It includes solid waste and semi-solid sludge (but not wastewater) from pulping and papermaking activities. The major waste flows from the paper life cycle, categorized in Chapter 6, are E-o-L discards, paper in sewage, black liquor, recycling sludge, papermaking waste, sludge and rejects, causticizing waste, and boiler ash (from the combustion of waste).

The treatment of solid waste leads to adverse environmental impacts including pollution of air, soil, and water through emissions from energy recovery and other forms of recovery, such as land spreading, composting, and use as aggregate or admixture in the construction sector. Landfill of waste leads to emissions to air, soil, and water. The wastage of materials implies unnecessary pressures on the natural environment and forests in particular.

4.3 Climate change and paper

4.3.1 The concept of climate change

The production, consumption, and landfill of paper is among the many drivers of climate change. Anthropogenic climate change is the additional warming of the planet caused by GHG emissions from human activities. These emissions enhance the ability of the atmosphere to trap sunlight and keep the planet warm (the greenhouse effect). The main contributors to the greenhouse effect are water (vapour), CO_2, CH_4, ozone, and nitrous oxide (N_2O) (IPCC 2014).

The logic of climate change was presented as early as the 19th century. In 1824, Fourier first suggested that the atmosphere, like a glasshouse, could trap heat. In 1859, Tyndall showed the absorption of heat by specific molecules. In 1895, Arrhenius made a largely correct prediction regarding the potential impacts of an increase in atmospheric CO_2. Carbon cycle science took off in the 1950s with a focus on CO_2 and water. In the 1970s, other GHGs including CH_4 were identified (Le Treut et al. 2007).

Climate change has a variety of impacts. IPCC (2014) lists more and longer heat waves, ocean warming and acidification, and global mean sea level rise. The consequences of this vary by location but are generally more severe for disadvantaged people and communities. Climate change is likely to disrupt human and natural systems: it causes species extinction, affects agricultural productivity, and leads to more and more extreme weather events such as floods, hurricanes, and droughts.

Global negotiations to address climate change started in 1992 with the UN Framework Convention on Climate Change (UNFCCC). The Kyoto Protocol, adopted in 1997, set the first legally binding emission targets. At the 2015 climate conference in Paris, countries agreed to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UN 2015b).

4.3.2 The carbon cycle and paper

Anthropogenic climate change is the human alteration of the global carbon cycle. Figure 4-3 summarizes carbon stocks and flows (fluxes) at the global scale. The main carbon stocks are the atmosphere, oceans, soils, vegetation, fossil fuels, and permafrost. The black arrows and numbers indicate stocks and flows for pre-industrial times (around 1750). The red arrows indicate annual anthropogenic flows of carbon averaged over 2000-2009. The red numbers indicate cumulative stock changes for the period 1750-2011.

The main anthropogenic flows of carbon result from fossil fuel combustion, cement production, and land use change. The global paper life cycle affects the global carbon cycle mainly through fuel combustion for the generation of electricity and heat. The use of renewable biomass leads to a relatively low carbon intensity (CI) of energy inputs compared to other industries. A significant amount of energy is supplied through energy recovery of black liquor from chemical pulping. The most widely used fossil fuels in the paper sector are coal and gas.

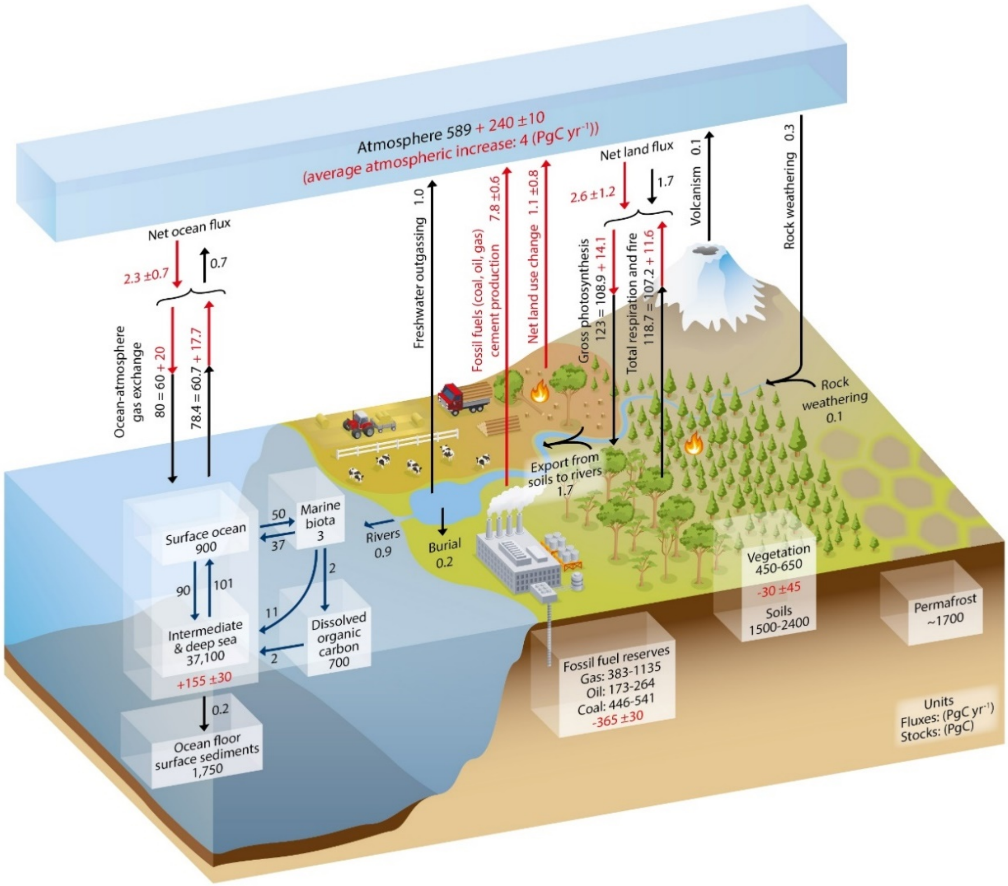

Figure 4-3. The global carbon cycle (Ciais et al. 2013).

Sequestration of carbon in forests and paper products affects the global carbon cycle. Net sequestration in forests occurs when growth exceeds harvest. When harvest exceeds growth, and products are not stored, there is a net loss of carbon. Sequestration in paper products is relevant for long-lived or recycled products. The decomposition of waste paper in landfills is a major source of CH_4. The warming effect of CH_4 is much stronger than the warming effect of CO_2. The precise value of the relative contributions of the two gases depends on the time horizon. The paper sector also emits a small amount of N_2O due to fuel combustion and the use of fertilizer (FAO 2010a).

4.4 Literature gap

The thesis responds to a gap in the literature for a model that describes emissions from the global paper life cycle based on a comprehensive material and energy balance, and which includes organic carbon stocks and flows. Table 4-1 lists the most relevant models in the literature that focus on the paper (or forest product) life cycle. The models are characterized by answering four questions.

– Is it a global model?
– Is it based on a full and consistent material balance?
– Is energy consumption analysed separately from emissions?
– Are fossil and organic carbon included?

No model yields a positive answer to all four questions. The suggested modelling approach addresses several gaps in the literature.

- Chapter 5 does a detailed global material flow analysis of life cycle paper flows. Similar balances have been published for steel (Cullen et al. 2012) and aluminium (Cullen and Allwood 2013; Liu et al. 2012). Only Allwood et al. (2010) provide an MFA of life cycle paper flows at the global level but the thesis provides more detail, especially regarding waste generation and treatment.
- Chapter 6 provides quantitative estimates for the current and potential use of waste in the global paper life cycle. The literature is limited to current paper waste management in the US (Bird and Talberth 2008) and the EU (Monte et al. 2009) and qualitative assessments of the potential use of waste (Suhr et al. 2015; Bousios and Worrell 2017; Bird and Talberth 2008).
- Chapter 7 calculates GHG emissions from the global paper life cycle based on a consistent and complete material and energy balance. It provides a breakdown of emissions by type of energy and includes organic carbon stocks and flows related to in-use products, recycling, landfill storage, and landfill gas. It goes beyond the state-of-the-art emissions account by FAO (2010).
- Chapter 8 projects future emissions from the global paper life cycle and goes beyond the state-of-the-art analysis by Allwood et al. (2010). It is based on the aforementioned material and energy balance, a new estimate for future paper demand, and experience curves for energy efficiency.

The studies reviewed in Table 4-1 are referred to throughout the thesis. All models are relevant for the analysis in the next four chapters and many of the parameters and assumptions in the thesis are based on the studies listed in the table.

Table 4-1. Relevant studies on paper and forest products in the literature.

Reference	Material	Temporal scale	Spatial scale	Material balance	Energy modelled	Type of emissions
(Allwood et al. 2010)	Paper	2006 & 2050	World	Yes	--	Fossil only
(CEPI 2016)	Paper	2015	CEPI area*	Yes	--	--
(Chen et al. 2016)	Paper	2010	Taiwan	Yes	--	--
(Cote et al. 2015)	Paper	2010-2040	Germany	Yes	--	Fossil only
(Counsell and Allwood 2007)	Paper	Early 2000s	United Kingdom	--	--	Fossil and organic
(FAO 2010a)	Forest products	2006/07	World	--	Partly	Fossil and organic
(Fleiter et al. 2012)	Paper	2007	Germany	Yes	Yes	Fossil only
(Heath et al. 2010)	Paper	1990 & 2004/05	United States	--	Partly	Fossil and organic
(Hekkert et al. 2000)	Forest products	1990	Netherlands	Yes	--	--
(Hong et al. 2011a)	Paper	2009	Taiwan	--	Yes	--
(Hong et al. 2011b)	Paper	2007	Korea	--	Yes	--
(IEA 2007a)	Paper	2004	World	--	Yes	--
(Krones 2016)	Paper	2010	United States	Yes	--	--
(Miner and Perez-Garcia 2007)	Forest products	Early 2000s	World	--	Partly	Fossil and organic
(Subak and Craighill 1999)	Paper	1990s & 2010	World	--	Partly	Fossil and organic
(Sundin et al. 2001)	Paper	1996	United Kingdom	Yes	Yes	--
(Ozalp and Hyman 2006)	Paper	1998	United States	--	Yes	--

*The Confederation of European Paper Industries (CEPI) represents its national counterparts in most European countries and covers most if not all of the paper industry in these countries.

4.5 Modelling approach

4.5.1 Goal, scope, system

The GHG emissions from the global paper life cycle will be modelled through a detailed assessment of material flows, energy inputs, and organic carbon stocks and flows. The analysis combines MFA and LCA and applies scenarios based on a paper demand projection up to 2050. In LCA terminology, this section covers the Goal and Scope definition and the

LCI. Section 4.6 covers the LCIA. The methods are described in more detail in the relevant sections "methods and data" in Chapters 5 to 8.

The goal of the study is to assess the climate change mitigation benefits of more efficient and circular use of materials in the global paper life cycle. Figure 4-4 displays the product system for paper and board consumption. The functional unit of the study is the fulfilment of global annual paper demand. For the base year, this is around 400 Mt of paper and board. For future years, a paper demand projection is used. The analysis covers all the unit processes within the system boundary indicated in the figure.

The assessment considers material flows and stocks, energy flows, fossil carbon emissions, and flows and stocks of organic carbon. Fossil carbon emissions result from electricity generation in the power sector and on-site fuel combustion. Organic carbon emissions result from the decomposition of paper waste in landfill. Changes in organic carbon stocks due to recycling, long-term product use, and landfill are also included. Avoided emissions are calculated for energy recovery from MSW and landfill gas[7]. No estimate could be derived for the (avoided) emissions due to land-use change and forestry.

The total GHG emissions from the paper life cycle are compared against GHG targets based on the global carbon budget for staying below 2 degrees average global warming. The model is run for three scenarios: REFerence (REF), Increased Efforts (IE), and Waste as a Resource (W-a-R). The latter scenario reflects the fulfilment of the recovery potential of all major waste flows. It is an optimistic scenario that aims to estimate the contribution of the efficient and circular use of materials to climate change mitigation.

All data used in the modelling is process data and not input-output data (see Section 2.3 for a description of EEIO). Input-output data does not show what happens inside a sector and gives insufficiently precise estimates of environmental flows. Besides, prospective modelling with input-output data requires projecting changes in the entire economy. With process data, only the parameters that directly describe the life cycle need to be considered. All of the models in Table 4-1 use process data except for Chen et al. (2016). The authors identify the high level of aggregation in the input-output tables as an obstacle.

[7] Avoided emissions are not aggregated with other emissions because this would be inconsistent with the calculation of the GHG targets. This is explained further in Section 7.2.4.

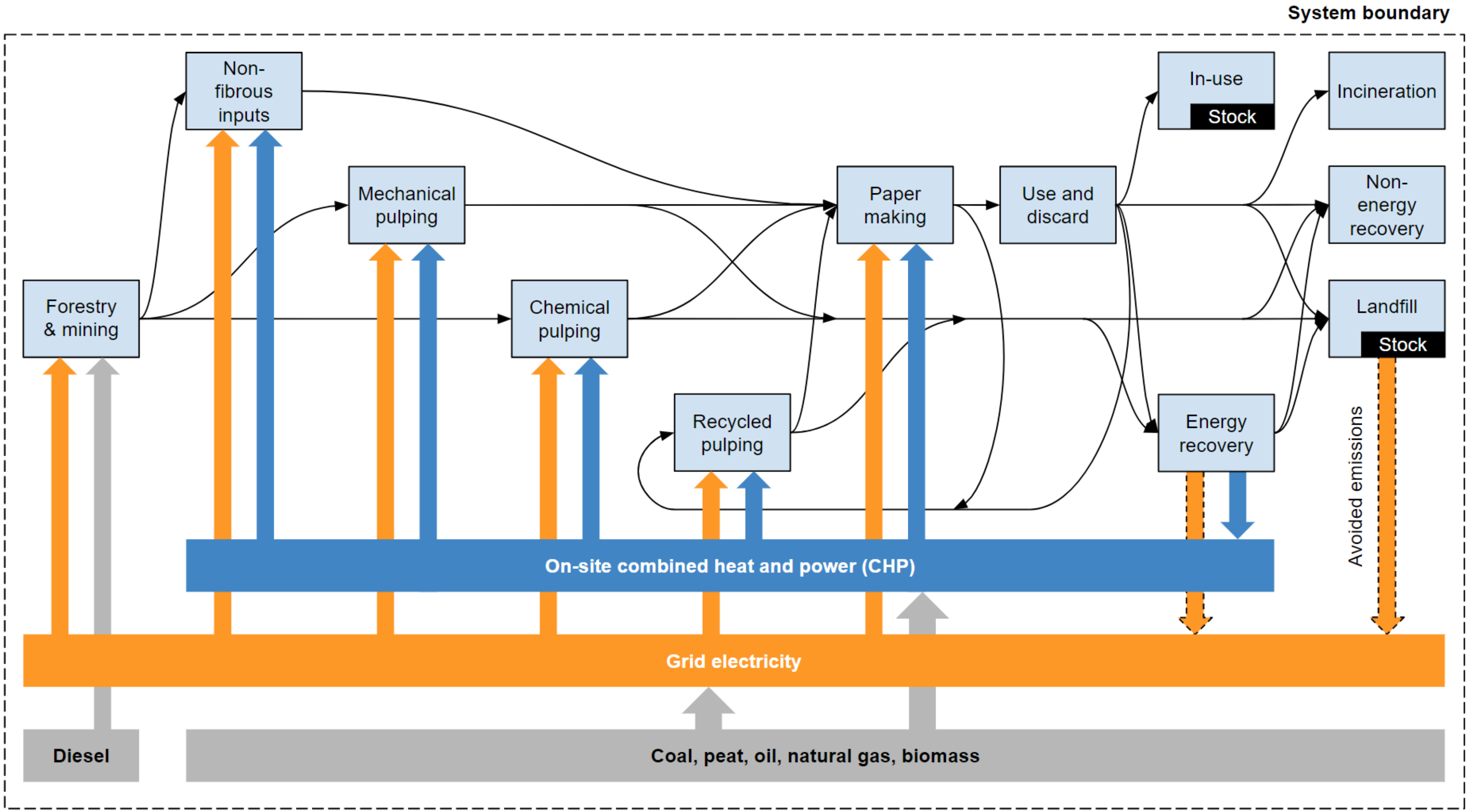

Figure 4-4. Process diagram of material and energy flows in the global paper life cycle.

4.5.2 Material flow analysis

The analysis starts with an assessment of material flows, which are estimated from a variety of sources, 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 FAO (2016). The flows in each life cycle stage are further specified using yield ratios, waste intensities, and waste treatment intensities from the literature and industry reports.

The material flows for the "W-a-R" scenario are estimated by recalculating the material balance under maximum use of waste as a resource. The recovery potential of waste is identified through a review of waste treatment options including recycling (substituting the original material), non-energy recovery (substituting other materials), and energy recovery (substituting fuels). The recovery potential is quantified as a numerical value between 0 and 1 and measured for E-o-L discards, black liquor, recycling sludge, papermaking waste, paper in sewage, sludge and rejects, causticizing wastes, and boiler ash.

4.5.3 Energy and emissions

Energy use and emissions are calculated based on the material balance. The energy used for extraction activities is calculated based on virgin fibre volumes and specific energy consumption (SEC) values. The electricity and heat demand for paper, pulp, and print are based on reported aggregate consumption, SEC values, and material flows. The fuels for on-site electricity and heat generation and the amount of bought electricity are derived from IEA (2016a). The CI of bought electricity is based on the global average fuel mix (IEA 2015a, 2015b).

Organic carbon flows from landfill are calculated using the default IPCC methodology (Pipatti and Svardal 2006) which describes landfill emissions as a function of landfill properties, waste properties, and the year of disposal of the waste. The calculation of organic carbon stocks covers long-term use of paper products, carbon storage in landfills, and repeated use of fibres (recycling). Changes in forest carbon stock could not be estimated due to a lack of consistent data on current forest carbon stocks, a lack of data regarding drivers of deforestation, and large uncertainties regarding alternative land use.

The use of waste from the paper sector is assumed to displace the use of high carbon fuels and therefore "avoid" emissions. Avoided emissions are calculated for energy recovery of E-o-L discards and landfill gas. The relevant electricity flows are indicated with dotted arrows in Figure 4-4 because they fall outside of the system boundary. Avoided emissions are calculated by multiplying the energy flows with the CI of the global average electricity mix based on IEA (2015b). For reasons listed in the preceding paragraph, the impact of forestry could not be accounted as avoided emissions (though this is common in LCA studies focusing on the national or sub-national scale).

4.5.4 Scenarios and demand

The emissions projection is based on three scenarios that reflect different levels of commitment to improved material and energy use. The REF scenario is largely based on the extrapolation of current trends and does not foresee increased climate change mitigation activities. The IE scenario reflects a heightened concern with climate change and more GHG reduction efforts. The very optimistic “W-a-R” scenario assumes full utilization of waste, radical changes in energy use, and near-perfect landfill practices.

All scenarios are run with the same paper demand projection. The projection is based on expected per capita consumption of different grades in two country groups (OECD and non-OECD). The projection considers demand saturation in OECD countries and substitution of graphic paper with electronics in all countries. For some grades, in non-OECD countries, demand is expected to grow proportionally with income. The demand projection includes a low, middle, and high estimate to account for uncertainty.

4.5.5 Data issues and uncertainty

Data quality and availability, in particular for waste generation and treatment, proved restrictive. Detailed waste data is reported mostly by the private sector but likely to be biased towards better performing companies. Besides, private sector reporting is likely to categorise operations with very modest benefits (if any) such as “landscaping” or “landfill cover” as genuinely beneficial recovery operations. Some data is available from national reports, but these tend to be outdated and limited to a few countries.

Energy data for the pulp and paper sector is very difficult to interpret due to the use of Combined Heat and Power (CHP). The data by the International Energy Agency (IEA) follows a reporting standard that does not specify fuel inputs for the on-site generation of electricity or heat that is sold (i.e. it only covers fuel inputs to heat used on-site). The total energy balance therefore relies on several assumptions. The data is cross-checked with a bottom-up estimate of energy use that is based on SEC values.

The allocation of emissions to grid electricity is based on power sector electricity outputs only. Emissions in the pulp and paper industry are allocated to heat and electricity based on energy content. The analysis uses global average values for grid electricity and global average fuel mixes for on-site generation of electricity and heat. This means that the conclusions only hold for the global level; at smaller scales, the carbon intensity of energy supply can be very different. The purpose of the thesis, however, is to show total global benefits and not local ones.

An uncertainty analysis is conducted for each stage of the analysis: the MFA, the recovery potential calculation, the calculation of current emissions, and the calculation of future emissions. The focus is on parametric uncertainty. For the material balance, the impact of uncertainty in the following parameters is quantified: pulping yield ratios, waste intensities, and net addition to stock. The recovery potential analysis quantifies uncertainties related to the recovery potential of causticizing waste.

For the emissions modelling, the impact of several parameter sets instead of individual parameters is quantified. The parameter sets cover the SEC values, the CI values, and the parameters for calculating emissions from landfill. Uncertainty ranges are taken from the literature where possible. Uncertainty analysis is also applied to account for the different possibilities for shifting between grid electricity and on-site generation in response to reduced energy recovery from black liquor in high recycling scenarios.

4.6 Greenhouse gas targets

4.6.1 Overview of identified targets

Political and scientific agreement has been reached over how much carbon may be emitted globally up to 2050 in order to limit climate change to acceptable levels. However, an abatement target for the paper life cycle, or any other material life cycle, is lacking. The focus of the climate change negotiations is on *who* needs to abate carbon; the subdivision of the carbon budget by sector, industry, or material is a related but unanswered question. An additional challenge is posed by the trade-off between long-lived CO_2 emissions and the more powerful but short-lived CH_4 emissions.

Table 4-2. Two climate change abatement targets for the impact assessment.

Target	Reference	Forecast	Criterion
CO_2 only	Paper life cycle CO_2 emissions in 2012 are A% of global CO_2 emissions in 2012	Cumulative paper life cycle CO_2 emissions in 2013-2050 are B% of the CO_2 budget for 2013-2050 for < 2 degrees warming	B ≤ A
All GHG	Paper life cycle GHG emissions in 2012 are X% of global GHG emissions in 2012	Paper life cycle GHG emissions in 2050 are Y% of global GHG emissions in 2050 for < 2 degrees warming pathway	Y ≤ X

The thesis suggests a *proportional* target, which implies the paper life cycle is not to exceed its current share in annual emissions. Table 4-2 shows two climate change targets for long-lived and short-lived gases. The first target focuses on CO_2 emissions and is based on cumulative emissions from 2013 till 2050 because the impact of CO_2 on warming is largely proportional to cumulative emissions. The second target focuses on total GHG emissions and is based on annual emissions to account for the short-term impact of CH_4 on peak warming. The targets are further explained and justified in the following two sections.

4.6.2 A proportional target

There is a global consensus among policymakers to limit global average temperature increase to "well below" 2 degrees above pre-industrial levels (UN 2015b). This can be translated into a carbon budget of 870-1,240 Gt CO_2 for the period 2011-2050 (Clarke et al. 2014; Meinshausen et al. 2009). Höhne et al. (2014) and Clarke et al. (2014) suggest allocation of regional carbon budgets may be based on *equity* or *cost-effectiveness*. Equity considerations include *responsibility*, *capability*, and *equality*.

- *Responsibility* is about past emissions. The countries or regions with the highest cumulative emissions should make the largest cuts.
- *Capability* is about the ability to reduce emissions. The countries that have the capacity to abate carbon should do so first.
- *Equality* is about equal shares per person. Every country is entitled to its share of the carbon budget based on the number of inhabitants.
- *Cost-effectiveness* is about reducing the overall cost of mitigation. Mitigation should occur first where this can be achieved cheaply.

Responsibility and equality have a social component that cannot be interpreted for the paper life cycle. Capability or cost-effectiveness can be applied to set targets for sectors or materials but this requires an extensive comparison of all sectors or materials.

An alternative and very simple principle is *proportionality*. This implies that every emission source must reduce its output of GHGs proportionally with the required global reductions. It is easy to apply and interpret and, if applied to all sectors or life cycles, would lead to consistent modelling outcomes. There is one caveat: under low paper demand, the targets may be easily reached, but consumers are still spending their money somewhere, possibly on materials that are more harmful than paper.

The principle of proportionality is implicit in Allwood et al. (2010); the authors argue that the minimum global reduction target of around 50% by 2050 equally applies to the industrial sector because any less stringent target would lead to even higher and probably unfeasible reduction requirements in other sectors. The thesis follows the same logic but does a more precise calculation and accounts for the difference between short and long-lived GHGs, which is explained in the next section.

4.6.3 Cumulative and annual target

For CO_2 and other long-lived gases, there is near-linearity between cumulative emissions and temperature response due to the interaction between several feedbacks in the climate system (Stocker 2014). Methane, a short-lived gas, has a strong temperature response shortly after it has been generated. The contribution of CH_4 to peak global warming therefore strongly depends on when it is emitted (Smith et al. 2012). On a 20 year basis, the Global Warming Potential (GWP) of CH_4 is equivalent to 84 units of CO_2 but on a 100-year basis, it is equivalent to 28 units of CO_2 (Myhre et al. 2013, p. 714).

The non-linearity of the contribution of short-lived gases poses challenges for establishing a single GHG target. The carbon budget only refers to carbon emissions but is calculated based on scenarios that include CO_2 and non-CO_2 gases. Different trajectories for CO_2 and non-CO_2 gases may yield the same level of warming, which leads to large uncertainty in the carbon budget: the 2011-2050 budget ranges from 870 to 1,204 Gt CO_2. The associated annual GHG emissions (including non-CO_2 gases) in 2050 are 16-22 Gt CO_2e based on a 100-year time window for CH_4 (Clarke et al. 2014, p. 431).

Cherubini (2016) suggests expressing long-lived gases in CO_2 equivalents and short-lived gases in CH_4 equivalents. This is a fruitful approach for comparative LCA. However, this approach does not work when defining budgets because the cumulative impact of short-lived gases depends on when the emissions occur. The thesis therefore opts for a focus on *cumulative* emissions for long-lived gases in the period 2013-2050 and a focus on *annual* emissions of aggregate long and short-lived gases in 2050 (when peak warming occurs). Appendix E shows the calculation of the two targets for the REF scenario.

4.7 Conclusions

This chapter outlined the methods and context of the research. It provided an overview of the history and context of paper and its main environmental impacts. It explained the concept of climate change and derived a GHG emission target for the paper life cycle based on the global carbon budget for keeping the average global surface temperature increase below 2 degrees.

The thesis investigates the climate change mitigation benefits of more efficient and circular use of materials in the global paper life cycle through quantitative modelling of material flows, energy flows, and GHG emissions. The model calculates emissions from 2012 to 2050 based on a paper demand projection and several scenarios that reflect different levels of fulfilment of the recovery potential of waste.

The next chapters describe the methods and data in detail, present the results, and discuss the results. Chapter 5 focuses on current material flows and Chapter 6 on the use of waste as a resource. Chapters 7 and 8 estimate respectively current and future emissions from the global paper life cycle.

5 Material flows in the global paper life cycle

5.1 Introduction

The empirical analysis starts with a material flow analysis of the global paper life cycle. A material balance helps identify options for reducing virgin material inputs and associated environmental impacts. Most importantly, it serves as the basis for further analysis of improved material use and climate change mitigation. 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 flow analyses for pulp and paper in the literature were listed in Table 4-1. Most of the MFAs are at the national level (Chen et al. 2016; Cote et al. 2015; Fleiter et al. 2012; Hekkert et al. 2000; Krones 2016; Sundin et al. 2001) or for a selection of countries (CEPI 2016). There is only one MFA at the global level but it is highly aggregated (Allwood et al. 2010). The aim of this chapter is to produce a detailed global material balance of paper flows like those published for steel (Cullen et al. 2012) and aluminium (Cullen and Allwood 2013; Liu et al. 2012).

The material balance is a useful contribution for two reasons. First, it is used in this chapter for comparing and analysing efficiency and circularity metrics. The chapter goes back to the idea of waste as a potential resource, described in Chapter 3, to improve these metrics. The potential for recycling of E-o-L discards is calculated to contextualize various metrics for circularity. The chapter also shows that efficiency metrics are more meaningful when contextualized with the recovery potential of "lost" materials.

Second, the material balance serves as a basis for more advanced analyses that may consider energy, water, emissions, land use and other environmental impacts of the global paper life cycle. LCA requires a material balance to start with, and no balance is currently available for the global paper life cycle. Chapter 6 uses the balance to review options for using waste as a resource; Chapter 7 uses the balance to calculate current GHG emissions; Chapter 8 uses the balance for projecting future GHG emissions.

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, in Section 5.3, and a discussion of recycling metrics, efficiency metrics, and appraisal of waste recovery in Section 5.4.

5.2 Methods and data

5.2.1 Overview

The material balance indicates the origin, destination, and size of global flows of wood, pulp, paper, and waste paper for 2012. The data is 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 FAO (2016). The flows in each life cycle stage are further specified using parameters from the literature and industry reports. All MFA parameters are summarized in Appendix A-1.

Material outputs that are not primary products (pulp or paper) are consistently referred to as waste in this analysis. Industrial waste includes papermaking waste and pulping waste. Consumer waste includes E-o-L discards and paper in sewage. 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 consumer waste paper that is neither recycled nor ends up in the sewer is referred to as residual waste paper.

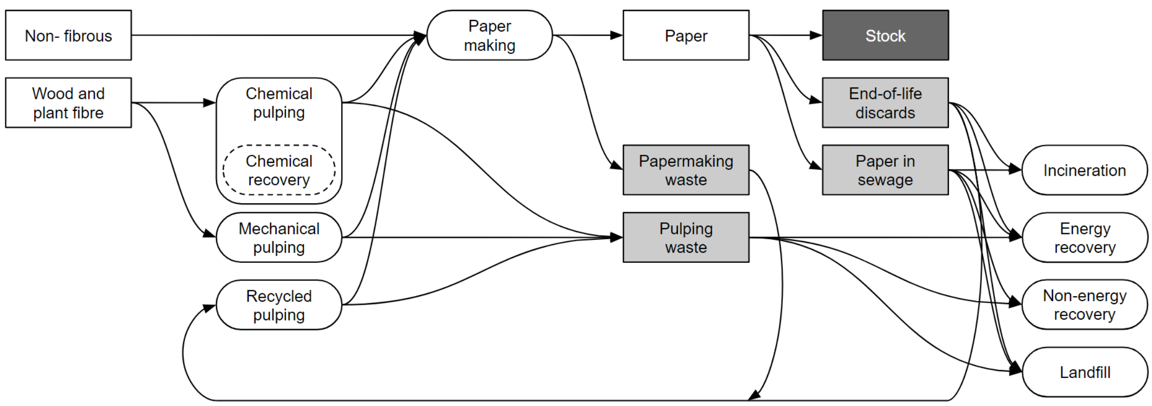

Figure 5-1. The paper life cycle.

Figure 5-1 displays the main stages in the life cycle of paper from harvest to waste treatment. Paper is produced from wood, non-wood fibre (plants), waste paper, and non-fibrous material. Wood is converted into mechanical, chemical, and semi-chemical wood pulp. Semi-chemical 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. The use of pulping chemicals is not included in the MFA.

Waste paper is collected from households and businesses (not shown in the figure). Local governments are generally in charge of collection from households and small businesses. Larger businesses have individual contracts for waste collection, with high levels of separation of paper from, for example, large offices or packaging providers. Source separation is generally preferred over separation in recycling facilities. Ideally, various grades of paper and board are source separated to avoid contamination of white paper with brown grades (Stawicki and Read 2010).

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 5-1). After consumption, paper is either added to stock, or becomes consumer waste, which may end up in recycling, incineration (with or without energy recovery), landfill, or the sewer. The paper sector generates industrial waste which includes paper for recycling and pulping waste (mostly black liquor and sludge). The latter is used for energy recovery, non-energy recovery, or landfilled.

5.2.2 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 5-1). Martin et al. (2000) suggest ranges of yield ratios for pulp relative to the wood input for mechanical pulping and chemical pulping. Other references such as MacLeod (2007) and Briggs (1994) suggest similar values. This chapter uses the median values from Martin et al. (2000). The yield ratios for non-wood pulping are assumed similar to those for chemical wood pulping.

The yield ratio of recycled pulping is dependent on the quality and deinking requirements of the relevant paper grade. The average weighted global recycled pulping yield ratio is calculated based on recycled content (see Table 5-2), production volumes per grade, and the recycled pulping yield ratio of each grade (Stawicki and Read 2010). Between 0% and 50% of recycled inputs to packaging is assumed to be deinked. The full calculation is shown in Appendix A-2. The quantity of non-fibrous filler materials is calculated from the final difference between pulp inputs, conversion losses, and paper outputs in papermaking. It is cross-checked with European data (CEPI 2013a).

Table 5-1. Yield ratios for pulping and papermaking.

Parameter	Range	Reference	Value used	Notes
Chemical pulping	0.40-0.55	(Martin et al. 2000)	0.48	Median value
Mechanical pulping	0.90-0.95	(Martin et al. 2000)	0.93	Median value
Recycled pulping	0.73-0.89	(Stawicki and Read 2010; FAO 2016)	0.81	Calculation in Appendix A-2
Papermaking	-	(Eurostat 2016; FAO 2016)	0.95	-

The yield ratio for papermaking is 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 EU28 (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 IEA (2007a, p.264) and used by Allwood et al. (2010). It should be noted that this waste results mostly from paper converting and printing and does not constitute an inefficiency in paper mills.

5.2.3 Production matrix

Table 5-2 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 FAO (2016). The total pulp and filler requirement is adjusted for losses in papermaking. The values 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 CEPI (2013a) and the yield ratio for recycled pulping. Each fraction of recycled pulp is scaled downwards based on the total amount of recycled pulp, to correct for the difference between European and global recycling levels.

Table 5-2. 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

Second, the fractions of non-fibrous material are approximations based on Cote, Poganietz, and Schebek (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. Finally, the further input to newsprint is assumed to be mechanical pulp, and for printing + writing and sanitary + household paper it is chemical pulp. These assumptions are in accordance with Laurijssen et al. (2010). The remaining quantity of mechanical pulp is allocated to packaging. The remainder of chemical pulp is allocated to "other".

5.2.4 Consumer waste and stock

Table 5-3 displays the relevant parameters for calculating consumer waste flows. Each year, consumers add some newly purchased paper to stock and dispose of some of their purchases or old stock. Net addition to stock (NaS) is calculated in two ways. First, a fraction is calculated based on product lifetime distributions (Müller et al. 2014). A Weibull distribution of total annual waste paper outputs in Germany is constructed based on the parameters determined by Cote et al. (2015).

Table 5-3. Parameters for net addition to stock and waste treatment.

Parameter	**Value**	**Reference**
NaS (fraction of consumption)	0.09 (0.06-0.12)	(Cote et al. 2015; IEA 2007a; FAO 2010a)
Fraction of consumption to sewage	0.03	(Cote et al. 2015)
Fraction of residual waste to energy recovery	0.12	(OECD 2017a; FAO 2016; NBSC 2013)
Fraction of residual waste to incineration	0.08	

Second, based on FAO (2010), a decay model is used, with a half-life of two years for all paper products. For both methods, the NaS 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 NaS fractions of 0.06 and 0.09 respectively.

IEA (2007a, p.264) suggests a value of 0.12-0.15 but does not explain how this was estimated. Because of the discrepancy with the results from the more advanced estimations only the lower value of 0.12 is considered. The total range thus becomes 0.06-0.12 and the used value is 0.09. A fraction of paper also ends up in sewage. The parameter for sanitary + household paper to sewage is derived from the fraction of toilet paper in total consumption reported for Germany (Cote et al. 2015).

It is assumed that all residual waste paper ends up as residual MSW. The quantities of residual waste paper per country are calculated from FAO (2016) and the parameters for NaS and losses to sewage. The residual MSW treatment fractions for energy recovery, incineration without energy recovery, and landfill (or other disposal) are obtained from OECD (2017) for three regions: OECD countries, China, and rest of the world. The global fraction is the weighted average based on residual waste paper generation in each region.

For China, the figures reported in OECD (2017) are based on the Statistical Year Book (NBSC 2013) but this reference covers waste from "main cities" only[8]. The fraction is therefore adjusted based on the percentage of people living in urban areas (according to the same source) and assuming rural waste management consists of landfill only. For the rest of the world, the total incineration fraction is assumed to equal that of China, with an equal split between incineration with and without energy recovery.

5.2.5 Industrial waste

The fate of industrial waste from pulping is extrapolated from industry sustainability reports and annual reports. Table 5-4 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 (t) 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

[8] Bo-Feng et al. (2014) collect landfill data based on a survey and find that the Statistical Yearbook underreports volumes of waste to landfill by a factor of 2. This confirms that the data from the Statistical Yearbook do not cover all of China.

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 et al. (2009) list many pre-treatments for energy recovery but company reports tend not to differentiate such pre-treatments.

Table 5-4. Paper production and industrial waste flows as reported by major paper producers.

Company	Country	Paper production (Mt)	Industrial waste treatment (Mt)	
			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*	0.6	0.5
Kimberly Clark	United States	4.8	0.3	0.6
	Total	42.2	2.6	2.7

*Based on reported capacity and assumed 90% capacity utilization.

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 is 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 fraction of waste that is burned but remains as ash is included with non-energy recovery or landfill. The figures reveal significant differences in performance between the companies. On average 0.06 (0.04-0.12) t/t of paper and cardboard production goes to non-energy recovery and 0.06 (0.04-0.11) t/t goes to landfill.

5.2.6 Uncertainty

The data from various sources is compatible to the extent that it allows construction of a complete and consistent material balance. The apparent match between parameters and values from independent data sources suggests the results are valid. However, primary inputs and final outputs cannot be corroborated using the mass balance principle. They include non-fibrous inputs, 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 and amounts to 15.1% of final paper and cardboard production in 2012. This value is very close to the amount of non-fibrous materials (14.9%) reported for CEPI countries (CEPI 2013a).

Waste treatment practices are likely to improve in the near future and should be updated accordingly. Industrial waste treatment figures were derived from four large companies only and may reflect the better performing fraction of the industry. More data is likely to become available as part of a general trend towards greater private sector transparency. More data may also be gathered through case study research. The figures for municipal waste generation also need improvement since waste management practices in developing countries are not widely reported. The paper to sewage ratio was extrapolated from country data and may be updated when more data becomes available.

The uncertainty of the 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 chapter 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 NaS affects the residual waste paper treatments, and the parameters for industrial waste treatment affect the total quantities going for non-energy recovery and landfill. All flows are reported to the nearest 1 Mt.

5.3 Results

Figure 5-2 shows a Sankey diagram of global paper flows in 2012. The diagram displays the flows of material from extraction (left) to E-o-L (right). The flow width reflects the quantity. Pulping waste is the sum of pulping losses and are used for on-site energy recovery, non-energy recovery, 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 enters the same recycling loop as consumer waste paper. Appendix A-3 contains the detailed material balance data including equations.

Table 5-5. Material flows and uncertainty ranges.

Material flow	Value (range) (Mt)
Virgin fibrous inputs	347 (307 - 411)
To stock	36 (24 - 48)
Consumer waste to energy recovery	20 (19 - 22)
Consumer waste to incineration	14 (13 - 14)
Consumer waste to landfill	130 (116 - 145)
Industrial waste to energy recovery	158 (133 - 178)
Industrial waste to non-energy recovery	24 (16 - 48)
Industrial waste to landfill	24 (16 - 44)

Table 5-5 shows the used values and the uncertainty ranges for several material flows based on the sensitivity analysis. The uncertainty ranges are largest (relative to the used value) for non-energy recovery and landfill of industrial waste. The ranges are skewed towards 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 analysing potential improvements. Over time, the balance may be updated and improved with new data.

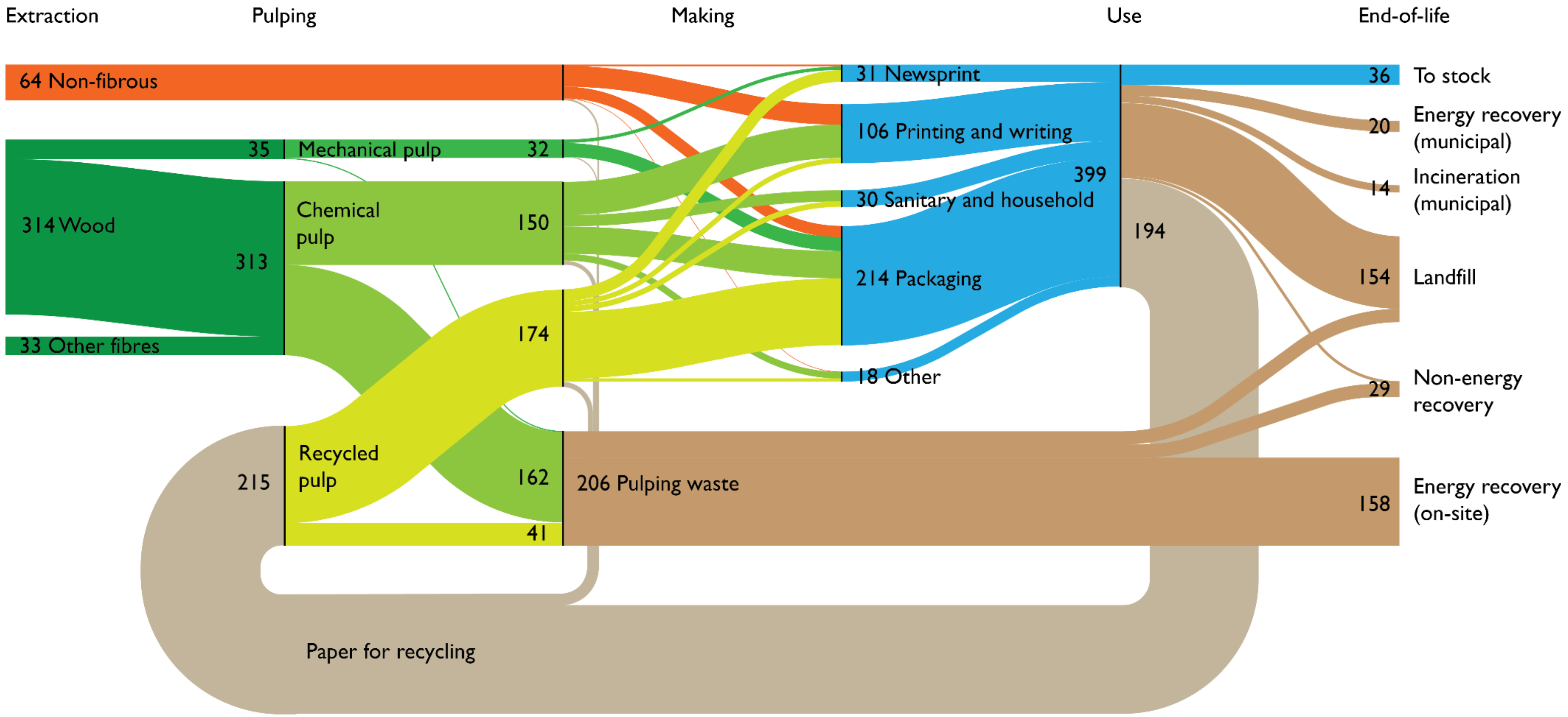

Figure 5-2. Global paper flows in 2012 in Mt.

5.4 Discussion

5.4.1 Recycling metrics

The material balance in the preceding section provides a detailed overview of the global paper life cycle. The circularity of the material flows can now be calculated using any of the three circularity metrics that were provided in Table 2-1 in Section 2.4.2. Most often, circularity in the paper life cycle is calculated using the Collection Rate (CR), which divides paper for recycling by total production of paper and cardboard (Ervasti et al. 2016). For the global paper life cycle, this results in a CR of 54%.

However, the CR is an inconsistent metric 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 stage (total production or consumption). The metric fails to reflect the purpose of recycling, which is the reduction of impacts by displacing virgin production and reducing landfill (Geyer et al. 2016). The CR reflects avoidance of landfill of consumer waste but the same material may still end up in landfill as pulping waste.

Nor does the CR show the avoidance of virgin inputs, because it is not clear to what extent the collected paper is actually used. The avoidance of virgin inputs can only be shown by focusing directly on the extraction stage of the life cycle. The Recycled Input Rate (RIR) is therefore more meaningful: it compares waste paper inputs (paper for recycling) with total inputs (paper for recycling plus virgin fibrous harvest). The value of the RIR is 38% whilst the CR is 54%. The RIR is lower because it accounts for the substitution ratio between secondary and virgin inputs.

The substitution ratio depends on the relevant 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.

Virgin pulps may also be substituted by non-fibrous inputs which would affect the RIR. It is beyond the scope of the thesis to discuss desirable levels of substitution of fibres by non-fibrous material. Another caveat is the emphasis on total secondary materials inputs: the metric could be inflated by counting additional secondary material that is not actually processed. The RIR should therefore be used with care (Chen 2013).

5.4.2 Maximum virgin input reduction

Recycling metrics that are expressed as percentages may create the false impression that a 100% recycling of paper is technically possible. In reality, some paper is added to stock and some is irretrievably lost in the sewer. These unavoidable losses should be taken into account when analysing recycling. Table 5-6 shows a calculation of the maximum potential for recycling, the associated virgin material requirements, and the values for the CR and RIR. The lower and upper bounds of each figure are based on variability in NaS. The calculation is explained in Appendix A-4.

Table 5-6. Calculation of the maximum CR and RIR based on the recovery potential of waste.

<table>
<tr><th></th><th>Scenario
Flow</th><th>Low
(NaS = 0.12)</th><th>Middle
(NaS = 0.09)</th><th>High
(NaS = 0.06)</th></tr>
<tr><td rowspan="3">Recycled input</td><td>E-o-L discards for recycling (Mt)</td><td>339</td><td>351</td><td>363</td></tr>
<tr><td>Papermaking waste for recycling (Mt)</td><td colspan="3">21</td></tr>
<tr><td>Total paper for recycling (Mt)</td><td>360</td><td>372</td><td>384</td></tr>
<tr><td rowspan="3">Pulp input</td><td>Potential recycled pulp supply (Mt)</td><td>263</td><td>272</td><td>280</td></tr>
<tr><td>Additional chemical pulp (Mt)</td><td>77</td><td>70</td><td>62</td></tr>
<tr><td>Additional mechanical pulp (Mt)</td><td>17</td><td>15</td><td>13</td></tr>
<tr><td rowspan="3">Virgin input</td><td>Fibre for chemical pulp (Mt)</td><td>160</td><td>145</td><td>130</td></tr>
<tr><td>Fibre for mechanical pulp (Mt)</td><td>18</td><td>16</td><td>15</td></tr>
<tr><td>Total virgin fibre (Mt)</td><td>178</td><td>161</td><td>145</td></tr>
<tr><td rowspan="2">Metrics</td><td>Collection Rate (CR)</td><td>90%</td><td>93%</td><td>96%</td></tr>
<tr><td>Recycled Input Rate (RIR)</td><td>67%</td><td>70%</td><td>73%</td></tr>
</table>

The calculation shows that about 351 Mt (± 12 Mt) of recyclable E-o-L discards and 21 Mt of papermaking waste are potentially available for recycling. This large supply of paper for recycling can only be used with improved control of contamination. Pivnenko et al. (2015) show 51 contaminants can be found in paper which may pose challenges for recycling. Contamination may exclude certain uses of paper for recycling or lead to lower pulping yields (Pivnenko et al. 2016). The calculation assumes the lower recycled pulping yield ratio of 0.73 to reflect the increased need for deinking.

The resulting recycled pulp supply is 272 Mt (± 8 Mt). The associated virgin input requirements can be calculated assuming a fixed non-fibrous content fraction and a fixed ratio between mechanical and chemical pulp for virgin fibrous inputs. Under these assumptions, the technical limit of the RIR is 67-73%. In other words, only 67-73% of fibrous inputs can be supplied by waste paper, the rest needs to be virgin fibres. This is more meaningful than the associated CR of 90-96% because the RIR clearly shows that the use of secondary fibre can still be doubled (the current RIR is 38%) but that the use of trees in papermaking cannot be phased out completely.

5.4.3 Material efficiency metrics

Another way to improve paper production is by increasing the material efficiency of conversion processes because 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 (0.90-0.95) than chemical pulping (0.40-0.55). However, the wastes from chemical pulping are used for energy recovery 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 but basic material efficiency calculations ignore the role of waste utilization. The standard metric for material efficiency, shown in Equation 2-1 in Section 2.4.2, only considers material used in the product and material supplied to it. However, the example of the paper industry shows that waste materials can be used beneficially for energy recovery inside the facility that produces the waste. In addition, waste can be used for non-energy recovery applications like composting or land spreading.

Material efficiency metrics would be more useful if they counted in all these types of waste use. In other words, the potential of the waste to be used as a resource should be considered, which was explained in detail in Chapter 3. This may include applying the reuse (or recovery) potential indicator by Park and Chertow (2014). A more complex efficiency metric that directly includes the reuse potential of waste might lack transparency. Instead, the following pieces of information may be presented separately.

- Material efficiency of the process
- Reuse or recovery potential of the waste
- Fulfilment of the reuse or recovery potential

There is a trade-off between the above three elements. For example, a more efficient process may yield less attractive waste with a low recovery potential. The challenge of fulfilling the recovery potential should be compared against the challenge of avoiding the waste in the first place (this, in fact, will be one of the main findings of the thesis).

The assessments of recycling rates and material efficiency both confirm the usefulness of the concept of waste as a potential resource. For consumer waste, the potential-based thinking helps identify the extent to which recycling can help reduce virgin material requirements. For joint production of product materials and waste, the potential use of waste may contextualize overall efficiency of the process. In summary, the performance of a system of production and consumption ought to be judged by the extent to which materials that can be used as resources are actually used as resources.

5.5 Conclusions

This chapter presents a detailed calculation of material flows in the global paper life cycle. 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 E-o-L waste treatment. The discussion of environmental performance metrics led to three distinct conclusions.

- 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 recycled input rate which divides paper for recycling by total fibrous inputs.
- Recycling metrics are more meaningful if the achievable potential is known. The potential use of waste is constrained by net addition 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.
- The reuse potential indicator (Park and Chertow 2014) may contextualize material efficiency metrics. A process that generates waste with a higher reuse potential can be more efficient overall. Both the waste reuse potential and its actual fulfilment should be considered.

Future work could use the material balance for a variety of environmental assessments. The next chapter will use the material balance to gauge the system-wide impacts of fulfilling the recovery potential of all waste in the global paper life cycle. The chapters after that will focus on the GHG emissions from the global paper life cycle.

6 Recovery potential of paper life cycle waste

6.1 Introduction

The preceding chapter established a material balance of the global paper life cycle and raised questions regarding recycling and material efficiency. This chapter goes one step further and explores the limits of efficient and circular material use. How do the limitations to efficiency and circularity, listed in Chapter 2, play out for the paper life cycle? Is it possible to reduce landfill to zero and phase out virgin material extraction?

To address these questions, the chapter operationalizes the potential-based concept of waste described in Chapter 3. It uses the logic of the "reuse potential" indicator (Park and Chertow 2014) but uses the term "recovery potential" instead for consistency with the WFD (EC 2008). Recovery includes recycling (substituting the original material), non-energy recovery (substituting other materials), and energy recovery (substituting fuels).

The purpose of this chapter is to assess the system-wide impacts of fulfilling the recovery potential of all waste in a single material system. The material balance in the preceding chapter is redrawn based on complete fulfilment of the recovery potential of all waste flows. The system-wide impact are measured as the landfill intensity and RIR. The balance is used for modelling the climate benefits of efficiency and circularity in Chapter 8.

Earlier work focused on waste management in the pulp and paper sector in the United States (Bird and Talberth 2008) and the EU (Monte et al. 2009). Suhr et al. (2015) outlined BATs for the European pulp and paper sector and Bousios and Worrell (2017) reviewed alternative feedstocks and waste treatment options for paper mills. None of these studies covers all stages of the paper life cycle nor quantifies the recovery potential of the technologies – this chapter addresses these gaps.

The next section discusses the methods and data for calculating current recovery and the recovery potential. Section 6.3 presents the results in two Sankey diagrams. Section 6.4 reflects on the conditions for using waste as a resource and the policy implications of the findings.

6.2 Methods and data

6.2.1 Recovery potential indicator

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

The thesis takes a slightly different approach. It has a larger scope but less detail than Park and Chertow (2014) and analyses all waste flows of the global paper life cycle. The assessment focuses on 1) the types of waste and the variety of waste recovery options and 2) the system-wide changes in material flows if the recovery possibilities are fully exploited. It applies the recovery potential to all waste flows in the global paper life cycle and optimizes the life cycle from a materials perspective.

Two methods are used for assessing the recovery potential: a review of technologies that are currently available or potentially available by the year 2050 and an assessment of benchmark performance. The review focuses on technologies and practices that may be commercially available by the year 2050, and which safely substitute a virgin alternative. Information regarding waste recovery options is compiled from the academic and grey literature and includes technologies that are currently in the research and development phase and those that are commercially applied.

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

6.2.2 Current recovery in the paper life cycle

The identification of a recovery potential requires first of all data regarding the type and quantity of waste that is currently generated and recovered or disposed. This section explains 1) the categories of waste, 2) the calculation of waste generation figures, and 3) the calculation of waste treatment figures. Figure 6-1 displays the global paper life cycle with a detailed breakdown of solid waste generation and treatment. The figure is an extended version of Figure 5-1 in the preceding chapter and includes five categories of industrial waste and two categories of consumer waste (E-o-L discards and paper in sewage).

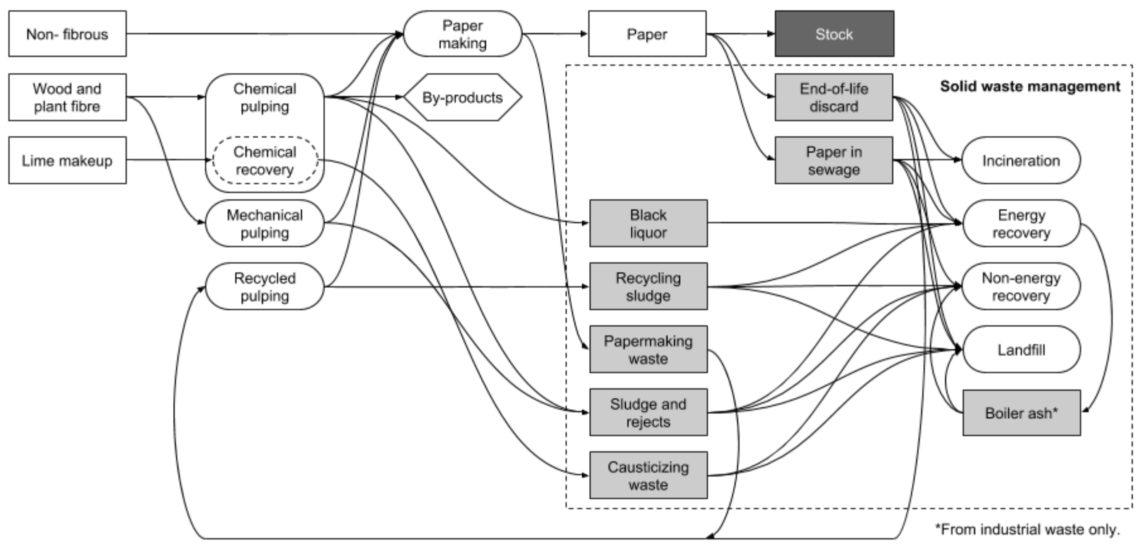

Figure 6-1. The paper life cycle with a detailed breakdown of solid waste management.

The industrial waste is difficult to categorize because different data sources use different categories and waste from different processes may be mixed during waste (water) treatment at the paper mill. Waste is nevertheless aggregated in the following categories based on their properties and volume.

1. *E-o-L discards* cover all the solid paper waste discarded from residential and commercial sectors, excluding the paper industry. It excludes net addition of paper to stock and toilet paper, which ends up in sewage. It is often recycled but may be contaminated.
2. *Paper in sewage* consists of toilet paper that ends up in the sewer system and is treated as sewage. It is considered separately because sewage receives a different waste treatment than E-o-L discards: these fibres are not available for recycling.

3. *Black liquor* is produced during the chemical (Kraft) pulping process and contains the lignin and hemicellulose separated from the cellulose for paper. It also contains inorganic chemicals used for pulping, but only the organic fraction is discussed in this chapter. Black liquor has a high heating value and is virtually always used for energy recovery (Naqvi et al. 2010).
4. *Recycling sludge* is generated during pulping and deinking of paper for recycling. It contains fibres, fillers, inks, adhesives, and inorganic materials. It is considered separately from other sludge because it has higher levels of contamination. It has a low heating value (Makinen et al. 2013; Monte et al. 2009).
5. *Papermaking waste* consists of losses from the converting of pulp and non-fibrous material into paper and the conversion of paper into paper products. It is a clean and convenient source of paper for recycling (Stawicki and Read 2010).
6. *Sludge and rejects* cover the aggregate losses from chemical pulping (excluding black liquor and by-products) and mechanical pulping. They are suspended in wastewater, have fibrous content, and a low heating value (Suhr et al. 2015).
7. *Causticizing waste* consists of inorganic sludge generated in the chemical recovery cycle. It includes green liquor dregs, lime mud, and slaker grits. These waste have high alkalinity and may be contaminated (Bird and Talberth 2008).
8. *Boiler ash* results from organic waste combustion. The focus of this chapter is on wood and sludge ash and it excludes mixed ash from co-firing of, for example, coal and wood. Boiler ash has a high alkalinity and is cementitious (Bird and Talberth 2008).

The figures for waste generation are calculated in four steps. First, the following flows are taken from Chapter 5: *E-o-L discards* and *papermaking waste*. Second, the waste from chemical pulping and the waste from mechanical pulping are further detailed and combined into the following flows:

- *Black liquor* is the proportion of chemical pulping waste that is not a by-product or part of sludge and rejects.
- *By-products* are mainly tall oil and turpentine. By-products are produced at 10-75 (50 typical) kg/t pulp (Suhr et al. 2015, p. 204).
- *Sludge and rejects* consist of two fractions of chemical pulping waste and all of the mechanical pulping waste. The two fractions of chemical pulping waste are Waste

Water Treatment Plant (WWTP) residuals, produced at a rate of 10 kg/t pulp (Suhr et al. 2015, p. 250), and screening rejects, produced at a rate of 2-20 (used value 11) kg/t pulp (Suhr et al. 2015, p. 251).

Third, causticizing waste consists of losses from the chemical recovery cycle and is compensated for with lime-make up. This flow is included as both an input and an output and leads to a larger overall waste generation than in Chapter 5. It is not part of chemical pulping waste because it results from a separate process. Causticizing waste is produced at an average rate of 30 (10-60) kg/t pulp (Suhr et al. 2015, p. 251).

Last, ash is included as a secondary waste from waste combustion and included as both an input and an output in the material balance. The quantity of boiler ash follows from the ash content of waste used for energy recovery, based on the following assumptions.

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

The current treatment of *E-o-L discards*, *papermaking waste*, and *paper in sewage* is estimated in Chapter 5. The waste treatment of the other waste flows is calculated in four steps.

1. Taking the total waste treatment intensities in kg/t paper for non-energy recovery and landfill from Chapter 5.
2. Estimating the fractions of non-energy recovery, energy recovery, and landfill for causticizing waste, boiler ash, and sludge and rejects based on the literature.
3. Calculating the quantities of boiler ash based on ash content of the relevant waste and the fraction of industrial waste to energy recovery.
4. Calculating the treatment fractions for recycling sludge by balancing waste treatment of all other flows, ash generation, and total waste treatment.

Because the data is very uncertain, the waste treatment fractions are rounded to quarters, except for the case of recycling sludge, since this is calculated from final differences. Below, the calculation of the treatment of the individual waste flows is discussed (steps 2 and 4).

- *Causticizing waste*. Bird and Talberth (2008) present US data gathered by NCASI for 1995 which shows 70% of lime mud, 95% of dregs, and 91% of grits go to landfill (or lagoon). Overall, 81% of these materials were landfilled. Data from the Finnish Forest Industries collated by Kinnarinen et al. (2016) suggests that 71% of dregs were landfilled in Finland in 2012. If the landfill rates of lime mud and grits have similarly improved, total causticizing waste landfill rates would be 61% in 2012 (71/95*81=61). However, the Finnish data represents above-average performance. It is assumed that approximately three quarters of global causticizing waste are landfilled.

- *Boiler ash.* The American Forestry and Paper Association (AF&PA) presented a report in 2002 which shows that about one third of boiler ash is recovered (Bird and Talberth 2008). In Canada, in 2002, about 80% of ash from pulp and paper mills was landfilled (Elliott and Mahmood 2006). In 2003, over half of wood ash from the pulp and paper industry in Finland was utilised (Emilsson 2006). Finland probably performs well above the global average, partly because of very little mixing of wood ash with coal ash. It is assumed that approximately half of wood and sludge ash from pulp and paper mills is used in non-energy recovery in 2012.
- *Sludge and rejects.* This waste covers mechanical pulping losses, Kraft rejects, and Kraft WWTP residuals and can also be categorized as WWTP residuals because they are suspended solids that first go through wastewater treatment. Bird and Talberth (2008) present data for WWTP residuals from a 2002 study by the American Paper and Forestry Association which suggests that 52% of the waste is landfilled, 22% is used for energy recovery, and 26% is applied to land or used for other non-energy recovery operations. It is assumed that globally one quarter is used for energy recovery and one quarter is used for non-energy recovery.
- *Recycling sludge.* The treatment fractions for this waste are based on the differences between final treatments of the total industrial waste flow based on the overall waste treatment intensities in Chapter 5 and the waste treatment of causticizing waste, boiler ash, and sludge rejects as described above. The calculation includes secondary waste in the form of ash from energy recovery. This implies that any increase in energy recovery entails an increase in the amount of waste that needs final treatment. The resulting fractions are 8% energy recovery and 50% non-energy recovery.

A number of smaller flows are not taken into account, such as fly ash from the recovery boiler, minor lime residues, and salt cake from chlorine dioxide production (Kinnarinen et al. 2016). Losses of pulping chemicals and ash from the combustion of materials other than the included waste are also excluded, as well as any waste from ancillary processes not described in Chapter 5. Bark and other wood waste fall outside the system boundary because they do not necessarily constitute process waste. When mills buy logs including bark (instead of chips) specifically for energy recovery purposes, the bark may be considered a fuel rather than an unintended process waste[9].

6.2.3 Waste recovery options

Waste recovery is categorized into recycling, non-energy recovery, and energy recovery. Table 6-1 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, E-o-L discards, is 0.9-1.7 t/t of virgin fibre (see Section 5.4.2).

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. All of the energy recovery options, apart from combustion, are either in the research and development stage or the pilot and demonstration stage, depending on the type of waste.

[9] In the energy analysis in Chapter 7, all bought waste will be defined as “bought fuel”.

Table 6-1. Waste recovery options for major waste flows in the global paper life cycle.

Type of recovery potential	Reuse option or application	E-o-L 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	Technolog y 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				CH_4, 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		

6.2.4 Matching waste flows and recovery options

The identification of the recovery potential of each waste flow is based on four main assumptions. First, all known technologies and practices, listed in Table 6-1, are assumed to be further developed in the next few decades and to become commercially available by 2050. Second, it is expected that improved contamination control allows for the functional and safe use of waste in non-energy recovery and energy recovery applications. Significant efforts would be required to achieve this in practice, including prevention (e.g. using different chemicals), removal (e.g. better deinking technology), constraining (e.g. encapsulated use of waste) and destruction of contaminants (e.g. thermal treatment). Third, for recycling, contamination is assumed to affect mainly the yield ratio of recycled pulping, because of the following issues.

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

These issues may be partly addressed through a greater extent of separate collection of paper instead of commingled collection (Miranda et al. 2013). However, increased recycling will inevitably require more thorough deinking and cleaning of recycled pulp, which reduces the pulping yield. Based on Chapter 5, the recovery potential calculation applies a lower pulping yield (73% instead 81%) under complete fulfilment of the potential for recycling.

Finally, the calculation excludes any restrictions on demand for waste inputs or recycled products. In reality, demand for recycled paper products may be limited because of qualitative losses. During recycling, fibres are damaged and lose flexibility and strength (Hubbe et al. 2007). Recycled paper products are therefore always of lower quality. Other limitations on demand are the limited number of recovery facilities, the transport costs of obtaining the waste, or negative attitudes towards waste and waste-based products. These factors, as well as contamination issues, are discussed further in Section 6.4.1.

Based on Table 6-1 and benchmark data, the following figures are identified for the recovery potential of the waste flows in the global paper life cycle.

1. *E-o-L discards* can be fully recycled but with aforementioned impacts on the recycled pulping yield. The benchmark CR is 91%, as reported in South Korea between 2012-2014 (FAO 2016)[10]. Using the global parameters for papermaking waste, NaS, and paper in sewage, this implies a fraction of 0.97 of E-o-L discards to recycling (see Appendix B-1 for the full calculation). The South-Korean performance is very close to the potential for recycling of 1.00 for E-o-L 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 treatments. The benchmark is 1.00 as evidenced by current practice in Germany (Wiechmann et al. 2013). The recovery potential for non-energy recovery and energy recovery is the same as the benchmark of 1.00. Direct use of sewage sludge on land is discouraged or prohibited in many countries because of negative impacts on soil quality (EC 2001a, 2001b). 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). Wiechmann et al. (2013) indicate incineration with phosphorus recovery as a preferred route.
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 transport 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

[10] 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.

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 suitable for recycling sludge include use as compost, fertilizer, aggregate, admixture, filler, or adsorbent. The combined recovery potential is therefore 1.00.

5. *Papermaking waste* is a clean and convenient source of recyclable material and, in Chapter 5, was assumed to be fully recycled. The current recovery level and the benchmark therefore equate to a recovery potential of 1.00.
6. *Sludge and rejects* can be used in a variety of ways but hardly any treatment data are available for this mixed waste stream. The benchmark is assumed to equate to the best performance for sewage sludge. Energy recovery options include combustion, anaerobic digestion, gasification, and pyrolysis. Full-scale facilities exist for anaerobic digestion of various types of paper mill sludge (Meyer and Edwards 2014). There are projects on gasification and pyrolysis technologies that focus on virgin biomass and biowaste including paper mill sludge (E4tech 2009; Meier et al. 2013). Non-energy recovery options include use as soil improver, compost, fertilizer, aggregate, filler, and adsorbent. The combined recovery potential is 1.00.
7. *Causticizing waste* is often contaminated and among the most problematic waste in the paper industry. Causticizing waste includes green liquor dregs, lime residues, and slaker grits. Not all of these substances are equally suitable for recovery and they are often mixed to improve the characteristics. When contamination issues are addressed, causticizing residuals may be used as soil improver, compost, neutralizer, aggregate, admixture, and adsorbent. Benchmark data suggests that green liquor dregs can be fully used in the cement industry (Mondi 2014). Another benchmark is provided by Nurmesniemi et al. (2007) who show 46% recovery of lime mud and green liquor dregs combined. The recovery potential is estimated at 0.50 – 1.0 and for the system-wide analysis, a value of 0.75 is used. Better estimation of the recovery potential requires further research on best practices.
8. *Boiler ash* can be recovered as compost, fertilizer, neutralizer, aggregate, admixture, and adsorbent. The benchmark at mill level is full utilization of boiler ash (Nurmesniemi et al. 2007; UPM 2015). The recovery options for coal ash or coal-wood ash are generally more limited than for pure wood ash because of toxic elements

(Park and Chertow 2014). The non-energy recovery potential of 1.00 can thus be achieved only if the wood is not co-fired.

The above recovery potential figures can now be use to recalculate the material balance that was derived in Chapter 5. The next section summarizes the recovery potential values and presents the recalculated material balance.

6.3 Results

The figures from the preceding sections are summarized in Table 6-2. It shows waste generated in 2012 and the fractions of current, benchmark, and potential recovery. Some waste can be used for both energy recovery and non-energy recovery. The assumed split between the two options, shown in the last column of Table 6-2, is necessary to create a complete material balance. For recycling sludge and sludge and rejects, the fraction of both treatments in 2050 is based on the relative sizes of the same fractions in 2012[11]. For E-o-L discards, recycling is preferred over energy recovery. For paper in sewage, incineration with energy and phosphorus recovery is most attractive and categorized as energy recovery.

Table 6-2. 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
E-o-L 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 reused (Mondi 2016). No individual benchmark data are available for lime residues and slaker grits.

[11] The calculation is as follows 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.

Figure 6-2 shows the current material flow pattern in the global paper life cycle in 2012 and the ideal flow pattern based on fulfilment of the recovery potential in 2050[12]. The demand for virgin materials is recalculated by keeping the ratios between chemical and mechanical pulp and between non-fibrous and fibrous inputs (pulp) constant. The flows are normalized to 100 units of consumption (for the base year 1 unit = 4 Mt). Appendix B-2 provides detailed material balances. It should be noted that the total industrial waste flow in the ideal scenario is about a tenth smaller because relatively high yield recycled pulping (73-89%) displaces low yield chemical pulping (40-55%). Boiler ash generation is much higher because of increased levels of energy recovery.

The ideal flow pattern improves performance in two ways: a large increase in recycling leads to a large reduction in landfill. Recycling dominates the ideal scenario because E-o-L discards is the largest waste flow in the system and almost all of it is recycled. The demand for virgin fibre is approximately halved which implies a proportional reduction of upstream environmental impacts. The RIR is almost doubled from 38% to 67-73% (as already shown in Chapter 5). A significant amount of virgin materials is still required, mainly because fibres are lost in the recycling process.

Wood is not the only virgin input that is avoided through waste reuse. The recovery of waste other than E-o-L discards or papermaking waste substitutes for various raw materials including virgin phosphorus, Portland cement, and fossil fuels. External recovery of industrial waste is much higher in the ideal scenario but increased recycling reduces external energy recovery of E-o-L discards in MSW incineration plants. The total impact of external recovery of waste in the ideal system is a function of the substitution potential of the waste. The extent to which waste materials can substitute for virgin inputs depends among others on waste properties, process efficiencies, and market conditions (Vadenbo et al. 2017).

[12] The visualization is inspired by the first use of the Sankey diagram by its originator, which was to depict conventional and ideal energy flows in a steam engine (Schmidt 2008; Sankey 1898).

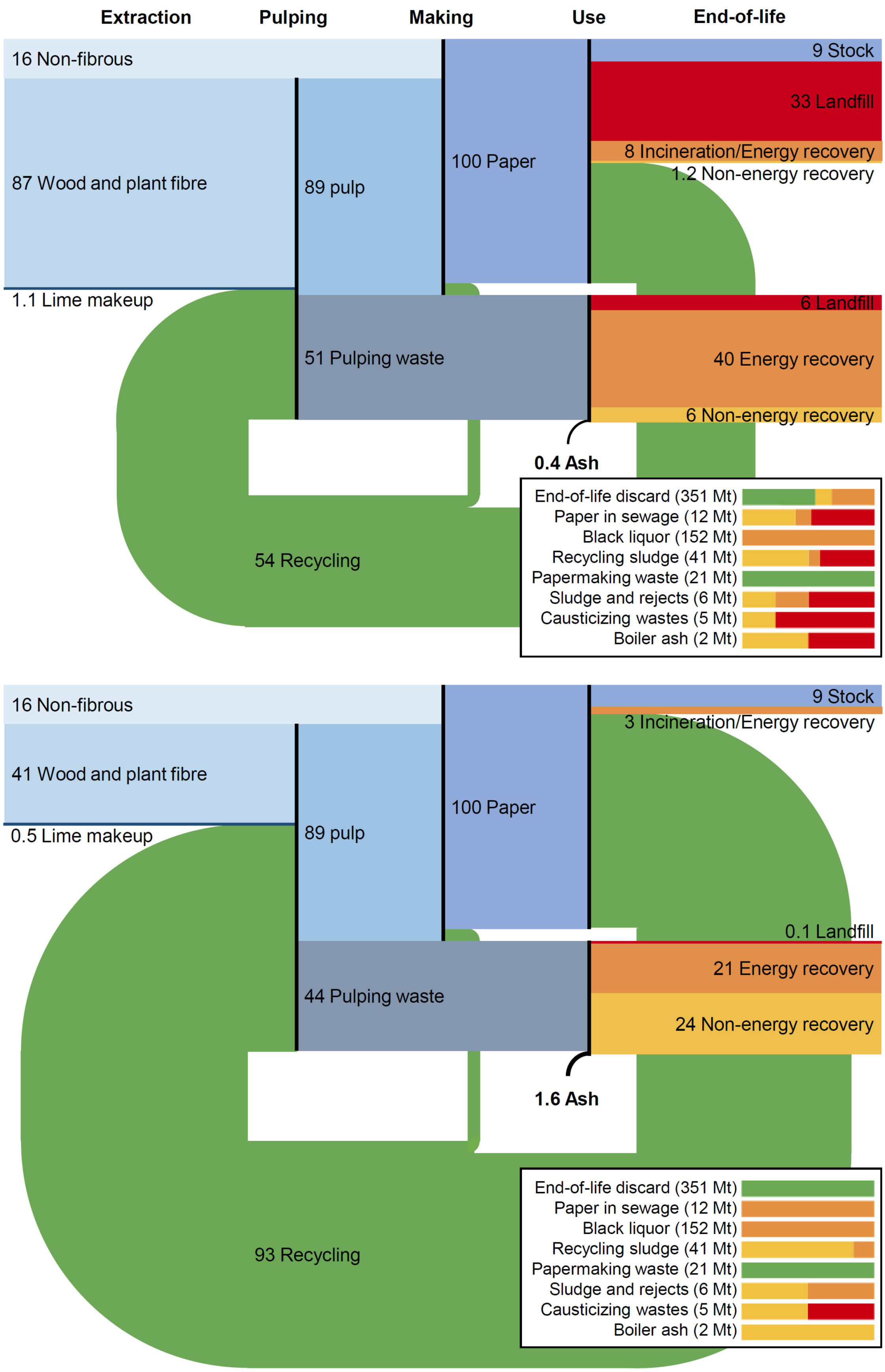

Figure 6-2. Normalized current (above) and ideal (below) flows in the global paper life cycle.

The diagram also features two boxes that show the quantities and waste treatment fractions of individual waste flows. The boxes reveal that in the ideal scenario, paper in sewage and black liquor are fully used for energy recovery, whereas almost all of recycling sludge and all of boiler ash go to non-energy recovery. The environmental impacts of particular combinations of a recovery option and a waste flow can be very different. For example, energy recovery of recycling sludge is likely to have smaller net environmental benefits than energy recovery of black liquor, mainly because the sludge is contaminated and has a relatively low heating value.

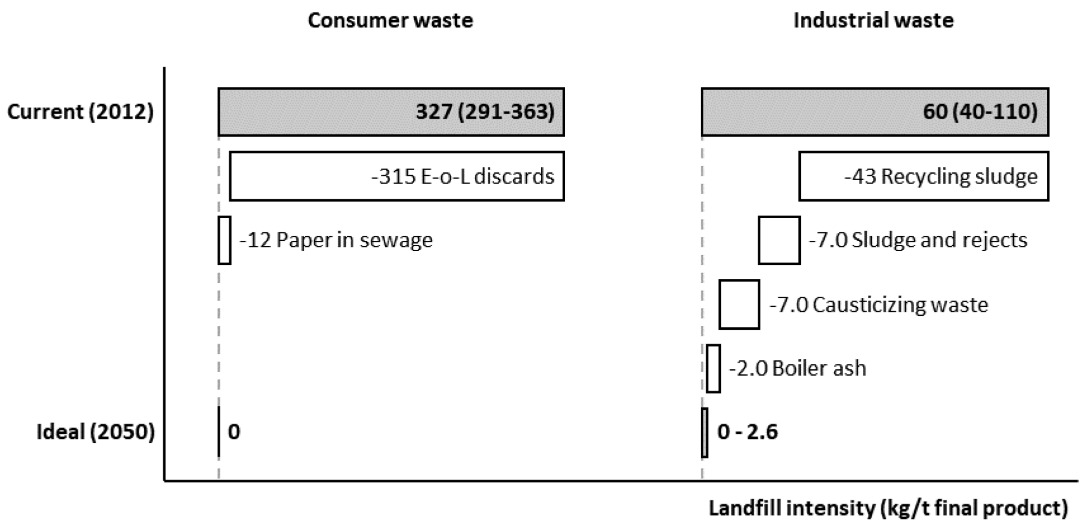

Figure 6-3. Contributions to a reduction in landfill intensity.

Figure 6-3 shows the landfill intensity of consumer waste (E-o-L discards and paper to sewage) and industrial waste (all other waste streams). The uncertainty range for current performance is again based on the extent of net addition to stock. The figure shows to what extent diversion of each waste flow contributes to the overall reduction in landfill in the ideal scenario. The largest improvement is through diverting E-o-L discards and recycling sludge from landfill. The overall landfill rate per tonne of final product decreases dramatically to only 0-2.6 kg/t. In the ideal scenario, the volume of landfill consists of causticizing residuals only. Near zero landfill may seem impracticable but a selection of paper mills in Europe already claims landfill rates as low as 14 kg/t (CEPI 2013b). Major paper producer UPM aims for zero landfill status by 2030 and claims to have achieved this already for several mills (UPM 2016).

6.4 Discussion

6.4.1 Limitations of the approach

This chapter assessed the system-wide changes in material flows when fulfilling the recovery potential of major waste streams in the global paper life cycle. In the "ideal" scenario, all recovery options that are expected to be commercially available by 2050, are implemented. This was shown to reduce virgin fibre requirements by approximately half and reduce waste to landfill to almost zero. However, due to various limitations, it was not possible to provide precise estimates that could directly inform decision-making. The lack of data on technology status and waste quality meant that only a single optimistic scenario could be constructed. The present results are suitable for long-term scenario analysis but do not directly indicate currently available opportunities.

The current analysis ignores many waste and material quality issues including qualitative losses during recycling. More detailed data regarding the quantity and quality of waste, the status of the technologies, and the waste properties required for successful recovery may be gathered for smaller spatial scales or a more limited number of waste streams. The data collection process revealed that country data is more widely available than global data; it should be possible to formulate more precise national recovery potentials. It should be noted that in the present chapter, the extrapolation of country data to the global level introduced bias. However, all national data are from countries with large pulp and paper sectors that have a significant share in the global pulp and paper market (Finland, United States, and Canada).

The optimization of the material flows did not consider the effect of waste generation and treatment on supply and demand of electricity and heat. On-site energy recovery is an efficient and attractive means of powering pulp and paper activities but the ideal paper life cycle features a much smaller role for energy recovery. This outcome is generally consistent with the waste hierarchy but may not actually be most beneficial for the pulp and paper industry. It is important to account for the heating value of the waste; only black liquor has a significant heating value and energy recovery from sludge makes only a small contribution to electricity and heat supply. At the same time, a shift from virgin to recycled pulping lowers energy demand for pulping, though increased deinking requirements partly negate these savings.

Not all non-energy recovery options are unambiguously beneficial. Land application of sludge could fertilize soils but may sometimes leave the soil quality unchanged. In the latter case, the waste is diverted from landfill but the recovery operation does not replace virgin fertilizer. Worse even, the sludge may contaminate and negatively affect the soil quality, which is why many countries discourage or prohibit these activities (Milieu Ltd. and WRc and RPA 2013). Another concern is the secondary waste resulting from waste recovery. For example, the use of waste as an adsorbent is a low added value application, which generates an equal amount of waste after adsorption. This waste then still needs to be dealt with and is probably incinerated. Ideally, the waste is recovered in such a way that another use is still possible afterwards. In other words, recovery should try to avoid a "dead end" at which only incineration or landfill remains.

The calculations were based on various optimistic assumptions and moving toward the ideal scenario would require the right conditions to be realized. For example, the analysis assumed universal collection for end-of-life discards, and hence fulfilling the recovery potential would first require establishing the relevant infrastructure. An important barrier to recovery is a lack of knowledge of recovery options and this chapter helps to overcome this barrier by presenting a quantified recovery potential. Other conditions for recovery can be categorized as technological (technological development), environmental (contamination and toxicity), economic (supply, demand and transport), and social (social and cultural context). Due to a lack of data, these conditions could not be incorporated in the quantitative analysis, but their relevance is further discussed in the next section.

6.4.2 The conditions for reuse

6.4.2.1 Technological development

The assessment focused on technologies that are likely to be available by 2050. Technological development is particularly important for advanced energy recovery technologies. Gasification (of black liquor or sludge) and pyrolysis (of sludge) are not currently commercially applied. These technologies are potentially more energy-efficient than combustion but require further development for large-scale applications. Moreover, energy recovery technologies are capital intensive. The shift from combustion to gasification of black liquor needs to fit the investment cycle. Worldwide, many recovery boilers will become obsolete in the next 15 years. As gasification is considered a promising technology, these old boilers may be replaced with gasification units (Naqvi et al. 2010).

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

Besides drying, several other pre-treatments may be needed to successfully recover waste. Such pre-treatments are required 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 and further technological development affect waste properties such as pH, water content, and level of impurities (Kinnarinen et al. 2016).

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

6.4.2.2 Contamination and toxicity

Contamination control is essential for safe and functional recycling and non-energy recovery. Regarding recycling, Pivnenko et al. (2016a) suggest the following hierarchy of priorities. Ideally, contamination is prevented. For example, certain inks should not be introduced into the paper life cycle and biomass waste should not be co-fired with coal to prevent ash contamination. When contamination is not prevented, it should at least be constrained, by excluding certain waste from certain uses and avoiding mixing of waste. Separate collection is a key step in constraining contamination and leads to lower levels of rejects and higher final quality (Miranda et al. 2013). A third option is to remove contaminants but doing so may negatively affect pulping yields since the largest losses in the recycling process are incurred during deinking (Pivnenko et al. 2016; Stawicki and Read 2010).

Toxicity can be a problem with non-energy recovery because sludge and rejects, ash, and causticizing waste can contain high levels of hazardous trace elements. This is most problematic when contaminants get dispersed into the natural environment through composting and use as fertilizer. Land spreading of contaminated paper sludge ash may affect soil quality, water quality, human health, and livestock. There may also be physical contaminants such as plastics and metals (Environment Agency 2015). The recovery options for mixed ash are more limited since there may be more contaminants in coal-wood ash including arsenic and lead (Park and Chertow 2014). For causticizing residuals, hazardous trace elements and residual alkali constitute barriers to recovery (Kinnarinen et al. 2016; Bird and Talberth 2008).

Energy recovery of waste generates flue gases, which may contain SO2, NOx, dust, dioxins, furans, PAHs, and heavy metals. Good design of the combustion process can reduce the generation of pollutants. The main process variables are time, temperature, and mixing, and these should be manipulated to minimize (but rarely to fully eliminate) harmful emissions. Dioxins in flue gases, for example, can be destroyed and removed through thermal treatment and adsorption, but partly end up in the remaining ash (Lam et al. 2010). The use of appropriate chemicals for printing, coating, and bleaching and the use of flue gas cleaning technologies such as electrostatic precipitators (to remove dust) also help minimize the impacts of energy recovery from waste (Suhr et al. 2015).

6.4.2.3 Supply, demand, and transport

Demand for waste from the paper industry is limited. For example, there is a finite capacity for using waste in cement because as a low quality contaminated resource, it cannot fully substitute for virgin inputs. In addition, the paper industry sometimes has to compete with other waste suppliers. The inelasticity of supply of waste can complicate reuse: the quantity, quality, and time of generation of waste may not respond to the preferences of the user. For example, deinking sludge generation, as a joint product of paper production, follows the market demand for paper, not for sludge (Deviatkin et al. 2014; Baumgärtner 2004). Sludge also varies in quality between mills and over time for the same mill. Reuse facilities must therefore operate with flexible quality standards and the quality must be measured more frequently than for regular products.

Supply of high-quality paper for recycling is dependent on separate collection efforts because it avoids contamination with other waste (Miranda et al. 2013). The South Korean benchmark provides a successful example of a recycling infrastructure. The opportunity to recycle is provided through universal collection infrastructure and motivated through a Volume-based Waste Fee (VWF) introduced in 1995. Waste must be discarded in standardized plastics bags in order to be picked up. The bags can be purchased from the local government. Recyclables are exempt from the fee and are source separated and collected from public bins at no charge. The fee on non-recyclables is supposed to incentivize consumers to shift as many recyclables as possible towards the recycling bin (Park and Lah 2015; Lee and Paik 2011). Fulfilment of the recovery potential of E-o-L discards requires such a system, or an equally effective one, to be implemented globally.

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

6.4.2.4 Social and cultural context

Waste is generally perceived negatively, reflecting deeply held cultural norms regarding products, materials, and their context. This can obstruct waste separation efforts by households and businesses and may lead to limited efforts of business managers to prioritize recovery of process waste. Waste is sometimes littered, discarded in the wrong bins, or tipped. The environmental hazard from waste thus partly stems from the disinterest of the waste holder and the prevailing culture of throwing waste away carelessly (Cheyne 2002). In particular, complex products or contaminated waste may be handled inappropriately which diminishes the chances of useful recovery. The "stigmatization" of waste may be reduced by relabelling waste and specifying its value in terms of the recovery potential (Park 2012).

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

To facilitate the use of waste as a resource between companies and industries, social proximity – such as friendly or professional relationships – may be just as important as geographical proximity (Velenturf and Jensen 2016). A much-cited and related social factor is trust (Gibbs 2003; Ashton 2008). The use of waste as a resource requires information sharing and investment in specific technologies and infrastructures. Trust enables firms to engage in such transactions with high asset specificity (Boons et al. 2017). Contingency plans and back-up contracts help companies deal with a defaulting supplier. The coordination of the exchange of waste as a resource should consider the embeddedness of decision making in social relationships and seek to build trust among the participants (Doménech and Davies 2011).

6.4.3 Implications and further research

The aforementioned barriers to waste recovery could not be incorporated in the analysis, but the results provide insights into the possibilities for the long term and exemplify a methodology that may be applied at smaller spatial scales. With better (local) data, more precise results may be calculated and used for regulatory purposes. In the EU, the Industrial Emissions Directive (IED) (EC 2010) lays down the rules for permitting industrial facilities based on Best Available Techniques (BATs). For example, the BAT for the pulp and paper industry suggests using waste as an industrial feedstock, for land spreading, or in construction materials (Suhr et al. 2015). There are, however, no quantitative estimates of the potential for using waste from the pulp and paper sector as a resource. When data allows, the BATs could be presented more usefully with the reuse or recovery potential indicator.

This chapter has highlighted the options for waste recovery in the global paper life cycle but without prioritizing among all options. What should decision-makers in the paper sector pursue? The waste hierarchy can provide some guidance for choosing between recycling, non-energy recovery and energy recovery but does not necessarily stimulate system-wide reductions of material use, nor does it consistently indicate lowest environmental impacts (Van Ewijk and Stegemann 2016). To choose between the different options, one might use the following performance criteria, in order of increasing difficulty of their assessment: diversion from landfill, substitution of virgin materials, reduction of individual environmental impacts, and reduction of systemic environmental impacts. The analysis in this chapter considered only the first two criteria based on a material flow analysis. Assessing the latter two criteria would require a life cycle assessment and is the subject of future research.

Future research may overcome the limitations of this study. Waste and material quality, including fibre quality upon recycling, is a key issue. Better data regarding current and potential recovery options may be obtained through industry collaboration. The calculated recovery potentials only reflect what is likely to be technically possible in 2050. Besides, the analysis has not shown the potential benefits of waste recovery beyond the confines of the paper industry. Paper waste recovery in agriculture has implications for this sector too, as well as for sectors that supply the agricultural sector. Furthermore, the analysis focused on final waste treatments within the paper life cycle and ignored the potential benefits of cascading biomass use across different sectors. For example, fibres could be used in timber, for paper, and as a fuel successively. There is also a potential to shift towards plants and agricultural residues as feedstocks (Bousios and Worrell 2017). Exploring all these possibilities requires a much wider system boundary and is left for future research. Finally, the approach demonstrated in this chapter may be applied to other material life cycles and sectors, primarily those that feature large waste streams and good data availability.

6.5 Conclusions

The analysis in this chapter uniquely combined the concept of a "recovery potential" with a full material balance of the global paper life cycle. The results show what the paper life cycle would look like if known technologies and best practices were further developed and implemented globally. The analysis distinguishes eight different waste streams and estimated the potential for recycling, non-energy recovery, and energy recovery. There are three main findings.

- Most waste flows from the paper life cycle can be fully used as a resource though often for low-value applications only. Increased use of recycled inputs lowers the efficiency of recycled pulping. There is high uncertainty regarding the potential of smaller waste streams from the paper industry.
- The fulfilment of the recovery potential of all waste flows significantly improves the system performance. The Recycled Input Rate (RIR) rose from 38% to 67-73% and the landfill intensity decreased from 331-473 kg/t paper to only 0-2.6 kg/t paper.
- The most important barriers to fulfilment of the recovery potential of waste in the paper life cycle are technological development, contamination control, a mismatch between supply and demand, and cultural barriers to engagement with "waste".

Further work may focus on obtaining better data and calculating more precise recovery potentials. It may also specify local barriers to the use of waste as a resource. In Chapter 8 of this thesis, the material balances presented in this chapter will be used for analysing GHG emission reduction options.

7 Current greenhouse gas emissions from paper

7.1 Introduction

The preceding two chapters established current material use in the global paper life cycle and described "ideal" material use in the paper life cycle. But to what extent does "ideal" material use lead to reduced GHG emissions? Is the use of waste as a resource sufficient to meet climate change targets? Answering these questions requires 1) an estimate of current emissions from the paper life cycle and 2) a projection of future emissions under "ideal" material use. This chapter focuses on the former and the next chapter on the latter.

The main GHGs from the life cycle of paper products are CO_2 and CH_4. Carbon dioxide results from the combustion of fossil fuels to generate electricity and heat. This may occur on-site or in external power plants. Methane is produced mainly during the anaerobic decomposition of paper products in landfills. The paper sector has relatively low carbon emissions per unit of energy due to the use of carbon-neutral renewable biomass waste for energy recovery, mainly black liquor from chemical pulping.

The global life cycle emissions from paper are significant and difficult to reduce (Allwood et al. 2010). The overview of current studies in Section 4.4 revealed that no single analysis includes both an energy balance and a detailed emissions analysis for the global paper life cycle. Many studies exclude forestry activities, biogenic carbon stocks and flows, and E-o-L waste management. The state-of-the-art analysis of current (2006) emissions is the FAO (2010) study on the global forest products sector. The most detailed assessment of energy use in the pulp, paper, and print sector is by IEA (2007a) and IEA (2009).

The analysis in this chapter goes beyond the emissions account by FAO (2010) by including three major improvements. First, the emissions calculation is based on the detailed material balance calculated in Chapters 5 and 6. Second, it combines electricity and heat consumption data for unit processes with reported global energy consumption data. Third, it provides more insight into the role of energy recovery from waste in meeting the energy demand for generation of electricity and heat in paper mills.

The chapter proceeds as follows. Section 7.2 describes the calculation of fuels and electricity, organic carbon, and avoided emissions. The results are presented in Section 7.3, including the associated uncertainties. Section 7.4 reflects on the differences and similarities between the findings here and those of other studies and discusses several methodological issues.

7.2 Methods and data

7.2.1 Life cycle overview

Each stage of the global paper life cycle acts as a sink or source of carbon. Table 7-1 summarizes sinks and sources of GHG emissions that are included in the analysis for the life cycle stages of extraction, pulping, making, printing, disposal, and E-o-L management. The emission sinks and sources are divided into four types.

- *Bought fuels* to generate electricity and heat and to power machinery for extraction.
- *Bought electricity* from the grid to power pulping, papermaking and printing.
- *Organic carbon* stocks and flows from forestry, in-use products, recycling, and landfill.
- *Avoided emissions* through energy recovery of consumer waste and landfill gas.

Energy recovery from waste and biomass is considered carbon-neutral. The impacts of forestry on organic carbon stocks will be discussed but no estimate is included in the final analysis.

Table 7-1. Greenhouse gas sinks and sources per life cycle stage.

Category	Extraction	Pulping	Making	Printing	Use	E-o-L
Fuels	X	X	X	X		
Electricity		X	X	X		
Organic carbon	X*				X	X
Avoided						X

*No estimate could be derived for impacts of forestry on organic carbon stocks.

Several small sinks and sources of GHG emissions were excluded from the analysis, mainly the following:

- GHG emissions other than CO_2 and CH_4 that are generated through for example combustion of fuels. Their contribution is relatively small.

- GHG emissions from transport of raw materials and final products, which have been consistently shown to make an insignificant contribution to total emissions (Villanueva and Wenzel 2007; Finnveden and Ekvall 1998).
- Indirect emissions associated with the production of fuels, materials, equipment, factories, and infrastructure that are used in the paper life cycle.

The following sections describe the calculations for the different emission sinks and sources: fuels and electricity, organic carbon, and avoided emissions. The sections are followed by a discussion of uncertainty in the estimation.

7.2.2 Fuels and electricity

7.2.2.1 Overview

Fuel and electricity consumption is calculated by combining two types of data which were collected independently. The following steps are taken to calculate energy consumption and associated emissions.

1. Material flows are multiplied by SEC values to obtain a bottom-up estimate of aggregate energy consumption. The SEC figures represent BATs.
2. Because BAT values tend to be lower than actual consumption, the total energy consumption figures are compared with available reported figures to obtain a scale factor. The energy consumption of every individual process is recalculated according to this scale factor.
3. The energy consumption figures are multiplied by the CI of the respective fuels or the CI of bought electricity.

All three steps were performed for pulping, papermaking, and printing. Only the first and third step could be performed for the extraction stage because no reported total energy consumption figures were found.

The SEC is a frequently used indicator for energy efficiency (Phylipsen et al. 1997) and approaches using SEC values include a model of the German pulp and paper industry by Fleiter et al. (2012). Equation 7-1 shows that SEC values for a process *i* are defined as the ratio between energy inputs (E) and material (M) outputs.

Equation 7-1.

$$SEC_i = \frac{E_i}{M_i}$$

The SEC may be defined at the level of a component (e.g. a dryer), a process (e.g. chemical pulping), or an entire industry (e.g. the pulp and paper industry). The subsequent analysis focuses on the process level and all SEC values are expressed in Gigajoule (GJ) per tonne of material output.

7.2.2.2 Forestry and mining

Table 7-2 shows the SEC values for fibre harvest and kaolin mining based on Laurijssen et al. (2010). During fibre harvest, fuels are used for logging and electricity is used for chipping. A detailed analysis of wood extraction in Sweden by Berg & Lindholm (2005) suggests a value of 60-85 MJ of energy per m^3 of wood for forestry operations. Based on a wood density of 0.40 t/m3 in the same publication, this corresponds to 0.15-0.21 GJ/t wood – the value for logging suggested by Laurijssen et al. (2010) falls within this range.

Table 7-2. SEC values for virgin material extraction (Laurijssen et al. 2010).

Process	Heat (GJ/t wood)	Fuels (GJ/t wood)	Electricity (GJ/t wood)
Fibre harvest		0.17	0.54
Kaolin mining	1.05		0.69

Laurijssen et al. (2010) also provide estimates for electricity and fuel use for the production of kaolin, which is one of the most widely used filler materials. Comparable figures for total energy use in kaolin mining activities are provided by Joelsson & Gustavsson (2008) and EC (2009). The CI of fuel consumption is assumed similar for all extraction activities and based on the CI of diesel oil (IPCC 2008) because it is the most widely used fuel in forestry activities (Berg and Lindholm 2005).

7.2.2.3 Pulping, papermaking, and printing

Energy flows in the pulp, paper, and print sector are complicated by the use of combined heat and power (CHP). In addition, the sector uses its own waste for energy recovery. On the supply side, there are three main categories of energy inputs, which fulfil the demand for electricity and heat for all processes.

- *Bought fuels* such as coal and gas are obtained externally. They include waste from other sectors but will be consistently referred to as bought fuels.
- *Mill waste* refers to industrial waste from the paper sector that is used for energy recovery. It includes black liquor, recycling sludge, and sludge and rejects.
- *Bought electricity* covers electricity supplied by the grid and excludes electricity that is generated through fuel and waste combustion in paper mills.

Total electricity and heat demand is calculated by multiplying material flows with SEC values taken from IEA (2007a) for pulping and papermaking and from Jepsen & Tebert (2003, p. 21) for printing. Consistent with Chapter 5, all paper for recycling is assumed to be deinked, except for 25% of the recycled inputs to packaging. Newsprint and printing + writing paper are all considered to be printed. A fraction of 0.17 of packaging is assumed not to be printed based on the share of case materials and carton board in total packaging in CEPI (2013a). The bottom-up estimate is 4,318 Petajoule (PJ) for heat and 2,045 PJ for electricity. The calculation is shown in Appendix C-1.

The bottom-up estimate is compared with aggregate energy consumption reported by IEA (2016a). However, the reported energy data is not complete, and covers only bought electricity, "bought heat"[13], and bought fuels for heat generation. It excludes fuels used for electricity generation. The comparison therefore needs to focus on heat only. Total heat demand is calculated based on the overall efficiency of electricity and heat generation (0.85), reported fuel inputs for heat (4,511 PJ), and reported "bought heat" (505 PJ). The calculation is shown in Equation 7-2.

Equation 7-2.

$$Total\ heat\ demand = 4{,}511\ PJ * 0.85 + 505\ PJ = 4{,}339\ PJ$$

The bottom-up calculation gave a slightly lower value of 4,318 PJ which implies a scale factor of 1.005. The scale factor of approximately one suggests that average global performance is at the same level as reported BATs. This is confirmed by IEA (2007a), who find that many developed countries were very close to BAT or even performing beyond BAT in 1990-2003. The BAT values may be outdated and the reported energy data may be incorrect; IEA (2007a) warns national reporting is not consistent and biomass use is likely to go underreported.

[13] This is a problematic category that is further explained later in this section.

The total energy balance for the pulp, paper, and print sector is presented in Figure 7-1. The calculation of heat and electricity use for pulping, papermaking, and printing is the same as in Appendix C-1 but using the scaled SEC figures from Table 7-3. Because the scale factor is very close to 1, the values hardly change, but the adjustment is nevertheless made to emphasize the importance of correcting bottom-up estimates with reported energy consumption. The figures should be adjusted again when relevant data energy consumption data becomes available.

Table 7-3. Scaled SEC values adapted from IEA (2007a) and Jepsen & Tebert (2003).

	Heat (GJ/t)	**Electricity (GJ/t)**
Mechanical pulping	0.00	7.54
Chemical pulping	12.31	2.09
Recycled pulping with deinking	2.01	1.63
Recycled pulping without deinking	0.50	0.36
Newsprint	3.80	3.18
Printing + writing	5.28	1.81
Sanitary + household	5.15	3.62
Packaging	4.34	1.81
Other	4.90	2.89
Printing	2.06	2.48

Figure 7-1 also shows the energy inputs to delivery of heat and electricity. These inputs were categorized as *bought fuels*, *mill waste*, and *bought electricity*. The figures for these flows were calculated based on the following efficiencies: an electrical efficiency of 0.25 and a heat generation efficiency of 0.60 for CHP, and a heat efficiency of 0.85 for heat only generation (based on figures collated by Suhr et al. (2015)).

- *Inputs for electricity* from CHP follow from the difference between electricity use and supply of bought electricity. The sale of electricity and heat by paper mills is assumed to be zero at the global level. All electricity (but not all heat) is assumed to be generated through CHP. In the CEPI area, about 96% of electricity generated onsite is from CHP installations (CEPI 2014b).
- *Fuels and waste* are calculated by aggregating fuel inputs to "bought heat", reported fuel use for heat generation, and *inputs for electricity*. The category "bought heat" most likely reflects on-site fuel use which, for reasons irrelevant to this thesis, is

reported under a different administrative entity[14]. The fuel inputs to "bought heat" are calculated based on the efficiency of generation of heat only.

- *Bought fuels* and *mill waste* are calculated by disaggregating *fuels and waste* based on the waste used for energy recovery calculated in the preceding chapter[15]. The energy content of waste to energy recovery is calculated by applying a heating value of 12.3 GJ/t for black liquor (IEA 2007b) and heating values of 2.8 GJ/t and 4.2 GJ/t for recycling sludge and sludge and rejects respectively (Gavrilescu 2008).

The parameters for the calculation of the energy balance are summarized in Appendix C-2 and the figures and equations for the energy balance are provided in Appendix C-3.

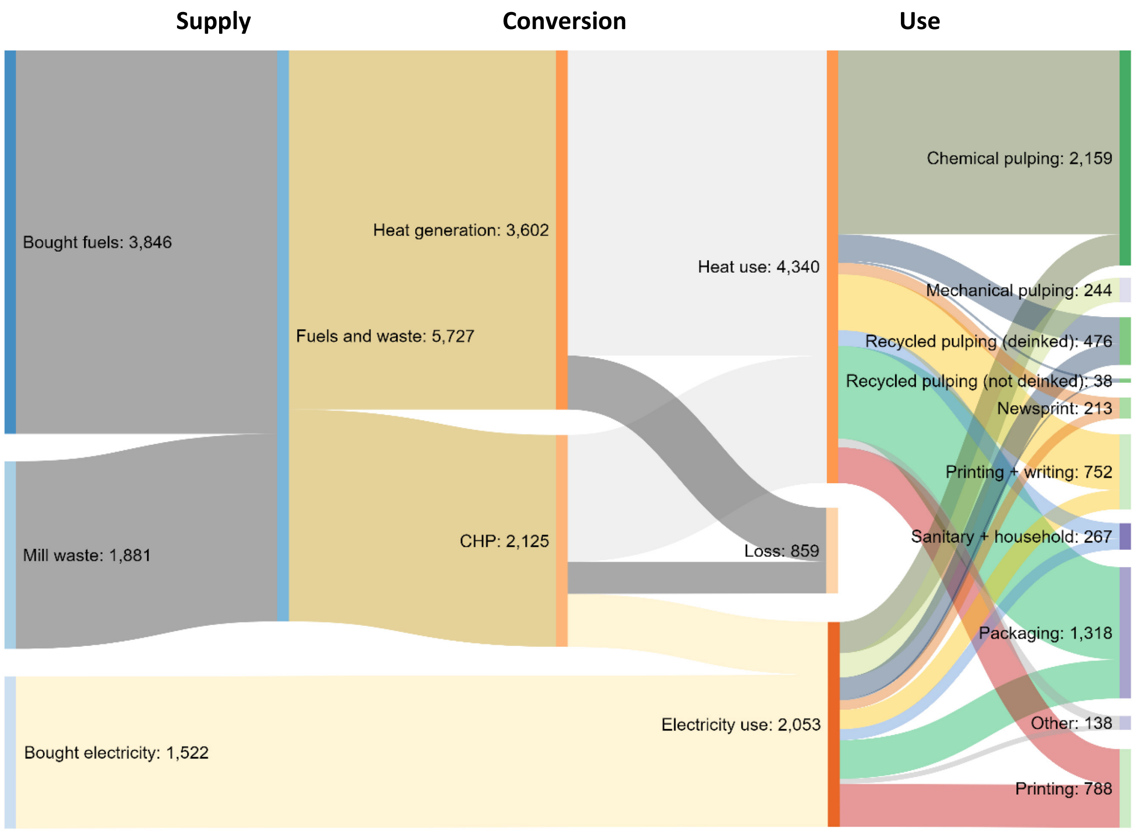

Figure 7-1. Energy balance for pulping, papermaking, and printing (PJ).

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[14] This conclusion was drawn by the author after personal communication with two university experts with 10-30 years of experience in research on energy and material efficiency.

[15] IEA (2016a) is of little use for estimating energy from mill waste because it only reports various fossil fuels and a single category "biomass and waste".

The most energy-consuming processes are chemical pulping and the making of packaging. Chemical pulping is highly energy-intensive and packaging is simply a very large material category. Printing is surprisingly energy-intensive – IEA (2007a) suggest the printing sector uses mainly electricity but Jepsen & Tebert (2003) show that printing also requires a significant amount of heat. Very few other sources account for the energy demand of printing. The analysis in this chapter shows that energy demand from printing is 12% of energy demand in the paper, pulp, and print sector.

7.2.2.4 Carbon intensity

The total carbon emissions follow from the complete energy balance and the CI of bought fuels, mill waste, and bought electricity. The CI of bought electricity (including electricity use in extraction) and heat is based on global electricity and heat generation and global carbon emissions by the electricity sector (IEA 2015a, 2015b). The CI of electricity amounts to 0.235 kg CO_2/GJ. The CI of bought fuels in the paper sector was calculated based on the carbon intensities of the relevant fuels as listed by IPCC (2008). Mill waste, and waste and biomass in the category bought fuels, are considered carbon-neutral. Only the fuel mix for the generation of heat, not electricity, is reported by IEA (2016a). It is assumed that the CI is the same for on-site generation of electricity and heat (including what IEA (2016a) calls "bought heat") as all electricity and heat is generated in similar units in pulp, paper, and print facilities. Emissions of CH_4 and N_2O from combustion are not included because they are very small (FAO 2010a).

7.2.3 Organic carbon

7.2.3.1 Overview

Organic carbon is the carbon stored in fibres used for paper production. Figure 7-2 shows the forest and paper carbon cycle. Carbon is taken up from the atmosphere by forests and added to the forest carbon stock. Extraction of wood from forests removes carbon from the forest stock unless new trees are grown at the same time. Harvested wood is used for pulp and paper. Some of the paper products are kept in use by consumers or recycled. Paper to landfill either decomposes or is stored indefinitely. Some paper is incinerated in MSW incineration plants. The following sections focus the estimation of forest carbon stock, emissions from landfill, and net addition to stock through long-term product use, recycling, and landfill.

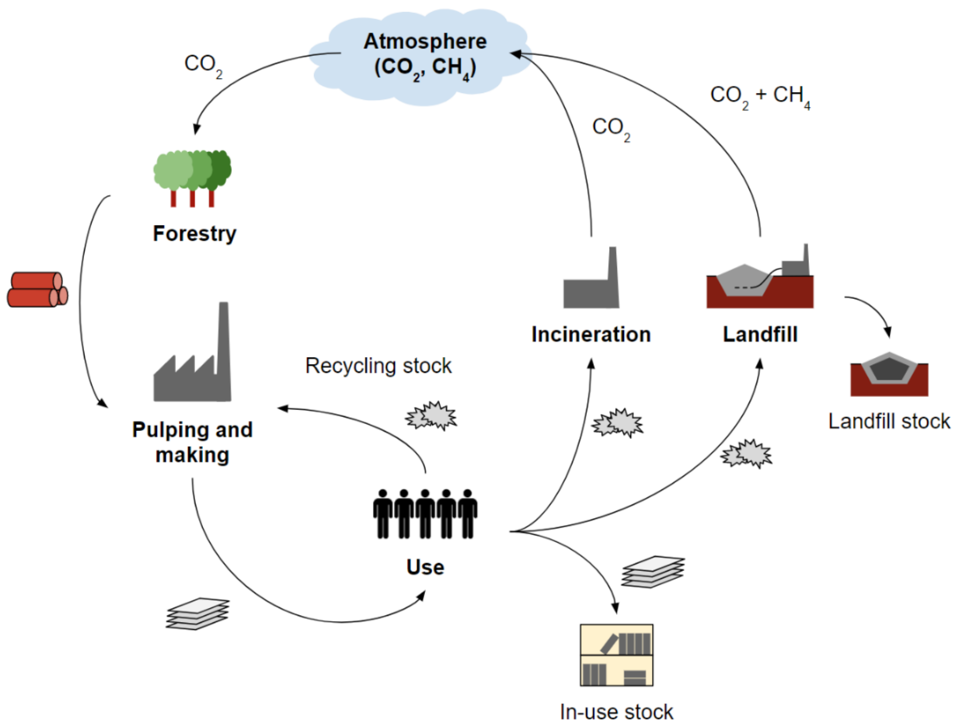


Figure 7-2. The organic carbon cycle.

7.2.3.2 Forest carbon stock

Deforestation and degradation are an ill-understood part of the carbon cycle. No estimate could be derived for forest carbon stock changes associated with the paper life cycle, for four main reasons. First, estimates for global carbon sinks and sources are highly uncertain. Pan et al. (2011) estimate the worlds' forests are a net sink of 1.1 ± 0.8 Gt CO_2 y-1 for the period 1990-2007 but FAO (2015) estimates a net source of 1.7 Gt CO_2 y-1 for the period 2001-2010 and 0.8 Gt CO_2 y-1 for the period 2011-2015. Kohl et al. (2015) reflect on both studies and conclude that "much work remains to be done" regarding global forest carbon stocks and flows.

Second, even if more reliable estimates of global forest carbon stocks and flows were available, the role of the paper life cycle would still be very hard to estimate, because the impact of forestry depends on the type of forest and the alternative land use (Subak & Craighill (1999). Very different assumptions could be made regarding both factors.

- *Plantations* are trees on land that was used for agriculture previously. The use of plantations is often assumed to imply a gain in the carbon stock.
- *Regrowth forests* are old forests that are assumed to keep a stable carbon stock when harvested sustainably (i.e. harvest does not exceed growth).

- *Original converted forests* imply a loss in carbon stock since a forest with a high carbon density has been replaced with a low-density forest.

These categories are disputed: mature forests, for example, may still take up carbon instead of being carbon-neutral, due to the increased CO_2 concentration in the atmosphere (Bellassen and Luyssaert 2014). Besides, forest management (e.g. rotation lengths) can be more important than land use change in terms of carbon stocks (Eggers et al. 2008). The sheer complexity of the matter makes McKechnie et al. (2011) conclude that LCA should be integrated with forest carbon modelling. However, at the global scale, the lack of agreement on global carbon stocks implies such modelling is not feasible for this thesis.

Third, commercial logging is not the only use of forests, and other uses must be known to do the proper allocation. Standard allocation methods in LCA suggest that environmental impacts should be allocated based on the relative economic value of the practice in question (Ekvall 1999; ISO 2006). This requires knowledge of the main practices and their economic value, which is not currently available at the global scale. Recreational uses are rarely charged directly and the value is therefore unknown. Besides, some of the activities that contribute to tropical deforestation and degradation, which include infrastructure extension, agricultural expansion, and selective logging (Geist and Lambin 2002), are illegal and their value is therefore not known either.

Lastly, even if all the above challenges were overcome, an estimate of zero carbon stock change is likely to be the result for the year 2012, because the demand for virgin fibre for paper is relatively stable. Vogtländer, Van Der Velden, & Van Der Lugt (2014) emphasize that only an *increase* in forests or an *increase* in products in stock yields carbon benefits. However, for the paper sector, virgin fibre demand has been stagnant for the past decade due to limited growth in total paper demand and an increase in recycling. Figure 7-3 shows this by depicting the consumption of virgin fibre and paper for recycling (the data is calculated according to the methods in Chapter 5). The relatively stable virgin fibre consumption over the past two decades supports an assumption of sustainable harvest from a fixed land area of forest.

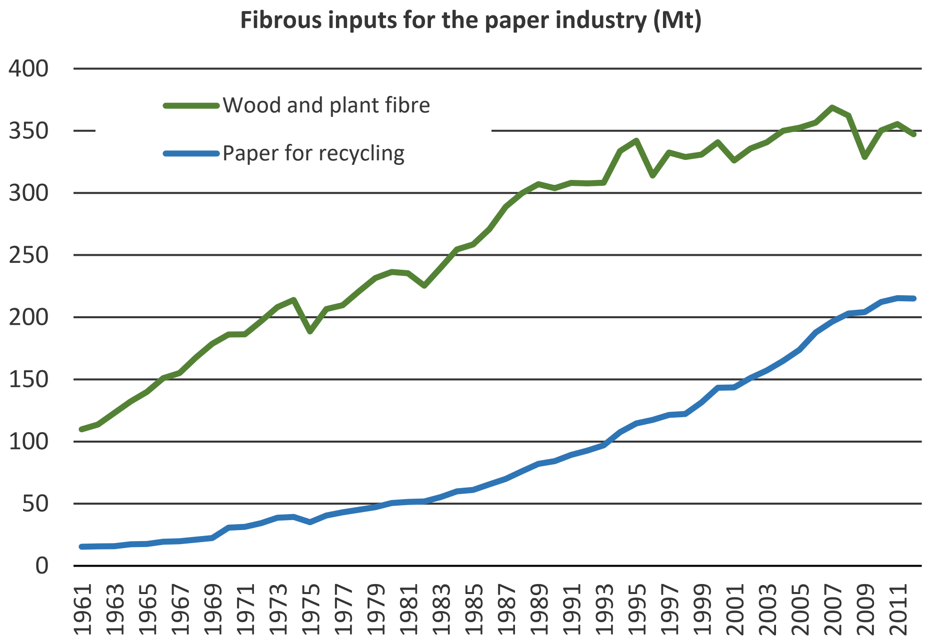


Figure 7-3. Wood and recycled inputs for global paper production.

Of the reviewed studies, only Miner & Perez-Garcia (2007) include a carbon stock change for forests. The authors argue that deforestation is caused by many variables other than commercial logging. However, they do not apply the same logic to afforestation and assume that all increases in forest stock can be allocated to the forest products industries (i.e. without the forest product sector all these carbon stock increases would not have happened). This leads to an overestimation of the positive impacts of forestry. It critically ignores that many forests are categorized as "multiple-use" (FAO 2010b) and valued, protected, and planted for a range of services besides commercial logging (García-Fernández et al. 2008).

In conclusion, the thesis presents a zero estimate for net carbon stock change of forests due to paper life cycle related activities. This is because of high uncertainty regarding forest carbon stocks, land-use change patterns, and multiple uses of forests. Moreover, virgin fibre consumption is currently stable which – if forest stock is stable too – suggests sustainable yield. Heath et al. (2010), who focus on the paper life cycle in the United States, also arrive at a zero estimate for forestry impacts and FAO (2010) confirms it is "not possible to develop a global estimate" of the impact of the forest products sector on keeping forests. The latter two studies are partly from the same authors and institutions as Miner & Perez-Garcia (2007) and represent the state-of-the-art (rather than an opposing view).

7.2.3.3 Emissions from landfill

Landfills are both a sink and source of carbon because paper is partly decomposed and partly held in stock indefinitely. Figure 7-4 shows the decomposition process. The paper fraction of solid waste in landfill consists of carbon and other elements. The carbon fraction is only partly degradable. The non-degradable carbon acts as a carbon sink. The degradable fraction is turned into CO_2 and CH_4 depending on how landfill management and depth affect oxygen availability. Some of the CH_4 may be captured and combusted and the non-captured CH_4 either oxidizes to CO_2 in the top layers of the landfill or escapes into the air. The CO_2 from decomposition also escapes into the air.

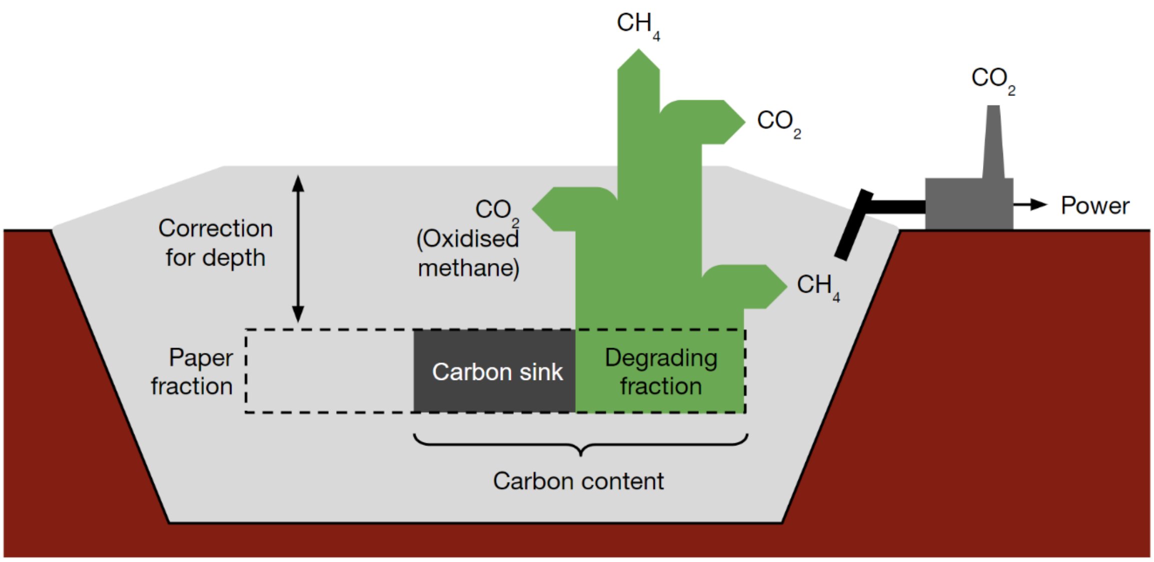


Figure 7-4. Emissions from the decomposition of paper in landfills (not to scale).

Methane emissions at the national or global level are modelled instead of measured. The production of CH_4 from paper in landfills is calculated with Equation 7-2, adapted from the default IPCC method (Pipatti and Svardal 2006). The equation calculates CH_4 emissions in year *t* due to landfilling of waste W_x in year *x*. The values for landfill emissions for the year *t* from each landfill deposit in year *x* are summed to arrive at the total CH_4 emissions in year *t*. The aerobic decomposition of paper and the combustion of landfill gas is considered carbon-neutral. The carbon that is stored indefinitely is accounted for as a negative emission.

Equation 7-3.

$$S\ (t,x) = \left(\left((1-e^{-k}) * W_x * MCF * DOC * DOCf * F * \frac{16}{12} * e^{-k(t-x)}\right)(1-R)\right) * (1-OX)$$

The factor 16/12 in Equation 7-2 reflects the conversion from C to CH_4. All other parameter values are summarized in Table 7-4. Unless indicated otherwise, the parameter values and ranges are based on IPCC default recommendations by Pipatti and Svardal (2006). The DOC is the weighted average of the Degradable Organic Carbon content of paper (DOC_p) and industrial waste (DOC_{iw}) based on the quantities of E-o-L discard and industrial waste to landfill in the relevant year. The DOC_{iw} is adapted from EPA (2017). Only the fraction (DOC_f) of the DOC will dissimilate and only the fraction F of landfill gas consists of CH_4.

Table 7-4. Parameter values for the landfill emissions calculation.

Symbol	Parameter	Lower bound	Used value	Upper bound
k	Half-life factor	0.04	0.05	0.06
MCF	Methane Correction Factor	0.63	0.70	0.77
DOC_p	Degradable Organic Carbon content paper	0.36	0.40	0.44
DOC_{iw}	Degradable Organic Carbon content industrial waste	0.090	0.145	0.200
DOCf	Fraction Degradable Organic Carbon dissimilated	0.40	0.50	0.60
F	Share of CH_4 in landfill gas	0.475	0.500	0.525
OX*	Oxidation factor for CH_4 in top layer	0.10	0.05	0.00
R*	Rate of CH_4 capture	0.30	0.25	0.20

*The upper boundary is a lower value because the lower parameter value leads to higher emissions from landfill.

The Methane Correction Factor (MCF) accounts for differences in landfill site conditions and varies between 0.4 and 1.0 for unmanaged shallow sites and managed anaerobic sites respectively (Pipatti and Svardal 2006). The calculation of a global MCF is summarized in Table 7-5 and is partly based on the data used for estimating MSW treatment (see Section 5.2.4). The OECD countries are assigned an MCF of 0.9. The unweighted average MCF for China, based on regional MCF values by Zhang and Chen (2014) is 0.8. The MCF for the rest of the world is assumed to be 0.4. From this follows a weighted global MCF of 0.7 with an uncertainty of ± 10%.

The CH_4 capture rate R varies by landfill and over time. Themelis & Ulloa (2007) suggests that about 10% of global CH_4 generation is captured in, presumably, the 2000s. Matthews and Themelis (2007) suggest a 12% capture rate globally for the period 2000-2030. Bogner and Matthews (2003) estimate a global collection efficiency of 6.6 – 18.2% in 1996 based on several data sources. The authors note that actual recovery might be higher because of reporting issues. The 1996 estimate is also outdated. This chapter uses a weighted estimate for three regions: the OECD countries, China, and the rest of the world are assigned a collection efficiency of respectively 0.50, 0.25, and 0.0. This results in a global fraction of 0.25 for the year 2012 with an uncertainty of ± 20% (see also Table 7-5).

Table 7-5. Calculation of the global methane correction factor and methane capture rate.

Region	Residual paper waste (Mt)	MCF	R
OECD Total	54	0.9	0.50
China	47	0.8	0.25
R-o-W	45	0.4	0.00
World	147	0.7 (weighted)	0.25 (weighted)

Methane emissions in the year 2012 stem from waste deposits in the preceding years. The figures for historical waste treatment are approximated based on the following data and assumptions.

- Annual consumption of paper and collection of paper for recycling in the period 1961-2011 are taken directly from FAO (2016).
- Incineration (with or without energy recovery) of MSW is assumed to increase linearly from 0 in 1970 to the value in 2012. This is based on the rapid increase in incineration in the US which started in the 1970s (EIA 2007).
- Energy recovery and non-energy recovery of sludge and rejects and recycling sludge is also assumed to have increased linearly from zero in 1970. Black liquor is assumed to have been used for energy purposes for the entire period.
- All waste that is not recycled or incinerated (with or without energy recovery) is assumed to go to landfill.

Landfill deposits before 1961 are not considered because they have a very limited effect on landfill emissions in 2012. A more precise estimate of MSW incineration is not required because incineration only reduces landfill of residual (non-recycled) waste by about one fifth (see Chapter 5); a fluctuation in incineration rates therefore has a very limited impact on the total quantity of consumer waste to landfill.

7.2.3.4 Net addition to stock

The build-up of product carbon stock occurs through three mechanisms. First, consumers do not discard all their purchases. The delay in disposal of purchased goods constitutes an addition to stock. Second, Cote et al. (2015) categorize recycling (and reuse) as "carbon-binding" or carbon sequestration processes: recycled material constitutes an addition to stock in one year and a removal from the stock in the preceding year. The net change in stock due to recycling in year *t* is the difference between recycled inputs from year *t-1* and paper for recycling in year *t*. Only an *increase* in recycling leads to negative emissions because it increases the amount of recycled fibre in use. Finally, some stock building occurs in landfills when paper does not decompose.

The carbon impact of paper held in stock by consumers over an extended period of time is calculated with Equation 7-3. The carbon content of paper was based on the IPCC default value which includes lignin (IPCC 2000; Bingemer and Crutzen 1987). The constant is needed to calculate the amount of CO_2 equivalent to the amount of C stored in products.

Equation 7-4.

$$S_{consumer}\ (t) = NaS * Total\ consumption * DOC * \frac{22}{6}$$

The net addition to stock due to recycling is calculated using Equation 7-4. The result is very sensitive to annual variations in total paper for recycling volumes. The quantity has therefore been averaged for the period 2008-2012.

Equation 7-5.

$$S_{recycling}(t) = (R_t - R_{t-1}) * DOC * \frac{22}{6}$$

The calculation of the sink function of landfills follows Equation 7-5. The non-degraded paper in the landfill acts as a permanent carbon sink. Some paper does not degrade because it contains lignin and some paper does not degrade because the environmental conditions are not conducive to decomposition.

Equation 7-6.

$$S_{landfill}\ (t) = W_t * DOC\ (1 - DOCf) * \frac{22}{6}$$

The stock only includes the permanent storage of paper that will not degrade in the year of disposal or the decades beyond that. Temporary storage of carbon in landfill – in between deposition in landfill and decomposition – is not considered because it has only a small, short-term impact on emissions (the total temporary stock may be large but only the annual changes are relevant to the carbon balance).

7.2.4 Avoided emissions

Energy recovery of waste and landfill gas can substitute virgin material inputs and associated emissions. Best practice in LCA suggests this should be accounted as avoided emissions outside of the studied system (e.g. in the power sector) (JRC/IES 2010). However, the approach in this thesis is different from LCA; total emissions are compared against a carbon budget for the paper life cycle and it is therefore not consistent to subtract emissions avoided *outside* of the paper life cycle. Any emission reduction outside of the paper life cycle should be compared against a target for the relevant sector to avoid double counting.

There are at least two ways to address this problem. First, avoided emissions may be excluded altogether. Second, avoided emissions may be included, but both ways. In other words, emissions avoided *by other systems* in the paper life cycle may be *added* to the total emissions in the paper life cycle. For example, the use of forestry waste for energy recovery in the paper sector constitutes an avoided emission from the perspective of the forestry sector. It is clearly beyond the scope of the thesis to include all these linkages.

The following compromise is chosen: avoided emissions are calculated but not aggregated with the other emissions. This provides some insight into the potential emissions reduction through energy recovery without falling into the trap of double counting. The avoided emissions are calculated as follows.

- *Paper in MSW*. The heating value of paper in MSW is 11-15 GJ/t (Merrild et al. 2008) and a middle value of 13 was used in the analysis. The electrical efficiency of MSW incineration plants is 0.17-0.30 (EC 2006a) for electricity only and a value of 0.25 is used in the calculation.
- *Landfill gas*. The heating value of CH_4 in landfill gas was assumed to equal that of natural gas (IPCC 2008). The calculation applies an electrical efficiency of 0.35 based on Wanichpongpan and Gheewala (2007) and Amini and Reinhart (2011). The estimation assumes zero flaring and should therefore be considered an upper estimate of the benefits of landfill gas capture and recovery.

The CI of the avoided energy generation, for both forms of energy recovery, is the same as the CI of bought electricity. The avoidance of the production of heat is not considered. Avoided emissions from wood that is not recycled but used for energy is ignored, for the same reasons that carbon stock changes in forests could not be estimated.

7.2.5 Uncertainty

The uncertainty analysis considers parametric uncertainty for each category of emissions. The uncertainty ranges were approximated as follows.

- *SEC values.* Macknick (2011) shows that global primary energy totals vary with 9.2% between different data sources, which can be interpreted as an uncertainty range. It is assumed that total energy demand for the paper life cycle features a similar level of uncertainty. The uncertainty ranges for SECs of electricity and heat are therefore assumed to be ± 10%.
- *CI values.* Macknick (2011) finds that estimates of CO_2 emissions from fossil fuels vary with 2.7% between data sources. Using the same logic as above, an uncertainty of ± 5% in the CI of fuels for extraction activities was assumed. For the CI of all other fuels, an uncertainty of ± 20% is assumed, to account for the assumption that "bought heat" and fuels for on-site electricity generation have the same CI as reported fuel use for on-site generation of heat.
- *Organic carbon.* The uncertainty in consumer product carbon storage is calculated based on the uncertainty ranges for net addition to stock of consumer waste, which was discussed in Chapter 5. The lower and upper bounds for the parameters for landfill (both regarding emissions and storage) were already shown in Table 7-4. The lower and upper limit for landfill emissions are estimated by calculating Equation 7-2 with respectively the lower and upper bounds of the parameters.

The amount of carbon storage due to recycling is very small and based on reliable data and therefore excluded from the uncertainty analysis.

7.3 Results

The results show the emission estimates by category of source and sink. Figure 7-5 displays GHG sources as positive emissions and GHG sinks as negative emissions. The main sinks and sources are fuels, electricity, consumer stock, recycling stock, landfill stock, and landfill gas. The total emissions from the global paper life cycle amount to 721 (-222/+317) Mt CO_2e. The largest source of emissions is electricity followed by bought fuels and landfill gas. Landfill acts as a considerable carbon sink which is about twice as large as net addition to stock due to in-use products. The effect on stocks of increased recycling is negligible.

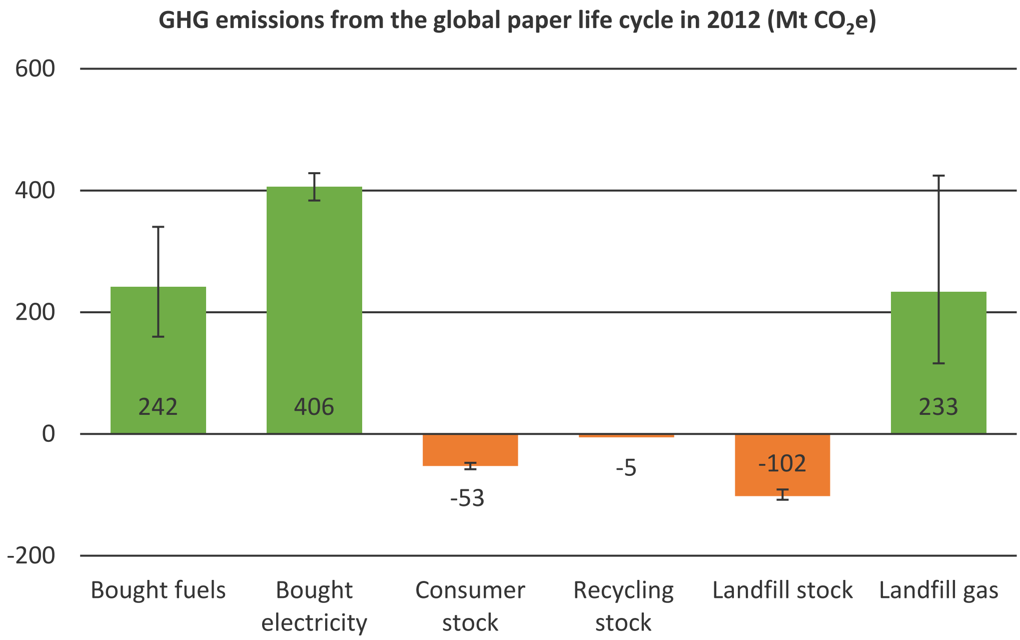


Figure 7-5. Greenhouse gas emissions by category (net emissions: 721 (-222/+317) Mt CO_2e).

The error bars show the uncertainty in the estimate for fuels (-82/+98), electricity (-22/+23), consumer stock (-5/+5), landfill stock (-6/+11), and landfill gas (-117/+191). The largest uncertainty is for landfill gas because several uncertain parameters are multiplied to obtain the answer. The uncertainty is also asymmetric because multiplication leads to exponential growth in uncertainty. Avoided emissions from energy recovery in MSW incineration and energy recovery from landfill gas both are both, coincidently, 15 Mt CO_2. These quantities are small compared to the aggregate emissions.

The results in Figure 7-5 are representative only for average global paper production. The emission intensity (emissions per unit of production) can be very different for a single country or an individual paper producer. For example, a paper mill may be supplied with zero carbon electricity in which case the GHG emissions of "bought electricity" would amount to zero. Some mills also use a much higher proportion of biofuels instead of coal and gas. The error bars do not reflect this kind of variability – they only show variation in the global estimate.

7.4 Discussion

This chapter estimated GHG emissions from the global paper life cycle in 2012. The findings are similar to those presented by other studies. Appendix F gives an overview of the emission estimates found in this and four other studies (Miner and Perez-Garcia 2007;

Allwood et al. 2010; FAO 2010a; Subak and Craighill 1999). The emissions are calculated per unit of paper consumption to adjust for different consumption levels across time. The following can be concluded from the comparison.

- Emission estimates per unit of paper for pulping, making, and printing are in between the values suggested by other global studies (Miner and Perez-Garcia 2007; Allwood et al. 2010; FAO 2010a; Subak and Craighill 1999).
- Emissions from landfill are similar in FAO (2010) but higher in Subak & Craighill (1999). The latter study is a much older analysis and reflects less advanced landfill gas recovery practices and lower levels of recycling.
- FAO (2010) calculates somewhat lower additions to landfill and consumer stock. The authors exclude industrial waste from waste to landfill and use an unusually low NaS fraction of 0.03 instead of 0.09 in this thesis.
- Allwood et al. (2010) estimate 686 Mt CO_2 emissions in 2006 against a comparable 721 Mt CO_2e in 2012 in this chapter. Stocks and landfill emissions, which are excluded by Allwood et al. (2010), together contribute 73 Mt CO_2e.

The results show that energy use is a significant contributor to overall emissions, with bought electricity being the biggest source. For pulping, papermaking, and printing, the energy supplied by bought fuels is 2.5 times as high as energy supplied by bought electricity. However, the CI of bought electricity is 3.9 times as high as the CI of bought fuels. The use of biomass in own generation, under the assumption of sustainable yield, leads to significantly lower emissions than if fossil fuels had been used; the CI of coal is 56% higher than the average CI of bought fuels (and the latter excludes mill waste).

The lower estimate for landfill emissions is almost fully offset by the landfill sink function. At the same time, within the uncertainty range, it is possible for landfill emissions to be four times the carbon storage in landfill. Ingerson (2011) finds that landfill of organic materials may lead to net carbon sequestration but only under select conditions. In the model, net sequestration of carbon in landfill could be achieved through for example tripling the CH_4 capture rate from 0.25 to 0.75. Improved landfill practices could thus potentially contribute to carbon removal from the atmosphere.

The model can only indicate the heat or electricity consumption per unit process but not the carbon emissions per unit process because the carbon emissions are based on the aggregate fuels, waste, and electricity consumption. In practice, some fuels and waste are used for certain processes only; for example, black liquor is used only in chemical pulping because it is a waste from chemical pulping. It is much harder to identify whether, for example, coal and natural gas are more prevalent in chemical pulping than papermaking. Future work may focus on the direct linkages between processes and fuel, waste, and electricity inputs.

The uncertainty in the estimate of total emissions largely results from the uncertainty regarding emissions from landfill. Even for individual landfills, landfill gas generation parameters are rarely known. Better data collection on the state of landfills, including CH_4 capture, could improve global estimates of emissions from landfill. There are ongoing efforts to improve and specify parameters on the national level (Choi et al. 2016). Another source of uncertainty is the reported energy data, which is incomplete and likely to contain errors. The data may be improved by simplifying the reporting standards for plants with CHP.

7.5 Conclusions

This chapter calculates GHG emissions from the global paper life cycle in 2012. It covers the following life cycle stages: forestry, pulping, papermaking, printing, and waste management (landfill and energy recovery). The analysis includes carbon sinks due to in-use stock, recycling stock, and landfill stock. The findings can be summarized as follows.

- Total emissions from the global paper life cycle amount to 721 (-222/+317) Mt CO_2e in 2012. The results are similar to earlier findings in the literature. The main sources of GHGs are bought electricity (406 Mt CO_2e) and bought fuels (242 Mt CO_2e).
- The largest uncertainty in emissions is associated with landfill gas because of the large number of uncertain parameters. There is also considerable uncertainty regarding fuel use because of missing data and likely reporting errors.
- The analysis assumed sustainable yield of forestry products and zero net emissions due to land use changes. This assumption reflects a lack of data and the current state of knowledge regarding forestry and land use change.

Future work should address the main sources of uncertainty and estimate the impacts of land use change. A prerequisite for modelling land use change is probably regional and temporal disaggregation. The next chapter will project future emissions starting from the base year described in this chapter.

8 Future greenhouse gas emissions from paper

8.1 Introduction

Rising population and economic growth stimulate future paper demand. At the same time, global emissions should radically decrease to limit average global warming to 2 degrees (see Section 4.6). This chapter estimates whether future emissions from the paper life cycle can stay within a proportional share of the carbon budget through improvements in material and energy use. Emissions are projected based on expected developments in paper demand, material use, energy use, and landfill practices.

The state-of-the-art analysis on future emissions from a selection of materials including paper is Allwood et al. (2010). The study relies on literature estimates of carbon emissions per unit process, which is less precise than using global energy data and does not allow fuel mix scenario analysis. The authors exclude organic carbon stocks and flows and use estimates for future paper demand from IEA (2008) that have been adjusted downwards more recently (IEA 2009, 2015c, 2016b; Elias and Boucher 2014).

This chapter addresses several shortcomings of previous studies. First, it develops a new estimate for future paper demand based on disaggregated trends for demand per grade and per category of per capita income. Second, it builds on a detailed material balance for both the base year and the years up to 2050. Third, it uses experience curves to estimate energy efficiency trends in the pulp, paper, and print sector as a function of cumulative production. Fourth, it considers organic carbon stocks and flows including CH_4 from landfill.

The next section describes the main scenarios, explains the demand projection, and details the trends in materials use, energy use, and landfill practices. The results are presented in Section 8.3 and discussed in Section 8.4. A more elaborate discussion of the results is presented in Chapter 9.

8.2 Methods and data

8.2.1 Overview

Emissions are projected based on three main scenarios: REFerence (REF), Increased Efforts (IE), and Waste-as-Resource (W-a-R). The scenarios provide internally consistent descriptions or "storylines" of possible future states of the world (IPCC 2013):

- The REF scenario is based on a continuation of currents trends and does not anticipate increased climate change mitigation.
- The IE scenario reflects a heightened concern with climate change and more GHG mitigation efforts.
- The W-a-R scenario assumes complete fulfilment of the recovery potential of waste and radical changes in energy use and landfill practices.

Each scenario is captured by three parameter sets regarding material use, energy use, and landfill practices. The parameters of each set may be at one of three levels, which are consistent with the main scenarios REF, IE, and W-a-R. Table 8-1 gives an overview of all possible scenarios based on the three parameter sets and their three settings. There are $3^3 = 27$ scenarios in total. Only the three main scenarios have the same settings for each parameter set and can be considered coherent descriptions of future pathways for the paper life cycle.

Table 8-1. Three main scenarios (marked grey) and 24 additional scenarios.

		Scenarios																										
Parameter set	**Level**	1 (REF)	2	3	4	5	6	7	8	9	10	11	12	13	14 (IE)	15	16	17	18	19	20	21	22	23	24	25	26	27 (W-a-R)
Material use	**REF**	X	X	X	X	X	X	X	X	X																		
	IE										X	X	X	X	X	X	X	X	X									
	W-a-R																			X	X	X	X	X	X	X	X	X
Energy use	**REF**	X	X	X							X	X	X							X	X	X						
	IE				X	X	X							X	X	X							X	X	X			
	W-a-R							X	X	X							X	X	X							X	X	X
Landfill practices	**REF**	X			X			X			X			X			X			X			X			X		
	IE		X			X			X			X			X			X			X			X			X	
	W-a-R			X			X			X			X			X			X			X			X			X

The 24 other scenarios are less coherent because performance in one domain (e.g. W-a-R material use) does not align with performance in another domain (e.g. REF energy use). These less coherent scenarios are essential for studying the individual impacts of changes in material use, energy use, and landfill practices. The settings for the relevant parameter sets are discussed further in the sections on material use (8.2.3), energy use (8.2.4), and landfill practices (8.2.5). The next section first describes the paper demand projection.

8.2.2 Demand projection

Table 8-2 summarizes recent projections for global paper demand in 2050. Not many forecasts are available and most are a component of energy modelling by the International Energy Agency (IEA). The only exception is Elias and Boucher (2014), which includes paper demand in a forecast for the forest products sector. The more recent the base year of the projection, the lower the expected demand in 2050. IEA (2008) forecasts a demand of around 960 Mt whereas the most recent forecast suggests a demand of 611 Mt (IEA 2016b). None of the references includes a detailed description of the methods.

Table 8-2. Demand projections for paper (demand in 2012 is around 400 Mt).

Reference	Base year	2050 demand projection (Mt)
(IEA 2008)	2005	≈ 960*
(IEA 2009)	2006	≈ 690-930**
(Elias and Boucher 2014)	2010	≈ 750
(IEA 2015c)	2012	758***
(IEA 2016b)	2013	611***

*Based on expected 164% increase and consumption figures from FAO (2016). **Based on expected per capita consumption (p. 146) and population in IEA (2008), p. 569. ***Figure from the data tables from the report website.

This chapter presents a new demand projection including methodological justification. An introductory discussion of the drivers for material use was provided in Section 2.2.2 and emphasized among others population and wealth. These drivers are reflected in the literature on demand forecasting. The *intensity-of-use hypothesis* (I-o-U) links material demand to expected economic growth. The I-o-U was established mainly by the work of Malenbaum (Malenbaum et al. 1973; Malenbaum 1973, 1978) and is described in Equation 8-1 as a function of material consumption (C_t) and gross domestic output (GDP_t).

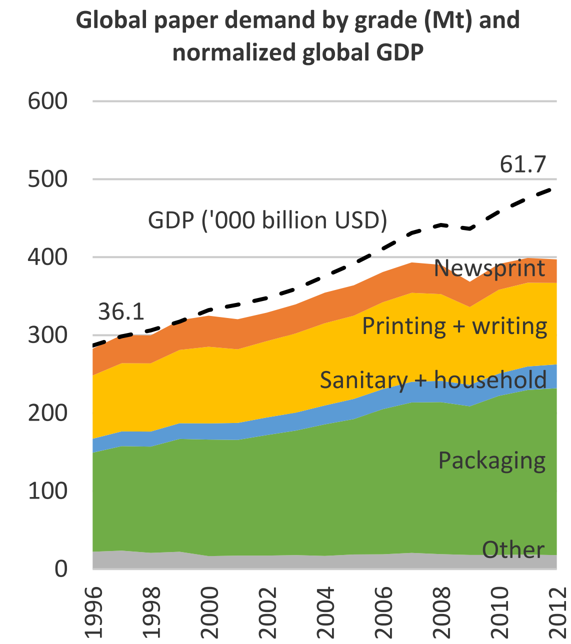
Equation 8-1.

$$IoU_t = \frac{C_t}{GDP_t}$$

The I-o-U is often found stable in the past and assumed to remain stable in the future. In other words, demand is generally expected to grow proportionally with GDP. Malenbaum (1973) and Roberts (1985) describe several mechanisms that may affect the I-o-U and complicate the relationship between GDP and material demand. The following five mechanisms are relevant at the global level (the literature also emphasizes trade but this matters only at the sub-global level).

- *Saturation of demand* may occur when economies shift from manufacturing and construction towards services. Societies in an early stage of industrial development may instead see a growth of manufacturing relative to agriculture.
- *Technological progress* leads to increasing technological efficiency and lower material requirements to fulfil the same function. A single product may need less material input and provide more functionality.
- *Substitution* occurs when a material gets superseded by more advanced alternatives. For example, demand for metals is affected by the rise of plastics and the demand for paper is affected by the emergence of electronic media.
- *Depletion* may dampen material demand. The difficulty of extracting materials drives up prices and shifts demand away before resources become fully depleted. The supply of renewable materials may collapse through overexploitation.
- *Stocks* of materials are functional without requiring further material inputs. Stocks of infrastructure and buildings have grown immensely in the developed world and reduce the need for construction materials.

How do these factors affect paper demand? Figure 8-1 shows global demand for major grades from 1996 till 2012 and normalized global GDP. The decoupling between global GDP and total paper consumption reveals that the I-o-U is not constant over time. Figure 8-2 reveals that only newsprint, sanitary + household, and "other" have decoupled from economic growth at the global level. Both graphs show a dip in global paper demand during the recent financial crisis (2008-2012). Consumption figures for this period should be considered outliers. The graph shows that newsprint and printing + writing became decoupled from GDP well before the crisis.



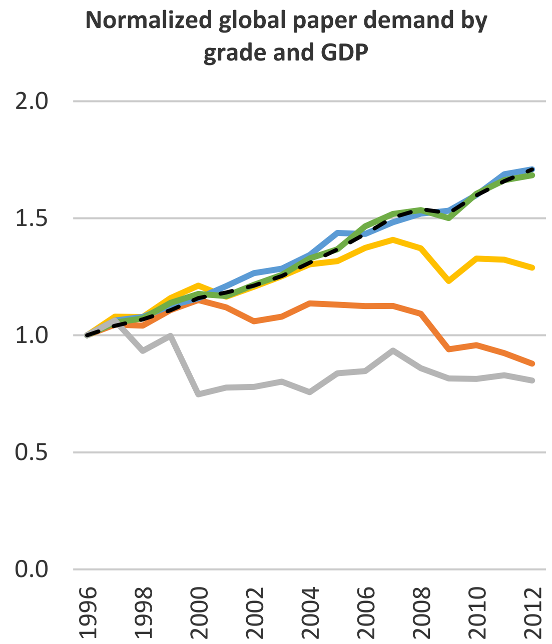


Figure 8-1. Paper demand and normalized GDP (based on FAO (2016) and OECD (2017)).

Figure 8-2. Normalized paper demand and GDP (based on FAO (2016) and OECD (2017)).

Decoupling of graphic paper demand from GDP is likely to be driven by substitution with electronics. An overview of physical daily newspaper circulation in several countries consistently shows a strong decline in sales (Media-CMI 2013). Decoupling of the category "other" is much harder to explain because it contains many different types of paper. It is likely that demand for specialty papers such as tobacco paper or wallpaper has reached a saturation level. It is also possible that the observed trend is simply the result of inconsistencies in the data collection and categorization process.

Substitution and saturation effects play a different role in rich countries and poor countries. Figure 8-3 shows consumption of the four main paper grades for two income groups: OECD countries and non-OECD countries[16]. The grade "other" is left out because it is small and ill-defined and fluctuates very strongly. For each graph, a regression line is shown. All regression lines are made to intersect with the origin and therefore represent a constant I-o-U (i.e. when GDP doubles, so does consumption). The R squared reveals whether the consumption data also reflects a constant I-o-U or not.

[16] A plot of I-o-U and GDP/capita is avoided because this relationship is very sensitive to small changes in GDP. Instead, consumption is shown for two income groups.

- An R squared close to 1 indicates a good fit with the regression line and therefore a constant I-o-U.
- A negative R squared indicates the data has a better fit with the mean of the data set than with a regression line through the origin. This implies the I-o-U is not increasing with GDP but stable or even declining.

The figure clearly shows that in OECD countries, demand for packaging, printing + writing, and newsprint has decoupled from GDP. For newsprint, demand is declining. The demand for sanitary + household correlates with GDP but the data points for 2006 and 2007 suggest it may have started to decouple. In non-OECD countries, the I-o-U of all grades is more or less constant. This demand growth will not continue forever but is likely to follow the same pattern as in OECD countries. Non-OECD countries may never reach the same levels of newsprint and printing + writing demand but instead "leapfrog" to electronics.

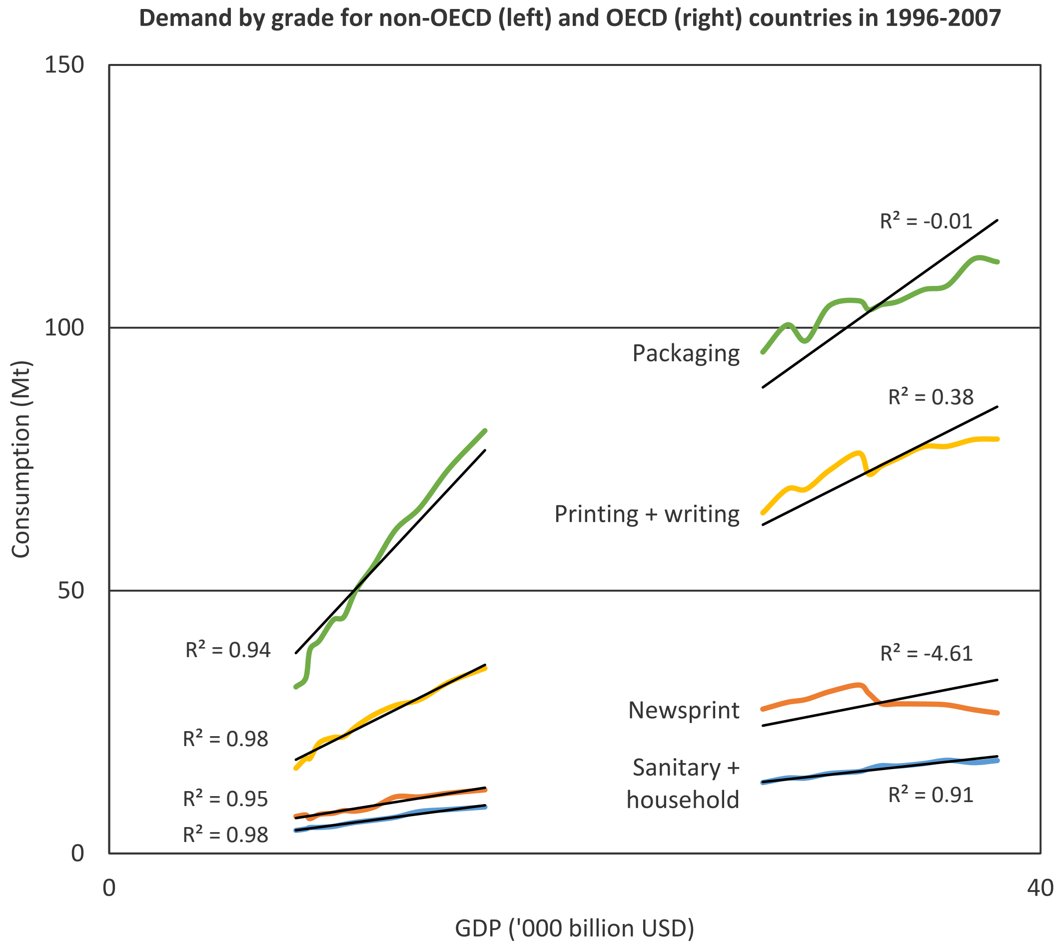


Figure 8-3. Demand by grade and income (based on FAO (2016) and OECD (2017)).

Table 8-3 summarizes the findings from Figure 8-3 for each grade and income group. It lists the R squared and the observed effect: constant I-o-U, substitution, or saturation. Saturation leads to future consumption levels *equal or higher* than current consumption whereas substitution leads to future consumption levels *lower* than current ones. The table also lists *projected consumption levels* in 2050. The projections are based on the historical data in graph A to E in Figure 8-4, which show per capita consumption of all five grades for OECD and non-OECD countries for the years 1961-2012 (with clear marking of the most recent pre-crisis year). The projections are shown in the same graphs.

For grades that experience substitution or saturation, future per capita demand is based on interpolation between current demand and consumption levels in 2050 using exponential growth curves. For grades with a constant I-o-U, demand is calculated based on GDP growth projections by OECD (2017). Uncertainty is captured by using ranges instead of single values for saturation levels. For grades with a constant I-o-U, an uncertainty of ± 20% in demand in 2050 is assumed. Aggregate demand follows from the individual estimates and population projections by UN (2015a) and is shown in graph F in Figure 8-4.

In conclusion, global paper demand is estimated to rise to 878 (673-1,084) Mt in 2050. Of the aforementioned five factors that affect the I-o-U, the analysis for paper demand only identified substitution and saturation. Depletion of virgin resources may matter but requires modelling the economics of fibre supply. Stocks hardly matter because the NaS is only 0.09 for paper (Section 5.2.4). Chapter 5 and 6 show how technological progress affects demand for virgin inputs (but not paper products) through higher levels of recycling. The potential effect of end-use technologies on final demand will be discussed in Chapter 9.

Table 8-3. Consumption scenarios for five paper grades.

Grade	Income group	R^2 of regression through origin	Effect	Projected consumption in 2050 (kg/capita) or uncertainty range
Newsprint	OECD	-4.61	Substitution	1-5
	Non-OECD	0.95	Saturation	1-5
Printing + Writing	OECD	0.38	Substitution	10-20
	Non-OECD	0.98	Saturation	10-20
Sanitary + Hygienic	OECD	0.91	Saturation	14-18
	Non-OECD	0.98	Constant I-o-U	± 20%
Packaging	OECD	-0.01	Saturation	80-100
	Non-OECD	0.94	Constant I-o-U	± 20%
Other	OECD	0.38	Saturation	3-7
	Non-OECD	0.98	Saturation	3-7

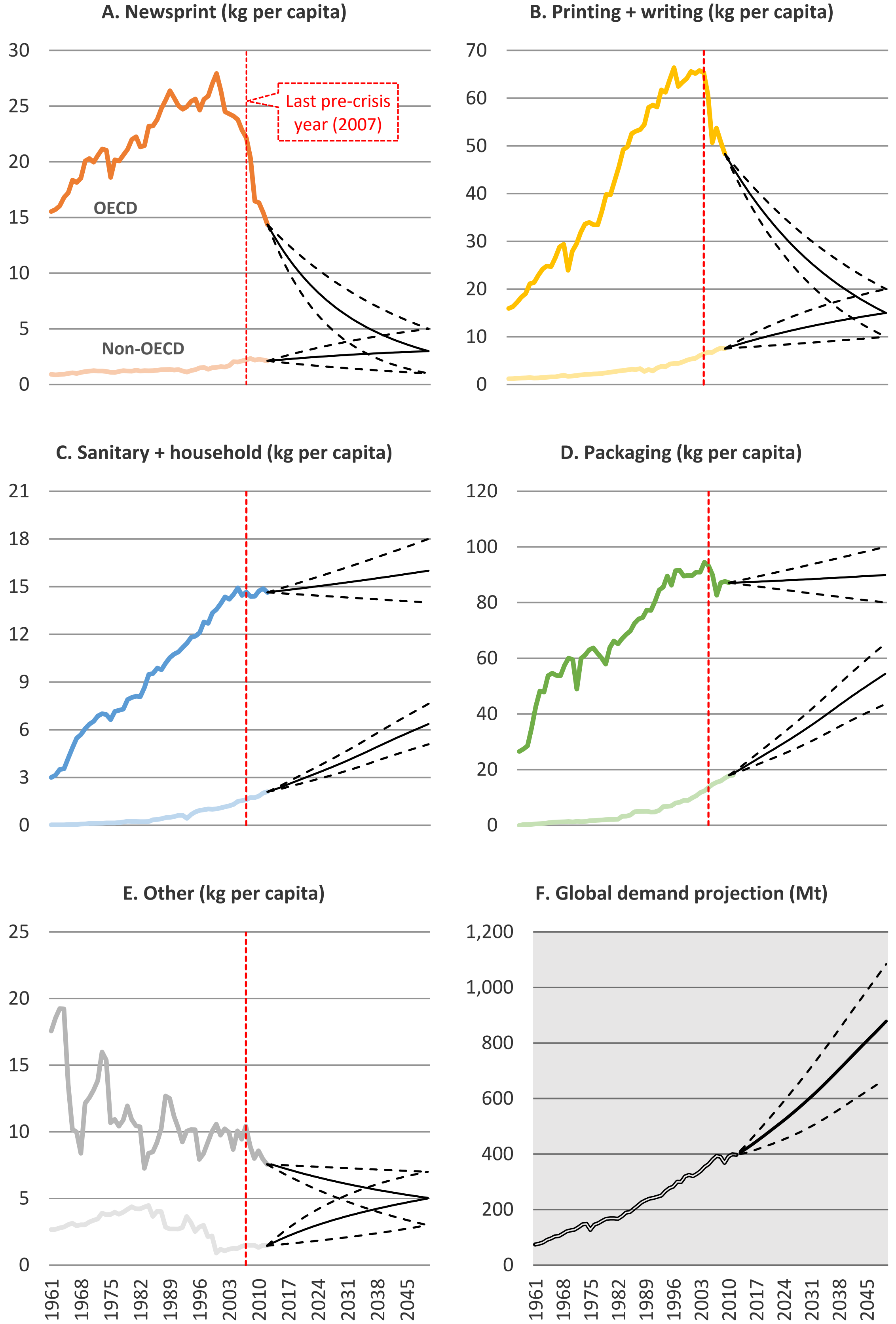


Figure 8-4. Per capita demand by grade and income group (A to E) and total demand projection (F).

8.2.3 Material flows

Trends in future material use are formulated based on Chapters 5 and 6. The W-a-R scenario corresponds with complete fulfilment of the recovery potential of waste in the paper life cycle, as described in Chapter 6. The rates of improvement in the REF and IE scenario are based on an equal partitioning of the gap between current performance and W-a-R performance. In other words, the REF scenario and the IE scenario close respectively one third and two thirds of the performance gap between recovery in 2012 (R_{2012}) and the recovery potential (RP) in 2050. The parameters R_i for the use of waste as a resource in the REF and IE scenario are described in Equation 8-2 and Equation 8-3.

Equation 8-2.

$$R_{REF,i} = R_{2012,i} + \frac{1}{3} * (RP_i - R_{2012,i})$$

Equation 8-3.

$$R_{IE,i} = R_{2012,i} + \frac{2}{3} * (RP_i - R_{2012,i})$$

The REF scenario roughly implies global performance will be raised to the levels currently found in rich countries only. For E-o-L discards, the current fulfilment of the RP is 0.69 in OECD countries, 0.41 in non-OECD countries, and 0.55 at the global level. The REF scenario implies an increase in the fulfilment of the RP for recycling of E-o-L discard from 0.55 to 0.70 (one third of the gap between 0.55 and 1.00 is closed). A recovery potential fulfilment R of 0.70, which coincides with a recycling rate of 68%, is about the same as average current performance in OECD countries. Parameters grow linearly between 2012 and 2050. The full set of parameters for current and future material use is summarized in Appendix D-1.

8.2.4 Energy use

The global paper sector consumes a large amount of fuel and electricity. Technologies and practices for increasing the energy efficiency of pulping and papermaking include improvement of components, their (combined) use, and better maintenance of equipment (Laurijssen 2013; IEA 2007a; Suhr et al. 2015). Example components are pumps, motors, and fans. Smart combined use of components minimizes the loss of heat. This chapter assesses the combined impacts of process improvements through the use of experience curves that describe trends in energy efficiency at the aggregate level.

Brucker et al. (2011) show how to use experience curves to estimate trends in industrial energy efficiency. The approach is based on the idea that energy efficiency increases with cumulative capacity rather than time. This makes sense because major improvements in industrial equipment are usually implemented when either 1) the equipment wears out based on intensity and duration of use or 2) new facilities are built to address increasing demand. Experience curves are widely used to assess price development in energy supply and demand technologies (Wiesenthal et al. 2012; Neij 1997; Krawiec et al. 1980; Weiss et al. 2010).

Industrial experience curves for final energy (electricity and heat) in the pulp, paper, and print sector are described in Equation 8-4 and Equation 8-5 based on the SEC in year t (SEC_t), Cumulative Production in year t (CP_t), and experience index (b) (Ramírez and Worrell 2006; Brucker et al. 2011).

Equation 8-4.

$$SEC_t = SEC_0 * {CP_t}^b$$

Equation 8-5.

$$LR = 1 - 2^b$$

The longer the period, the more reliable the index (Ramírez and Worrell 2006). The earliest available data is for 1971 and a complete energy balance is constructed for this year. The method and data sources are the same as for the energy balance in 2012 described in Section 7.2.2.3. From 1971 till 2012, cumulative production more than quadrupled and the SEC for final energy decreased with around 14%. This implies a learning rate of 6.8%, i.e. with every doubling of cumulative production the SEC decreases with 6.8%. Cumulative paper production up to the earliest recorded year in FAO (2016) is calculated based on a linear increase in consumption from 0 in 1900 to the reported value of 74 Mt in 1961. Of course, paper was in use before 1900, but the historical quantities are too small to significantly affect cumulative production figures. The learning rates in the REF, IE, and W-a-R scenario are respectively 6.8%, 10.2%, and 13.5%.

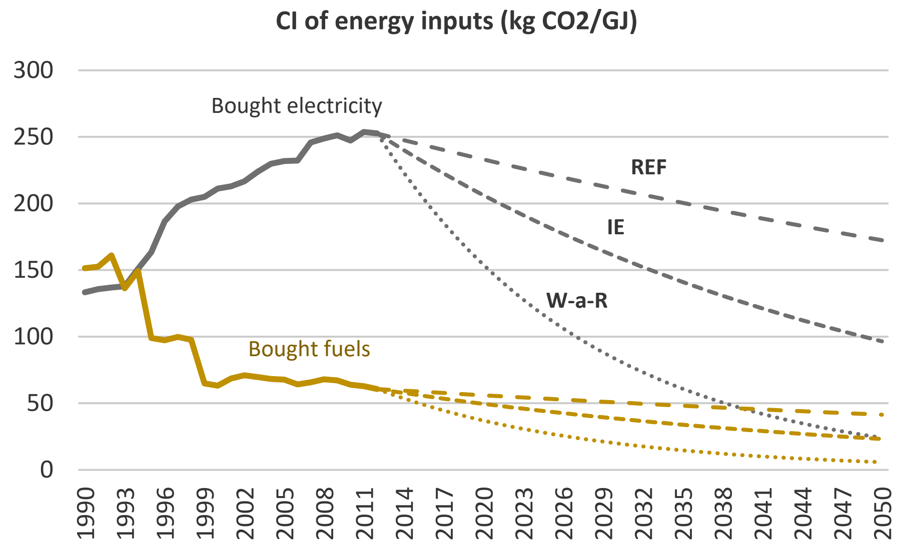


Figure 8-5. Carbon intensity projection of electricity and heat.

The CI of bought fuels and bought electricity is expected to decrease in the future. Figure 8-5 shows the historical development and the expected trajectories for the REF, IE, and W-a-R scenario.

- For fuels, there is a stable trend in the years 2002-2012 and the CI decreased on average 1.0% per year. This trend is assumed to continue under the REF scenario, including for fuels in forestry and mining.
- For electricity, the CI has grown strongly over the past decades but stabilized closer to 2012. A reasonable estimate for future decarbonization under the REF scenario is 1.0%, which is the same as for fuels.

A 1.0% decarbonization rate leads to an overall reduction in the CI of both energy sources of 32% between 2012 and 2050. The decarbonization rates for the IE and W-a-R scenario for both energy sources are respectively 2.5% and 6.0% annual reduction. This equates to total reductions by 2050 of approximately 62% and 90% of the CI. The latter reduction is very ambitious; the EU, which is a climate change mitigation leader, states that “current and planned policies” are not nearly sufficient to achieve almost zero emission electricity (EC 2012b). A similar reduction in the carbon intensity of fuels is also very ambitious because of the already large global demand for biofuels and land. The parameters for energy use and emissions are summarized in Appendix D-2 and D-3.

8.2.5 Landfill practices

Future improvements in landfill practices are captured by changes in the parameters MCF and R (the parameters are explained in Section 7.2.3.3). Because of a shift towards deep managed landfill, the MCF changes from 0.7 in 2012 to the following values in 2050: 0.8 in the REF scenario, 0.9 in the IE scenario, and 1.0 in the W-a-R scenario. The MCF of 1.0 reflects the use of deep controlled landfills only. The CH_4 capture rate R is 0.25 in 2012 and expected to increase to 0.50 in the REF scenario. In the IE and the W-a-R scenario, the average performance rises to that of respectively basic landfills (R = 0.75) and engineered landfills (R = 0.85) (USEPA 2013). The parameter values grow linearly between 2012 and 2050. The parameters for current and future landfill practices are summarized in Appendix D-3.

8.2.6 Uncertainty

Three sources of uncertainty affect the emission estimates: the demand projection, fuel use developments, and the carbon target for the impact assessment. Future demand may follow the low, middle, or high scenario with consumption levels of respectively 673, 878, and 1,084 Mt paper in 2050. Paper demand approximately proportionally affects aggregate emissions beyond the base year. Fuel use development is uncertain because bought fuels complement mill waste, for the generation of electricity and heat, but the amount of mill waste is dependent on the feedstocks; recycled pulping generates much less waste than chemical pulping and the waste is not as suitable for energy generation.

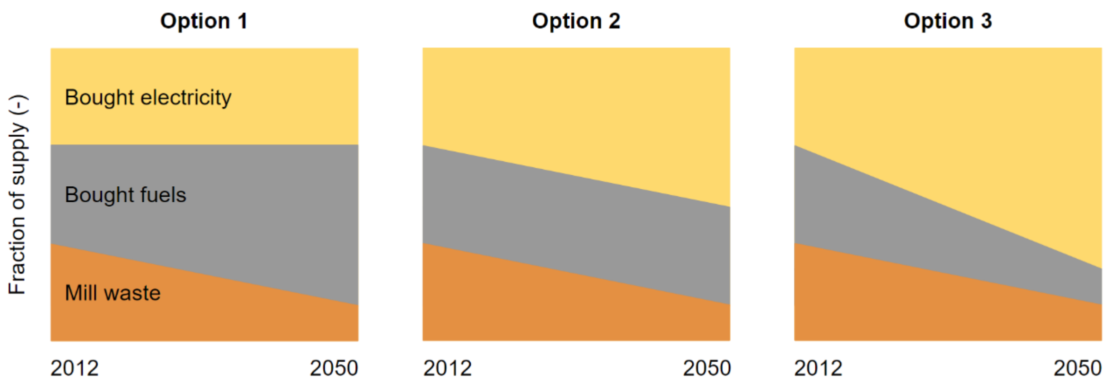


Figure 8-6. Options for meeting energy demand with declining black liquor generation.

The key question is: how will the industry respond to a decline in black liquor under increased recycling? Figure 8-6 visualizes three possible routes regarding the fractions of (low carbon) bought fuels and (high carbon) bought electricity in total energy supply. The options can be explained as follows.

1. The fraction of bought fuels and mill waste together grows proportionally with energy supply. Bought fuel use grows faster than total energy supply and compensates for declining black liquor production.
2. The fraction of bought fuels in total energy supply grows proportionally with total energy supply. The loss of black liquor does not affect the relative popularity of bought fuels as an energy input.
3. The fraction of bought fuels in total energy supply declines proportionally with the availability of mill waste. The logic is that low availability of black liquor deters investment in on-site generation.

It should be noted that in some scenarios, the fraction of mill waste in total energy supply *increases* because energy efficiency improvements outpace increases in recycling, in which case option 3 leads to a higher share of bought fuels than option 1. In addition, there is one overriding setting in the model for cases in which heat demand exceeds heat supply as defined by the three options – in this case bought fuels are increased to meet the demand for heat but all electricity is bought from the grid (this only occurs under a combination of W-a-R material use and fuel use option 3).

The two GHG targets (cumulative and annual) are defined as ranges to reflect uncertainty in the estimates of the global carbon budget. Future emissions may meet the upper limit but not the lower limit in which case it is uncertain whether sufficient carbon abatement takes place. Finally, the parametric uncertainties considered in Chapter 7 (see Section 7.2.5) need to be considered again here. However, because the GHG emission target focuses on the relative decrease or increase in emissions between 2012 and 2050, only the effect of parametric uncertainty on this relative increase or decrease needs to be considered.

8.3 Results

The results are presented in Figure 8-7, which shows the emissions profile for 2012 and for 2050 in the three main scenarios. The net emissions are indicated by black lines and the target range of annual emissions in 2050 is presented by dotted lines. The calculation of the target range was explained in Chapter 4 and is calculated in Appendix E. The emissions are broken down by three types of stock, fuel use, electricity, and landfill gas. Net emissions grow slightly from 721 Mt CO_2e in 2012 to 736 Mt CO_2 in 2050 in the REF scenario.

The net emissions in the IE scenario are much lower and fall within the range of the emission target. The net emissions of the W-a-R scenario fall well below the target range. The net negative emissions of -19 Mt CO_2e in the W-a-R scenario suggest paper production and consumption can potentially serve as a carbon sequestration strategy. Both the IE and W-a-R scenario rely on ambitious decarbonisation scenarios for bought fuels and electricity; the climate change target can therefore only be met through profound changes in both the paper sector and the electricity sector.

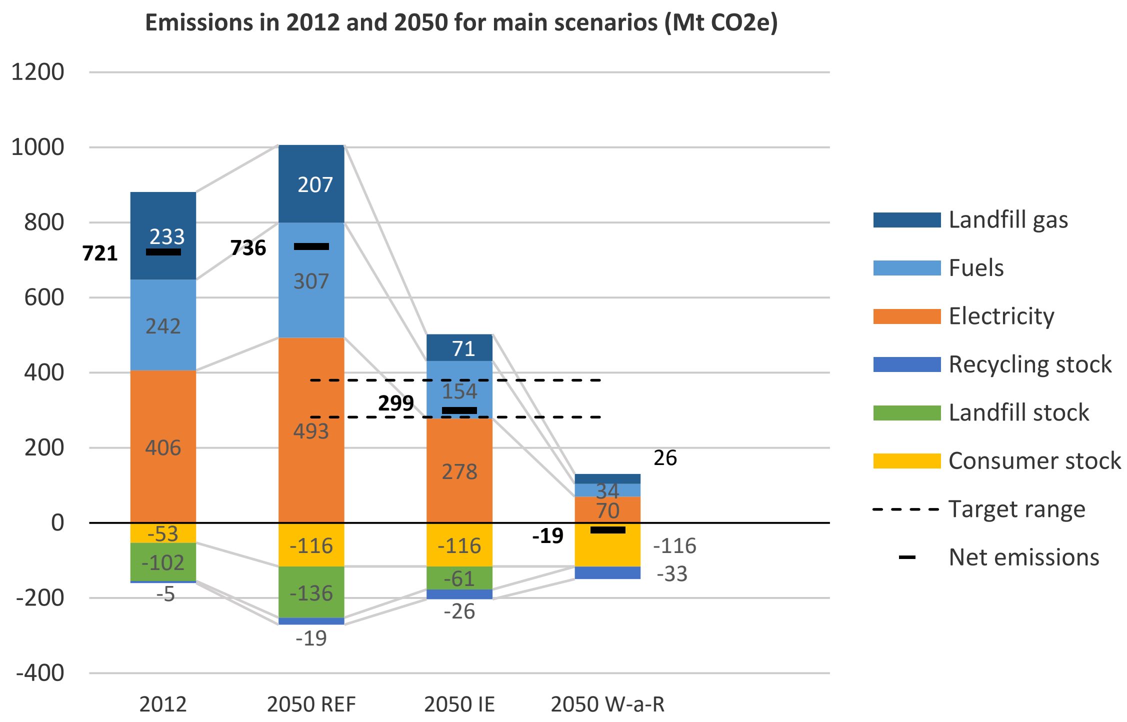


Figure 8-7. Emissions from the global paper life cycle in three scenarios.

The underlying drivers for carbon reduction can be found by studying the impact of other scenarios than the three main scenarios. Table 8-4 describes aggregate emissions for 8 of the in total 27 scenarios. The scenarios cover the REF and W-a-R settings for each parameter set. The colour coding instantly reveals that energy use impacts aggregate emissions most. Surprisingly, higher ambitions regarding the use of waste as a resource lead to an increase instead of decrease in total emissions. Under W-a-R material use, all else being equal, emissions in 2050 are 10% higher than under REF; the observed emission reductions in the IE and W-a-R scenarios are driven by improvements in energy use and landfill practices but not by changes in material use.

Table 8-4. Total emissions in 2050 (Mt CO_2e) for selected scenarios (names between brackets).

Material use	**Landfill practices**	**Energy use**	
		REF	*W-a-R*
REF	*REF*	736 (REF)	28 (7)
REF	*W-a-R*	591 (3)	-117 (9)
W-a-R	*REF*	808 (19)	42 (25)
W-a-R	*W-a-R*	748 (21)	-19 (W-a-R)

The minor increase in emissions when using waste as a resource can be clarified by comparing a breakdown of the emissions in the REF scenario and scenario 19, which combines REF settings for energy use and landfill with W-a-R material use (see also Table 8-1). Figure 8-8 shows that W-a-R material use leads to significant emission reductions for recycling stock, fuels, and landfill gas. At the same time, there are more emissions from electricity and (a reduction of) landfill stock. A decrease in waste to landfill leads to a net change of +31 Mt CO_2e in scenario 19 because it instantly limits additions to landfill stock but only reduces landfill gas with a considerable time delay.

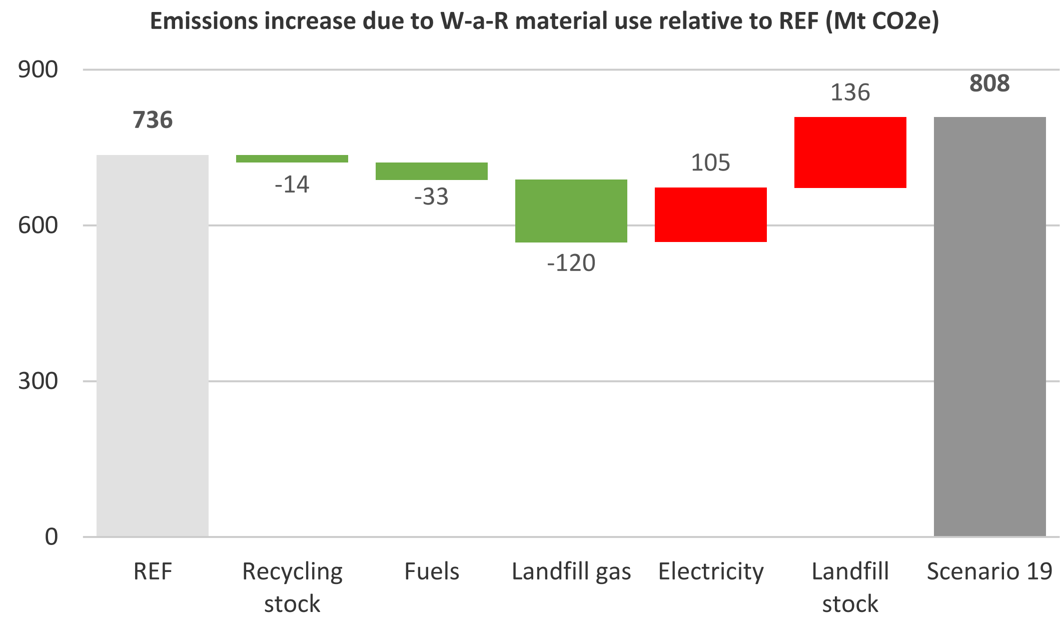


Figure 8-8. Breakdown of differences between W-a-R and scenario 19.

The main uncertainties relate to aggregate demand, fuel mix developments, and the emission targets. Table 8-5 presents the results of the three scenarios as either 1) a further reduction required to meet the target or 2) the carbon savings beyond the target. The results are given for both the lower (L) and higher (H) emission target for both cumulative (2013-2050) CO_2

emissions and annual (2050) GHG emissions. The outcomes are given for variations in demand and different developments in the fuel mix. Demand is included as low (L) and high (H) demand and fuel mix developments are indicated as low (L) and high (H) bought electricity. The latter corresponds with options 1 and 3 described in Section 8.2.6.

The reference scenario rarely meets the targets. Only with a low demand projection does the REF scenario meet the higher target for cumulative emissions. The REF scenario does not meet the annual emission target under any circumstance. The IE scenario meets the targets in most cases but not under particular combinations of demand and fuel mix developments. The W-a-R scenario always meets the target and achieves cumulative and annual savings of up to respectively 13 Gt CO_2 and 422 Mt CO_2e. The results indicate that the REF scenario is insufficient and the W-a-R scenario sufficient to meet the targets. These findings are robust because they are the same under virtually all variations of demand, fuel use developments, and emission targets. Whether the IE scenario can meet the targets is uncertain.

Table 8-5. Required further reductions or savings beyond the targets.

	Model uncertainty			Emission target	
Scenario	**Demand**	**Fuel mix**	**Target**	**Cumulative**	**Annual**
REF	L	L	L	24%	56%
			H	48%	67%
		H	L	26%	58%
			H	49%	69%
	H	L	L	1 Gt	32%
			H	26%	49%
		H	L	0 Gt	36%
			H	31%	52%
IE	L	L	L	1 Gt	2%
			H	26%	27%
		H	L	2 Gt	42 Mt
			H	20%	17%
	H	L	L	5 Gt	118 Mt
			H	0 Gt	20 Mt
		H	L	6 Gt	150 Mt
			H	0 Gt	52 Mt
W-a-R	L	L	L	11 Gt	401 Mt
			H	6 Gt	303 Mt
		H	L	12 Gt	422 Mt
			H	7 Gt	324 Mt
	H	L	L	12 Gt	382 Mt
			H	7 Gt	284 Mt
		H	L	13 Gt	395 Mt
			H	7 Gt	296 Mt

The parametric uncertainty in the SEC, CI, and landfill parameters (discussed in Section 7.2.5) has a limited impact on the relative change in emissions between 2012 and 2050. The estimate of percent changes in emissions between 2012 and 2050 under the three main scenario vary by ± 3 percent point. For example, in the REF scenario, emissions increase from 721 in 2012 to 736 Mt CO_2e in 2050, which implies an increase of +2%. This percentage is +4% and -1% for respectively lower and higher estimates of the parameters. It should be noted that the landfill parameters for MCF and R in 2050 are not subject to the uncertainty analysis because their future values have been defined as part of the scenarios (all other landfill parameters are constant over time).

Avoided emissions are not considered in relation to the carbon target. They are nevertheless relevant to carbon abatement generally. In the REF scenario, avoided emissions due to energy recovery of end-consumer discards grow from 15 Mt CO_2 in 2012 to 32 Mt CO_2 in 2050. Avoided emissions due to energy recovery of landfill gas grow from 15 Mt CO_2 to 26 Mt CO_2. The avoided emissions are low compared to aggregate emissions. It can be concluded that the paper life cycle makes a modest but significant contribution to carbon abatement in other sectors through energy recovery. The inclusion of avoided emissions would not change the finding that W-a-R material use leads to higher net emissions: increased recycling leads to a reduction in landfill and energy recovery from E-o-L discards and thus to a reduction of avoided emissions (and therefore higher net emissions).

8.4 Discussion

The findings of this chapter follow from a complex interplay between model design, parameter values, and modelling assumptions and reflect the empirical work in Chapters 5 – 8 and the theoretical and conceptual work in Chapters 2 and 3. This section will only reflect on how the model produced the results shown in the preceding section and compares them with Allwood et al. (2010). The next chapter provides a general discussion of 1) how the results relate to findings in the LCA literature, 2) the generalizability of the results, 3) alternative abatement strategies, and 4) implications for decision making.

The most significant finding is that W-a-R material use contributes very little to emission reduction. In fact, all else being equal, pursuing W-a-R material use (scenario 19) leads to a minor increase (around 10%) in overall emissions. The shift towards recycling reduces total demand for electricity and heat by around 10%. At the same time, the share of electricity in total energy supply increases from approximately 21% to 28%. This shift is the consequence of a reduction in the availability of black liquor from chemical pulping since recycled pulp replaces chemical pulp.

The results in Table 8-5 suggest that fuel use developments are very important since an emphasis on bought fuels (option 1 instead of option 3) leads to better performance in the IE and W-a-R scenarios. In fact, when the paper industry commits to own generation from a relatively low carbon fuel mix, scenario 19 does not exceed emissions in the REF scenario. If the industry behaves in accordance with option 1 and maintains the same share of on-site electricity and heat generation in total energy use, increased use of waste as a resource leads to 5% *lower* emissions in 2050 compared to REF. With fuel use options 2 and 3, the emissions are respectively 10% and 19% higher than under REF.

Energy efficiency significantly reduces overall GHG emissions. Under IE energy use, all other settings being REF, the total emissions are 53% lower. For W-a-R energy use, the total emissions are only 28 Mt CO_2e. The thesis aims to gauge the importance of improving material use for climate change mitigation in the paper life cycle but these results seem to suggest that the CI of energy use is the single most important factor. Efforts aimed at reducing the CI of energy use are much more likely to yield climate benefits than changes in material use patterns. A decrease in energy demand, a cleaner fuel mix, and cleaner electricity yields the greatest reductions in the model.

Emissions of landfill gas are strongly dependent on material use because W-a-R material use results in zero waste to landfill. Because emissions from landfill are delayed, even the W-a-R material use scenario still involves generation of CH_4 in 2050. Improved landfill practices can cut CH_4 emissions from landfill in 2050 by a factor 3-4 under both W-a-R and REF material use. The landfill sink function is not affected by better landfill design and management since this only affects how and how quickly decomposition takes place but not the actual amount of material that is ultimately decomposed (and thus the amount of carbon that is stored indefinitely).

None of the reviewed studies listed in Table 4-1 reveals how recycling affects aggregate emissions, except for the model by Allwood et al. (2010). For the year 2006, the authors apply a CI of recycled pulping which is 10% higher than the CI of virgin pulping. For the year 2050, the CI of recycled pulping is 84% higher. The article does not explore scenarios with low levels of recycling but their model can be easily duplicated. In the reference case, the fraction of E-o-L discards going to recycling increases from 43% to 81%. If instead recycling is maintained at the same level, the model projects around 10% lower emissions in 2050[17], similar to the findings in this chapter.

There are also significant differences between Allwood et al. (2010) and this chapter. Total emissions from the global paper life cycle (excluding stock changes or landfill gas) increase by 75% from 2006 to 2050 in Allwood et al. (2010). The thesis findings show an increase of 23% in emissions excluding stocks and landfill gas. The main explanations for this discrepancy are the following.

- Allwood et al. (2010) use a slightly higher demand forecast: paper demand grows between 2006 and 2050 with a factor 2.5 instead of a factor 2.2 in the thesis. This has a roughly proportional impact on emissions.
- Allwood et al. (2010) assume different decarbonization rates for different processes. The authors assume very limited decarbonization of recycling (20% lower CI in 2050 compared to 2006) which leads to relatively high future emissions.
- Allwood et al. (2010) do not discriminate between different grades of paper. The thesis accounts for a shift towards packaging, which has the lowest energy requirements of all paper grades, leading to lower overall emissions.

The scenarios for increased carbon abatement show similar results. Allwood et al. (2010) present a "beyond best practice" scenario which constitutes a reduction of around 40% against the reference. The IE and W-a-R scenario in this chapter lead to reductions of 33% and 84% against the reference (again excluding stocks and landfill gas). The "beyond best practice" scenario is thus in between IE and W-a-R. Allwood et al. (2010) conclude only demand reduction or a further reduction of carbon emissions from energy use are sufficient to meet the carbon target. The findings from the W-a-R scenario confirm that only decarbonization of energy (and not more recycling) is sufficient.

[17] A minor error was found in the calculation by Allwood et al. (2010). For the base year 2006, the amount of end-of-life discards going for recycling is calculated as $Y_0*(1-\alpha_1)$. For 2050, it is incorrectly calculated as $Y_0*(1-\alpha_1-\alpha_2)$. The emissions in 2050 should be 1200 Mt CO2 instead of the reported 1130 Mt CO2.

Finally, it should be noted that the findings represent *average* values at the *global* level. The CI of electricity is highly variable across countries. In some cases, increased recycling and a shift from own fuel use to electricity may therefore lead to a reduction of emissions. However, it is likely that paper mills in countries with low carbon electricity also use relatively clean fuels. The local opportunities for carbon reductions through increased recycling are thus likely to be limited. At the company level, the circumstances are different again. Recycling paper mills could choose to purchase green electricity only in which case the average CI of electricity in the relevant country does not affect the relative merit of recycling.

8.5 Conclusions

This chapter estimates future emissions from the global paper life cycle based on a projection of paper demand and several scenarios for material use, energy use, and landfill practices. The demand projection considers per capita income levels, expected aggregate economic and population growth, and saturation and substitution effects. The model produces three main insights.

- The paper life cycle can only meet the GHG target compatible with less than two degrees warming through strong decarbonization of energy inputs.
- Increased use of waste as a resource most likely leads to higher emissions due to reduced availability of black liquor and the time delay in landfill emissions.
- Increased use of waste as a resource may lead to lower emissions when the loss of black liquor is compensated for with bought (low carbon) fuels and the fraction of bought electricity in total energy use is not increased.

Future work should investigate whether the limited impact of the use of waste as a resource can also be observed for other material life cycles. The next chapter will do the first attempt by briefly discussing the similarities and differences between paper recycling and recycling of other materials. The chapter will also reflect on all the preceding chapters and provide a broad discussion of the thesis findings.

9 General discussion

9.1 Introduction

The previous chapters described the relevant literature on sustainable use of materials and argued for a potential-based concept of waste. The thesis aim – *to assess the climate change mitigation benefits of the efficient and circular use of materials in the global paper life cycle* – was met by modelling the material flows, energy flows, and GHG emissions of the global paper life cycle for the base year 2012 and for several scenarios up to 2050.

This chapter considers the implications of the most significant findings. Does the literature confirm that the use of waste as a resource leads to more rather than less emissions from the paper life cycle? Can the findings be generalized to other materials and environmental issues? And what other options are available for climate change mitigation in the global paper life cycle?

The next section first compares the thesis findings with those in the LCA literature. Section 9.3 discusses whether the conclusions hold for other materials than paper and other impacts than climate change. Section 9.4 discusses alternative routes for carbon abatement in the paper life cycle. The chapter concludes with a synthesis of improvements for guiding principles for material use with a focus on the potential-based concept of waste and methods for sustainability assessment.

9.2 Comparison with life cycle assessment

9.2.1 Overview of issues

The most significant finding of the study is the likely increase in emissions under increased use of waste as a resource. This result is consistent with earlier modelling by Allwood et al. (2010). However, the LCA literature overwhelmingly suggests that paper recycling has climate change mitigation benefits (Schmidt et al. 2007; Laurijssen et al. 2010; Merrild et al. 2008; Villanueva and Wenzel 2007). This discrepancy results from the methodological differences between the thesis and typical LCA studies.

The thesis aims to test to what extent certain abatement efforts in the paper life cycle are sufficient to meet targets for GHG reduction. Because of the sufficiency criterion, the outcomes are compared against an absolute limit based on the carbon budget. In LCA, the outcomes are only compared between scenarios. The sufficiency criterion has two important consequences.

- *Temporal developments* need to be considered because the carbon budget is a function of time. In contrast, most LCA studies are static.
- *Avoided emissions* are not aggregated with the other sinks and sources because only absolute emissions are relevant for the carbon budget. Most LCA studies include avoided emissions in total emissions. Most importantly, LCA studies often calculate avoided emissions from energy generation from trees that are not recycled, but the thesis presents a zero estimate of the impact of land use change.

The following two sections elaborate on how these two methodological differences affect the relative merit of recycling. They will be shown to explain the discrepancies between the findings of the thesis and LCA studies.

9.2.2 Static versus dynamic

All of the reviewed LCA studies on the paper life cycle are static and exclude time delay in landfill gas emissions (Villanueva and Wenzel 2007; Schmidt et al. 2007). The lack of temporal specification in LCA is a well-known methodological shortcoming (Ekvall et al. 2007; Haes et al. 2004). The ISO standard considers the lack of temporal information in the inventory data an "inherent limitation" of LCA and suggests additional information is needed to interpret LCA results (ISO 2006).

In the thesis, landfill emissions from waste are emitted years *after* disposal. In the W-a-R scenario, in spite of near zero landfill in 2050, landfill emissions still make up about 10% of total emissions. At the same time, the removal of carbon from the atmosphere through storage in landfill is reduced proportionally with improvements in recycling and amounts to practically zero in 2050. In LCA studies, higher recycling instantly reduces both removals through storage and landfill gas emissions. The LCA studies therefore present increased recycling more favourably than in the thesis.

It should be noted that static approaches in LCA do not reflect best practices. Brandão et al. (2013) summarize six strategies for including time delay in LCA. The basic logic of the strategies is that they adjust future emissions with a weighting factor between 0 and 1. For example, a linear downward adjustment based on a 100-year time horizon, starting in 2012, implies emissions in 2050 will only be relevant for another 62 years and should be multiplied with a corresponding factor 0.62.

The strategies reviewed by Brandão et al. (2013) had not been developed at the time the LCA studies on paper were published. In the reviewed studies, CH_4 is calculated using the GWP for a 100-year time horizon (GWP100) and one unit of CH_4 in 2050 has the same warming effect as one unit of CH_4 in 2013. If the reviewed LCA studies had considered landfill with a time-dependent weighting they would have estimated lower impacts from landfill and therefore also lower avoided impacts through recycling.

The weighting of future emissions is implied in the thesis because it relates future emissions to future carbon targets. The targets are derived from the global carbon budget, which is based on a probabilistic analysis of emissions pathways that would keep warming below 2 degrees throughout the twenty-first century (Meinshausen et al. 2009). These pathways consider temporal developments including decay of short-lived gases. The results for non-CO_2 gases are expressed as annual emissions only (using GWP100).

Another potential issue regarding temporal change and recycling is decarbonization over time of energy inputs. This, however, does not lead to a discrepancy between the thesis findings and LCA studies because bought fuels and bought electricity are assumed to be decarbonized at the same annual growth rate. The ratio between the CI of fuels and electricity therefore remains constant over time and the effect of a shift in energy inputs is independent of time (like in static LCA).

9.2.3 Avoided emissions

Most LCA studies include avoided emissions in the total emissions. That is, avoided emissions are subtracted from the actual emissions. The purpose of including avoided emissions is to fully account for the consequences of a decision by considering its impacts outside of the system boundary. There are two main categories of avoided emissions in LCA studies on paper (Villanueva and Wenzel 2007).

- *Avoided emissions through energy recovery of wood.* In most LCA studies, recycling leads to a reduced demand for virgin fibre and virgin fibre is allocated instead to energy generation. The energy use of wood leads to avoided emissions in the electricity and heat sector by substituting fossil fuels. Including these avoided emissions from saved wood makes recycling appear *more* attractive in LCA studies. This is also pointed out by Merrild et al. (2008) and Laurijssen et al. (2010).

- *Avoided emissions through energy recovery of E-o-L discards.* Increased recycling may reduce incineration of E-o-L discards. In most LCA studies, energy recovery of E-o-L discards is expected to substitute other electricity generation technologies. An increase in recycling thus implies a reduction in avoided emissions. The thesis calculates these avoided emissions but excludes them from the emissions totals. Most LCA studies thus present recycling *less* favourably in this respect.

The above methodological choices have opposite effects but will, on balance, lead to a more favourable assessment of recycling in LCA.

1. An increase in recycling by 1.0 kg leads to a reduction in energy recovery of E-o-L discards of 1.0 kg (when the alternative is energy recovery, not landfill).
2. At the same time, paper for recycling substitutes on average 1.5 kg of wood, which is used for energy recovery (see Section 5.4.1 for the substitution ratio).
3. Altogether, there is -1.0 + 1.5 = 0.5 kg more organic material (either paper or wood) that goes to energy recovery.
4. The additional energy recovery of organic material reduces overall emissions through the avoided use of fuels in the power sector.

Some of the LCA studies assume energy recovery of wood or paper substitutes fossil fuels rather than an average electricity mix, which further increases the savings from avoided emissions through higher recycling (Villanueva and Wenzel 2007).

There are several reasons why avoided emissions have been excluded from total emissions in the thesis. Most importantly, the subtraction of avoided emissions from the totals is not consistent with carbon targets based on the global carbon budget. The carbon budget is based on absolute emissions and cannot be met through "avoiding" emissions. If all sectors were allocated lower emissions by subtracting avoided emissions, the aggregate figure would fall below actual economy-wide emissions.

A second reason for not including avoided emissions is the high uncertainty associated with estimates for the alternative use of wood. At the local scale, in the short term, it may be possible to identify alternative uses of wood. In the long run, at the global level, the relationship between forest carbon stocks and commercial use of wood is currently not well understood. Section 7.2.3.2 explained why the alternative use of wood on the global scale is very hard to estimate and why suitable data is lacking.

The avoided emissions through energy recovery of E-o-L discards were calculated based on reliable data but not aggregated with the total emissions. Only including this type of avoided emissions would merely reinforce the conclusion that recycling has limited benefits because increased recycling leads to a reduction of avoided emissions related to E-o-L discards. The thesis also calculates avoided emission through energy recovery of landfill gas. None of the reviewed LCAs includes this type of avoided emissions. It was found to be a small quantity that does not change the overall findings.

9.3 Generalizing the results

9.3.1 Materials other than paper

The findings show that the use of waste as a resource is not always a beneficial climate change mitigation strategy. In particular, the use of one waste stream, E-o-L discards, goes at the expense of the generation and use of another waste stream, black liquor. The impact of the use of other waste is dwarfed by the impacts of recycling and black liquor recovery because of the sheer quantity of the latter two waste streams. This section assesses whether this pattern is likely to hold for other material categories.

To find the answer, it is necessary to compare the main properties of several material life cycles. The analysis by Allwood et al. (2010) provides a logical starting point because it covers five materials and the model parameters also suggest paper recycling is not unequivocally beneficial. However, the authors show that the CI of recycled processing of steel, aluminium, and plastics is 5-19 times lower than virgin processing of the same materials. Recycling thus helps reduce CO_2 emissions for these materials. Only concrete is different because it can only be “recycled” as low-value aggregate.

The low CI of virgin processing, relative to recycling, is unique to the paper sector. Paper and timber are the only materials in high demand that are co-produced with renewable biomass waste that can be used for energy recovery. All other materials – steel, aluminium, plastic, concrete – are produced in facilities that make direct use of fossil fuels or obtain electricity from the grid. Among the few exceptions are aluminium smelters which may be co-located with hydropower plants (IEA 2007a).

Recycling of other materials than paper leads to reduced energy use and lower CO_2 emissions, but how recyclable are these materials? Chapter 2 listed five main limitations to the efficient and circular use of materials, among which net addition to stock. Interestingly, most materials have much higher NaS than paper. IEA (2007a) suggests 53-83% of annual consumption of steel, aluminium, and plastic is either lost or added to stock.[18] This means that their potential for recycling is more limited than for paper.

Another limitation to recycling is material demand growth: today's material discards are not sufficient to cover tomorrow's material demand. Expected demand growth varies by material. For example, the IEA Energy Technology Perspectives (IEA 2016b) suggest steel demand will grow slightly slower than paper demand but aluminium demand will grow much faster. For all three materials, demand growth is a limiting factor for the substitution of virgin inputs with recycled material.

Finally, contamination and loss of quality limit the potential for recycling. This barrier is relevant for all materials and implies a continued need for virgin material inputs. Only some metals can be reprocessed to their elemental form but steel and aluminium will inevitably become contaminated (Reck and Graedel 2012). Modaresi and Müller (2012) find that current recycling practices will lead to a surplus of highly alloyed aluminium for which few applications exist. Paper and aluminium are similar in this respect.

A separate in-depth analysis would be required to tell exactly which dynamics govern the environmental impacts of other materials than paper. It is clear though that the potentially higher GHG emissions under increased recycling in the global paper life cycle should not be expected for other materials. For other materials, recycling is clearly beneficial, but the lack of available scrap due to net addition to stock may limit the potential climate change mitigation benefits of recycling. In addition, as for paper, recycling of many materials is constrained by demand growth and material contamination.

[18] IEA (2007a) also suggests 28% of paper is lost or added to stock which is considerably higher than the estimate of the thesis: 12%. In either case, it is true that NaS values are higher for other materials than for paper.

9.3.2 Impacts other than climate change

The drivers, limits, and impacts of climate change are much better understood than for the other eight planetary boundaries. The dominance of CO_2 as a greenhouse gas, the importance of fossil fuels as sources of CO_2, and the linear response of the climate to cumulative CO_2 emissions are convenient properties for the analyst. None of the other planetary boundaries exhibits the same kind of causal simplicity as climate change. They have also received much less attention in research generally and in research on material use.

Can the thesis findings be generalized to other planetary boundaries? The most urgent environmental problems, besides climate change, are genetic diversity, land-system change, and biogeochemical flows of phosphorus and nitrogen. The boundaries can be explained as follows (Steffen et al. 2015).

- *Genetic diversity* is one of two components of biosphere integrity. Genetic diversity represents the "information bank" that helps the biosphere persist and adapt to abiotic change. It is currently (imperfectly) measured as the species extinction rate. A better measure would be the Phylogenetic Species Variability (PSV) but no such data exists for the global scale.
- *Land-system change* focuses on the bio-geophysical processes in land systems which help regulate the climate. Relevant land systems include forests, woodlands, savannas, grasslands, shrublands, and tundra. The boundary focuses on forests because they play an important role in the land surface-climate coupling. The boundary is defined for total forested land and for tropical, temperate, and boreal forest cover.
- *Biogeochemical flows of phosphorus (P) and nitrogen (N)* impact the state of air, soil, and water. For example, the oversupply of nutrients in water stimulates growth of plants and algae and leads to oxygen depletion of the water. The human perturbation of phosphorus and nitrogen flows is driven mainly by the use of fertilizer in agricultural activities. The boundary is defined in terms of phosphorus flows into the ocean and erodible soils, and industrial and intentional biological fixation of nitrogen.

The paper life cycle is relevant to all three boundaries because of forestry. Deforestation and degradation of forests directly drive loss of genetic diversity and land-system change.

Plantations have ambiguous impacts on biodiversity; they generally feature lower species diversity than primary or secondary forests, depending on their management, the use of indigenous and mixed species, and the previous or alternatives uses of the land (Bremer and Farley 2010). Forests also play a role in the nitrogen cycle through use of fertilizer and nitrogen deposition from the atmosphere. Unfortunately, in the thesis, forestry is only analysed in terms of fuel and electricity use in extraction activities, and none of these findings can therefore be generalized to the other planetary boundaries.

Pulping and papermaking play a role in biogeochemical cycles by releasing wastewater that contains excess N and P. The nutrients are introduced into the system to feed bacteria in biological wastewater treatment systems. They are also introduced through the use of chemicals such as defoamers, water conditioners, scale inhibitors, chelants, biocides and slimicides, wet and dry strength additives, and dyes and pigments. When the aggregate nitrogen and phosphorus inputs exceed the nutrient requirements in the treatment system, or leave the system unused for other reasons, the wastewater will contain excess N and P (FPAC 2008). Finally, fuel combustion contributes to emissions of nitrous oxides, which play a part in the nitrogen cycle (and which contribute to problems like acid rain).

The model in the thesis could be extended to include N and P flows to estimate the contribution of the global paper life cycle to the boundaries formulated by Steffen et al. (2015). The results could be related to the "industrial and intentional biological fixation of N" and the "P flow from freshwater systems into the ocean". Regional distribution is more important for N and P flows than for GHG emissions and further modelling would be needed to arrive at meaningful figures. In addition, the contribution of plantations to "P flow from fertilizers to erodible soils" could be calculated, though it should be expected to be very small compared to agriculture (Smethurst 2010).

Section 4.2.3.2 – 4.2.3.4 discussed local environmental impacts of the paper life cycle including air pollution, water pollution, odour, and noise. The estimated GHG emissions are not a good proxy for these local impacts. Air and water pollution can be greatly reduced through pollution prevention techniques like flue gas treatment. Similarly, harmful elemental chlorine for bleaching is not inherent to paper production but can be substituted for by elemental chlorine free (ECF) or totally chlorine free (TCF) bleaching agents. These technologies would have to be modelled separately to estimate local impacts. In addition, the study of local problems requires a spatially disaggregated model. Even if for example air pollutants were included in the analysis, it would have limited meaning, since exposure levels cannot be calculated.

In summary, it is difficult to generalise the findings to impacts other than climate change. However, an expanded version of the model could cover several other environmental issues. A better understanding of forestry could provide more insight into the contribution of the global paper life cycle to land use change and loss of genetic diversity. It would also provide more insight regarding climate change. The contribution of the paper life cycle to biogeochemical cycles may be estimated with an extended version of the model. A better understanding of local environmental problems requires a different type of model which is spatially disaggregated and which includes a variety of pollution prevention technologies.

9.4 Alternative abatement options

9.4.1 Intensity of use

The scenario analysis explored different routes for meeting the same final demand for paper. An alternative route to climate change mitigation is to reduce demand by using paper more intensively. This could be done by light-weighting paper or reusing paper. In both cases, the same amount of service would be derived from a lower quantity of paper. A review of the literature reveals at least two technologies for demand reduction: light-weighting graphic paper and "un-printing" office paper.

Hekkert et al. (2002) suggest that different grades of graphic paper can be 7-15% lighter (though this may already have happened). An optimistic reduction of 15% of newsprint and printing + writing paper would reduce total demand by about 5%. The literature does not contain any estimates of the potential weight savings for other paper grades. A weight saving of 15% for all grades, which is very unlikely, would lead to proportionally lower emissions. However, such savings still fall within the uncertainty range for total paper demand.

Un-printing could drastically reduce paper demand but only for particular grades. Toshiba introduced a heat sensitive toner for their "e-blue" system which allows print to be removed from regular office paper at 140 degrees Celsius (Toshiba 2003). The latest model still requires special ink and allows paper to be reused five or six times. Some of the old print remains visible after treatment, which is a problem in case of confidentiality, and the toner is limited to the colour blue (Toshiba 2013).

Un-printing regular ink from regular paper may be done using ultraviolet radiation, infrared light, or laser ablation (Leal-Ayala et al. 2011). The laser ablation process damages the paper least and a comparison of modelled and experimental results suggest the toner-removal process can be controlled. The technology has been shown to be technically feasible but has not been commercialized. Its potential depends on further development of the technology and the practices and behaviour of paper users.

The un-printing technology is most promising for offices. The consumption of cut size paper is about 5% of total paper and board consumption in the United Kingdom (PPL Research Ltd 2012) and about 75% of cut size paper is used in offices (Hekkert et al. 2002). The share of paper suitable for un-printing is thus around 4% of total consumption and un-printing could reduce total paper consumption with a modest 3% if all office paper were to be unprinted about five times on average. In summary, the potential impacts of more intensive use of paper are very limited.

9.4.2 Substitution

Paper products are expected to be increasingly substituted with electronics. The thesis does not consider substitution of paper beyond the expected trends captured by the demand projection. Since the phenomenon is happening already, it is difficult to draw the line between substitution that will happen anyway and additional substitution that may be achieved through policy changes. Instead, this section focuses on whether substitution is at all desirable: does it lead to environmental benefits or not?

Graphic paper and packaging makes up about 88% of total consumption and may be substituted with electronics or plastics. Much of the interest regarding substitution focuses on graphic paper and electronic devices. Most evidence suggests potential benefits for substitution of paper by electronics.

- E-readers have a lower climate change impacts when they are used intensively: when a single user reads at least around 30 books, the impact per book is lower than for paper books (Moberg et al. 2011).

- Watching the news on television or the internet has a lower impact than reading a newspaper unless a single news item could be consumed without the need to produce the entire paper (Reichart 2002).
- Electronic journals may or may not have energy benefits compared to print academic journals. Critical factors are readings per article, the inclusion of transportation, and the copying or printing technology (Gard and Keoleian 2002).

The above studies all emphasize the importance of the modelling assumptions. The environmental benefits of substitution with electronics are very hard to estimate with LCA because most electronic devices are multi-purpose devices and substitute a range of paper products and other products. For example, the smartphone renders both writing paper and postal mail redundant. It also provides access to the internet for which no paper substitute exists. A direct comparison based on a functional unit is therefore hardly possible.

The largest paper category by volume is packaging. Packaging material may be substituted with plastic or metal packaging with the additional advantage of potential reuse. Well-established reusable packaging systems already exist for pallets, beer kegs, trolleys, bins, and tote boxes (Breen 2006). The reuse of packaging requires advanced reverse logistics to return the packaging to the manufacturer. The attractiveness of disposable paper packaging is that no return journey is required (which could save time, effort, and emissions).

The evidence regarding the environmental benefits of substituting paper packaging with reusable alternatives is ambiguous. A review of studies finds that reusable plastic carrier bags generally outperform single-use paper bags (Lewis et al. 2010). An LCA of reusable plastic fruit containers and disposable ones from corrugated board suggests the latter have slightly lower climate change impacts (Levi et al. 2011). Silva et al. (2013) show that the introduction of reusable packaging for the transportation of automotive parts increases climate change impacts.

9.4.3 Carbon storage

Climate change mitigation efforts may alternatively focus on carbon storage. The thesis treats carbon storage as a side-effect of scenarios that focus on better material use and energy use. It calculates storage for in-use products, recycling, and landfill. It does not explore carbon storage as a mitigation strategy because the research question focuses on the merit of the efficient and circular use of materials only. A deliberate push for carbon storage may help reduce emissions from paper.

Carbon storage may be achieved by increasing the forest carbon stock or by increasing the in-use stock. Forest carbon stock can be increased through better forest management and the generation of new forest on land that would otherwise not have been forested. Leaving native forests to grow further also increases the carbon stock (Keith et al. 2014). However, forests are more than "sticks of carbon" and optimizing a forest for carbon storage only may go to the detriment of biodiversity and other ecosystem services (Jacob et al. 2014).

Indefinite storage of paper makes for a considerable carbon sink. However, under current conditions, the net impact would be approximately zero because the average CO_2 emissions per kilogram of paper roughly equal its carbon content (in CO_2 equivalents)[19]. A more obvious choice for carbon storage is timber because it has much lower process emissions. It would also replace carbon-intensive materials like steel and cement and therefore lower emissions from construction activities.

Carbon may also be stored as CO_2 through Carbon Capture and Sequestration (CCS). CCS can be applied to any point source of CO_2. Carbon is stored underground or in the ocean. Some leakage of carbon is to be expected as well as additional energy requirements. In total, a fossil fuel power plant with CCS would emit 80-90% less CO_2 (Metz et al. 2005). The capturing of organic CO_2 could make for a carbon sink in case of sustainable yield. CCS technology is currently still in the pilot and demonstration phase (Reiner 2016).

9.4.4 Other feedstocks

The thesis only considers existent waste streams from the paper life cycle and their potential use as a resource. It does not cover the recovery potential of waste that is generated outside of the paper life cycle and that may be used as a feedstock for paper production. This is not an inherent limitation of the approach but merely the result of the system boundary: if for example agriculture had been included in the system then the recovery potential of agricultural residues as a feedstock would have been part of the analysis.

[19] The emissions for extraction, pulping, and papermaking were estimated at 1.6 kg CO2/kg paper in 2012. The carbon content of paper is approximately 0.40 which equates 1.5 kg CO2/kg paper.

Bousios and Worrell (2017) suggest a Multiple Input-Multiple Output (MIMO) mill that uses a variety of fibrous inputs including agro-industrial residues and plants. Residues from the agricultural sector include wheat straw, rapeseed straw, sunflower stalks, vine shoots, tree trimmings, and greenhouse waste. Suitable plant material includes switchgrass, miscanthus, reed canary grass, giant reed, and cardoon. The authors also suggest a variety of utilization options for mill waste, which were also discussed in Chapter 6.

The use of alternative feedstocks may have climate change mitigation benefits. Kissinger et al. (2007) calculate a lower footprint for wheat straw than for spruce and aspen. The estimated footprint of flax straw and aspen are equal. Unfortunately, no other studies could be found that compare the environmental merit of different feedstocks. This is not surprising given the persistent uncertainty surrounding the climate impacts of forestry; the carbon impacts of other feedstocks may be even harder to calculate.

9.5 Implications for material use

9.5.1 Waste as a potential resource

The thesis argued for a potential-based concept of waste which may be measured through the "reuse potential indicator" developed and applied by Park & Chertow (2014). The thesis shows that the notion of waste as a potential resource presents an improvement over the principles of efficiency and circularity because it merges both concepts and takes into account their limitations. For example, recycling metrics implicitly suggest a maximum rate of a 100%, but the recovery potential indicator reflects that net additions to stock make it impossible to cycle everything.

The thesis refined the recovery potential approach by applying it to all major waste flows in the global paper life cycle. The findings show that the recovery potential can be used to gauge the system-wide impacts of fulfilling the recovery potential of several individual waste flows and to optimize a complex material system. The usefulness of the recovery potential approach is constrained mainly by the system boundary since any system may exchange waste or resources with its surroundings.

Chapter 3 suggested the recovery potential has three main benefits besides providing a measurable concept of efficiency and circularity. First, as opposed to the legal definition of waste, the potential-based concept of waste was expected to show the importance of the context. However, at the global level, the available data only allowed for crude estimates of the recovery potential and a very general discussion of contextual factors. The analysis nevertheless provides a foundation for a more local assessment of reuse.

Second, the potential-based concept of waste was said to compensate for the asymmetry between the waste holder and the waste user in the legal definition. The recovery potential estimates included, to some extent, an indication of the next user, including the construction industry and agriculture. In practice, a more precise indication may be needed to enable waste holders to identify a next user for their waste, which probably requires direct participation of waste holders and users, like in the National Industrial Symbiosis Program (NISP) in the United Kingdom (Jensen et al. 2011).

Third, the communication of the potential resource value of waste was expected to reduce the risk of careless discarding. The analysis featured sufficient detail and clarity to push waste holders to rethink the potential value of their waste. However, it does not explore how this potential needs to be communicated beyond the academic discourse (it can be safely assumed the relevant waste holders will not read this thesis). The suggestions in Chapter 3 regarding the inclusion of the recovery potential indicator in BAT documentation remain the subject of further study.

In summary, the potential-based concept of waste signifies an improvement over current guiding principles for material use. It merges the idea of efficient and circular use of materials and considers their inherent limitations. The potential of waste may be measured through the recovery potential indicator. The application of this indicator to a large material system is shown to reveal the system-wide benefits of efficiency and circularity. However, further research is needed to illustrate how exactly the potential-based concept of waste can address the shortcomings in the legal definition of waste.

9.5.2 Fulfilment of the recovery potential

The thesis analysed to what extent efficiency and circularity, measured as the fulfilment of the recovery potential of waste, help meet GHG targets for the global paper life cycle. Surprisingly, the modelling results show that on average, all else being equal, a push for higher recycling of paper is not likely to yield carbon mitigation benefits. The main reason for this outcome is a trade-off between the use of E-o-L discards for recycling and the associated reduction in the generation of black liquor waste from virgin pulping.

What is the implication of this finding for guiding principles for material use? At the most basic level, the results show that it is necessary to balance waste generation and the use of waste as a resource across material systems. The potential-based concept of waste should not be applied to a single waste in isolation. However, there is no need to question the benefits of recycling generally: the discussion of the modelling outcomes revealed that the findings cannot be generalized to steel, aluminium, plastic or cement.

The thesis also showed that efficiency and circularity alone are not sufficient to meet GHG targets for staying below 2 degrees average global warming. This was also found by Allwood et al. (2010) for not only paper but also steel, aluminium, plastics, and cement. The limited impacts of efficiency and circularity can be explained by the five inherent limitations that were listed in Chapter 2, and which include energy requirements for material processing, net addition to stock, demand growth, contamination and quality losses, and changes in consumer demand.

In summary, it is recommended to pursue the use of waste as a resource, but whilst taking account of possible negative side-effects. There may be trade-offs between the generation and use of different types of waste; for paper, recycling may increase instead of decrease emissions, but this should not be expected for other materials. The finding that efficiency and circularity alone are *insufficient* to achieve GHG targets is likely to be generally valid, and should always be kept in mind when discussing resource efficiency and the circular economy as a means to achieve sustainability targets.

9.5.3 Sustainability assessment

The limited climate change benefits of increased recycling calls for caution in the formulation of material use strategies. Such strategies, it appears, need to be constantly evaluated to know whether they contribute to an overall reduction of environmental impacts and whether or not they are sufficient to meet global environmental targets. At the same time, there is a need for rules of thumb, to save time and effort, and speed up decision making.

It is therefore useful to know what kind of assessment should be done first when the means for it are limited. Based on the analysis, the following assessment criteria may be used, in order of the amount of time and effort that goes into generating the necessary evidence.

1. Avoidance of landfill
2. Avoidance of virgin inputs

3. Reduction of individual energy demand and impacts
4. Reduction of system energy demand and impacts

This “sustainability assessment hierarchy” may be used as a guideline for prioritizing environmental assessment. The first two options require only material flow analysis. The last two options require an analysis of energy flows and environmental pressures such as CO_2 emissions. Adhering to the assessment hierarchy contributes to the improvement of guiding principles for material use. Each assessment criterion in the hierarchy calls for different data and methods.

1. *Avoidance of landfill* can be estimated from waste generation and treatment data. Data availability at the national level is relatively good because the waste sector is partly public, heavily regulated, and most waste is transported over relatively short distances (unlike virgin materials). Diversion from landfill figures have limited meaning because they do not tell the size of the environmental benefits. Some alternatives to landfill, as discussed in Chapter 6, are hardly more desirable.
2. *Avoidance of virgin inputs* can be deducted from a full material balance which includes virgin processing and E-o-L waste treatment (and recycling in particular). The material balance in the thesis is constructed from publicly available data, parameters in the literature, and industry reports. This takes considerably more effort than analysing waste treatment only but yields valuable insights regarding the continued need for virgin inputs even with high CRs.
3. *Reduction of individual energy demand and impacts* can be calculated based on energy and environmental data. An example is a comparison between virgin and secondary input processing without assessing the rest of the life cycle. Energy data availability is relatively good and environmental impacts may be assessed using, for example, LCI databases. The thesis does not include an analysis of individual energy demand and impacts but applies a systems approach instead.
4. *Reduction of system energy demand and impacts* can only be assessed through a systems approach. Such an approach is taken in Chapters 7 and 8. The larger the system boundary, the more indirect effects and interactions can be included. Ideally, a whole systems approach is chosen, which covers the interaction between several life cycles or sectors in the economy. This approach requires most time and effort but yields the most valuable results.

In summary, the assessment hierarchy ranks options in terms of feasibility and usefulness of the results. The choice of method should depend on the question and the available resources. For the paper life cycle, each assessment yields additional insights: fulfilment of the recovery potential can phase out landfill, but does not phase out virgin material requirements, and is never a sufficient strategy for meeting the GHG targets. A system-wide impact assessment requires most effort, provides the most valuable results, and is imperfect nonetheless.

10 Conclusions

10.1 Main findings

The thesis investigated the climate change mitigation benefits of the efficient and circular use of materials in the global paper life cycle. It presented a model of material flows, energy flows, and GHG emissions, and showed how the fulfilment of the recovery potential of major waste flows in the global paper life cycle affects emissions between 2012 and 2050. The results were compared against GHG targets based on the carbon budget for staying below 2 degrees average global warming.

The efficient and circular use of materials was defined as the fulfilment of the potential of waste to be used as a resource. The potential-based concept of waste was argued to address shortcomings in the European regulatory concept of waste. It indicates to what extent and how waste can be used as a resource and can be measured with the "reuse potential indicator" (Park and Chertow 2014), which indicates how "resource-like" a waste is with a score between 0 and 1.

The fulfilment of the recovery potential of all major waste flows in the global paper life cycle was estimated to reduce waste to landfill to close to zero. The fraction of paper for recycling in total fibrous inputs can be almost doubled but some virgin inputs remain indispensable. The recovery potential indicator was shown to provide useful context for the interpretation of mass-based recycling and material efficiency metrics. It was successfully applied to optimize material use in the global paper life cycle.

Only profound changes in energy use and landfill practices were found to be sufficient to meet the GHG emission targets. The use of waste as a resource is likely to increase total GHG emissions unless the reduced availability of renewable chemical pulping waste (black liquor) for energy recovery is fully compensated for with bought (low carbon) fuels. Another factor that limits the benefits of increased recycling is the time delay between a reduction of waste to landfill and a reduction of landfill emissions.

10.2 Implications of the findings

The analysis confirmed that demand growth, in-use stocks, energy requirements, and contamination and degradation limit the potential benefits of the efficient and circular use of materials. The findings suggest that any strategy for better material use should consider the inherent limitations of efficiency and circularity and the implications of these limitations for reducing impacts on the natural environment.

The use of a potential-based concept of waste was shown to help anticipate these inherent limitations. The recovery potential of waste shows to what extent waste can be used as a resource. Fulfilment of the potential of waste as a resource equates to efficient and circular of materials. Application of the recovery potential indicator in environmental assessment reveals the extent to which efficiency and circularity contribute to emission reductions.

The results showed that only strong decarbonization of energy inputs is sufficient to meet the GHG targets. This result is consistent with other studies on paper and with studies on other materials. The finding implies that the debate on resource efficiency and the circular economy should not be a distraction or a delay in attempts to decarbonize the power sector or to explore other abatement options besides efficiency and circularity.

The complexity of production and consumption requires guiding principles to be constantly evaluated regarding their energy and environmental impacts. The following assessment criteria may be used, in order of the amount of time and effort that goes into generating the necessary evidence: reduction of landfill, avoidance of virgin inputs, reduction of individual energy demand and impacts, and reduction of system energy demand and impacts.

10.3 Future research

The thesis suggested a potential-based concept of waste and explored the use of the recovery potential indicator for optimizing complex material systems. Further research may specify the recovery potential of different types of waste in more detail. Industry collaboration may be required to obtain good quality data. It is also necessary to improve our understanding of the non-technical barriers to using waste as a resource and the possible trajectories for overcoming these barriers.

The estimates of GHG emissions from the global paper life cycle may be improved by addressing the uncertainties surrounding land use change, fuel use, and landfill gas generation. Further modelling may reveal to what extent the patterns found for the paper life cycle and climate change also hold for other materials and other environmental problems. Other options for carbon abatement that may be explored are the use of different feedstocks and substitution for other materials.

Finally, the thesis presents mitigation pathways that meet climate change targets. Following these pathways in practice is considerably harder than modelling them. The human impacts on the natural environment, which define the Anthropocene, are the unintended consequences of activities that are otherwise considered very desirable. Sustainability research should seek to address this inconvenient linkage and focus on how societies can move beyond current patterns of production and consumption.

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Appendix A. Material flows

A-1. Model parameters

Table A-1 gives an overview of the parameters in Chapter 5. The abbreviated names are used in Table A-3. The fourth columns refers to additional explanation in the relevant table in the thesis chapter or, for the recycled pulping yield ratio, the relevant appendix.

Table A-1. Model parameters for Chapter 5.

Parameter	Value used	Explanation	References
η_mp	0.93	Mechanical pulping yield ratio	Table 5-1
η_cp	0.48	Chemical pulping yield ratio	Table 5-1
η_rp	0.81	Recycled pulping yield ratio	Table A-1
η_pm	0.95	Papermaking yield ratio	Table 5-1
NaS	0.09	Addition to stock as fraction of consumption	Table 5-1
TP	0.03	Toilet paper as fraction of consumption	Table 5-3
RW_er	0.12	Energy recovery as fraction of residual waste	Table 5-3
RW_inc	0.08	Incineration as fraction of residual waste (without energy recovery)	Table 5-3
IW_lf	0.06	Landfill of industrial waste in tonne/tonne production	Table 5-4
IW_ner	0.06	Non-energy recovery of industrial waste in tonne/tonne production	Table 5-4

A-2. Recycled pulping yield ratio

Table A-2 shows the calculation of the global recycled pulping yield ratio. The ranges for yield ratios per paper grade were taken from Stawicki and Read (2010, 84). The paper grades listed by FAO (2016) were matched with the grades in Stawicki and Read (2010) in the following way: Newsprint = Newsprint, Printing and writing = SC / LWC; Sanitary and household = Tissue; Packaging = Market DIP; Other = Market DIP. The calculation of the recycled pulp (second row) considers losses in papermaking. Between 0% and 50% of packaging is assumed to be deinked.

Table A-2. Recycled pulping yield ratio calculation.

Inputs	**Outputs**						**Total**	
	Newsprint	**Printing and writing**	**Sanitary and Household**	**Packaging**		**Other**	**Packaging not deinked**	**Packaging 50% deinked**
				No deinking	**50% deinking**			
Recycled content (-)	0.68	0.08	0.34	0.56		0.27		
Recycled pulp (Mt)	22	9	11	127		5	174	
Pulping yield ratio (-)								
Lower bound	0.78	0.65	0.60	0.90	0.75	0.60		
Upper bound	0.85	0.70	0.70	0.95	0.80	0.65		
Paper for recycling (Mt)								
Upper bound	28	14	18	142	170	8	210	238
Lower bound	26	13	16	134	159	8	196	221
Overall yield ratio (-)								
Lower bound							83%	73%
Upper bound							89%	79%
Value used (average)							81%	

A-3. Material balance

Table A-3 lists the size of all the flows depicted in Figure 5-2. The fifth column explains the source of a flow or how it was calculated from the other flows and the parameters in Table A-3. The flow MC refers to total consumption and is the sum of flows M35-39. The last column shows the reference or thesis table that further explains the calculation.

Table A-3. Material balance and the equations.

Flow	Input	Output	Qt (Mt)	Calculation method or database flow	References
M1	Wood	Mechanical pulping	35	M5 / η_mp	-
M2	Wood	Chemical pulping	279	Chemical pulp / η_cp	FAO Stat
M3	Other fibres	Chemical pulping	33	Other fibre pulp / η_cp	FAO Stat
M4	Paper for recycling	Recycled pulping	215	Recovered paper	FAO Stat
M5	Mechanical pulping	Mechanical pulp	32	Mechanical pulp + 0.5 * Thermomechanical pulp	FAO Stat
M6	Mechanical pulping	Mill waste	2	M1 * (1 - η_mp)	FAO Stat
M7	Chemical pulping	Chemical pulp	150	Chemical pulp + Other fibre pulp + 0.5 * Thermomechanical pulp	FAO Stat
M8	Chemical pulping	Mill waste	162	(M2 + M3) * (1 – η_cp)	FAO Stat
M9	Recycled pulping	Recycled pulp	174	M4 * η_rp	-
M10	Recycled pulping	Mill waste	41	M4 - M9	-
M11	Recycled pulp	Newsprint	21	Allocation matrix	Table 5-2
M12	Recycled pulp	Printing and writing	9	Allocation matrix	Table 5-2
M13	Recycled pulp	Sanitary and household	10	Allocation matrix	Table 5-2
M14	Recycled pulp	Packaging	121	Allocation matrix	Table 5-2
M15	Recycled pulp	Other	5	Allocation matrix	Table 5-2
M16	Recycled pulp	Paper for recycling (out)	9	M9 * (1 – η_pm)	-
M17	Chemical pulp	Newsprint	0	Allocation matrix	Table 5-2
M18	Chemical pulp	Printing and writing	66	Allocation matrix	Table 5-2
M19	Chemical pulp	Sanitary and household	20	Allocation matrix	Table 5-2
M20	Chemical pulp	Packaging	48	Allocation matrix	Table 5-2
M21	Chemical pulp	Other	9	Allocation matrix	Table 5-2
M22	Chemical pulp	Paper for recycling (out)	7	M7 * (1 – η_pm)	-
M23	Mechanical pulp	Newsprint	7	Allocation matrix	Table 5-2
M24	Mechanical pulp	Printing and writing	0	Allocation matrix	Table 5-2
M25	Mechanical pulp	Sanitary and household	0	Allocation matrix	Table 5-2
M26	Mechanical pulp	Packaging	24	Allocation matrix	Table 5-2
M27	Mechanical pulp	Other	0	Allocation matrix	Table 5-2
M28	Mechanical pulp	Paper for recycling (out)	2	M5 * (1 – η_pm)	-
M29	Non-fibrous	Newsprint	3	Allocation matrix	Table 5-2
M30	Non-fibrous	Printing and writing	32	Allocation matrix	Table 5-2
M31	Non-fibrous	Sanitary and household	0	Allocation matrix	Table 5-2
M32	Non-fibrous	Packaging	21	Allocation matrix	Table 5-2
M33	Non-fibrous	Other	4	Allocation matrix	Table 5-2
M34	Non-fibrous	Paper for recycling (out)	3	(M29 + M30 + M31 + M32 + M33) * (1 - η_pm) / η_pm	-
M35	Newsprint	Consumption	31	Newsprint	FAO Stat
M36	Printing and writing	Consumption	106	Printing+Writing Paper	FAO Stat
M37	Sanitary and household	Consumption	30	Household+Sanitary Paper	FAO Stat
M38	Packaging	Consumption	214	Wrapg+Packg Paper+Board	FAO Stat
M39	Other	Consumption	18	Other Paper+Paperboard	FAO Stat
M40	Consumption	Stock	36	MC * NaS	Table 5-3
M41	Consumption	Recycling (Out)	194	M4 - M16 - M22 - M28	Table 5-3
M42	Consumption	Landfill	130	MC - M40 - M41 - M42 - M43 - M44 - M45	Table 5-3
M43	Consumption	Energy recovery	20	(MC - M40 - M41) * RW_er	Table 5-3
M44	Consumption	Incineration	14	(MC - M40 - M41) * RW_inc	Table 5-3
M45	Consumption	Non-energy recovery	5	(MC * TP) * 0.5 * (1 - RW_er - RW_inc)	Table 5-3
M46	Mill waste	Landfill	24	MC * IW_lf	Table 5-4
M47	Mill waste	Energy recovery (on site)	158	M6 + M8 + M10 - M46 - M48	Table 5-4
M48	Mill waste	Non-energy recovery	24	MC * IW_ner	Table 5-4

A-4. Virgin input reduction

Table A-4 shows the calculation of the results shown in Table 5-6. Only the figures for the calculation with a NaS of 0.09 are shown. The calculations with a lower and higher NaS (shown in Table 5-6) are performed analogously.

Table A-4. Calculation of CR and RIR under maximum recycling.

	Scenario / **Flow**	**Middle (NaS = 0.09)**	**Flow**	**Equation (based on A-1 and A-3)**
Recycled input	E-o-L discards for recycling (Mt)	351	R1	MC * (1 – NaS – TP)
	Papermaking waste for recycling (Mt)	21	R2	M16+M22+M28+M34
	Total paper for recycling (Mt)	372	R3	R1+R2
Pulp input	Potential recycled pulp supply (Mt)	272	R4	R3/η_rp
	Additional chemical pulp (Mt)	70	R5	(MC –M29+M30+M31+M32+ M33+M34))*M7/(M5+M7)
	Additional mechanical pulp (Mt)	15	R6	(MC –M29+M30+M31+M32+ M33+M34))*M5/(M5+M7)
Virgin input	Fibre for chemical pulp (Mt)	145	R7	R5/η_cp
	Fibre for mechanical pulp (Mt)	16	R8	R6/η_mp
	Total virgin fibre (Mt)	161	R9	R7+R8
Metrics	Collection Rate (CR)	93%	R10	R1/MC
	Recycled Input Rate (RIR)	70%	R11	R4/(R4+R9)

Appendix B. Recovery potential indicator

B-1. Recycling rate and recovery potential

The recovery potential (RP) for recycling is not calculated as a CR because it needs to consider inevitable losses due to net addition to stock and paper in sewage. The RP also distinguishes between papermaking waste and E-o-L discards. The description of the CR and RP are as follows:

- The CR divides total paper for recycling collection by total consumption. It includes paper for recycling from the pulp, paper, and print industry (papermaking waste) and from consumers.
- The fulfilment of the RP for E-o-L discards indicates the fraction of E-o-L discards that is recycled. E-o-L discards consist of total consumption minus net addition to stock and paper in sewage.
- The fulfilment of the RP for papermaking waste indicates the fraction of papermaking waste that is recycled. Papermaking waste is calculated based on the yield ratio of papermaking.

The fulfilment of the potential for recycling E-o-L discards can be calculated from the recycling rate based on the flow quantities detailed in Appendix B-2. The CR can be calculated as follows:

$$CR = \frac{F25+F15+F17+F19+F21}{F22+F23+F24} \quad \text{Equation B-1}$$

The RP for E-o-L discards and papermaking waste is 1.00. The actual quantity of recycling under fulfilment of the RP can be calculated with the following two equations.

$$RP_{EoL\ discard} = F24 * 1.00 \quad \text{Equation B-2}$$

$$RP_{papermaking\ waste} = (F15 + F17 + F19 + F21) * 1.00 \quad \text{Equation B-3}$$

The current performance for recycling of E-o-L discards is lower than the potential. The fulfilment of the potential can be calculated as follows.

$$RP_{EoL\ discard_{fulfilled}} = F25/F24 \quad \text{Equation B-4}$$

Based on the above, a CR of 0.91, as for South-Korea, can be converted to a figure for the RP fulfilment. Consumption is assumed to be 100 units. The calculation starts with distinguishing the papermaking waste (PMW) based on the yield ratio of papermaking of 0.95 (see Chapter 5).

$$PMW = \frac{100}{0.95} - 100 = 5.3 \qquad \textit{Equation B-5}$$

Now the amount of E-o-L discard that is recycled can be calculated, assuming PMW is fully recycled.

$$EoL_{recycling} = 0.91 * 100 - 5.3 = 86 \qquad \textit{Equation B-6}$$

Availability of E-o-L discards follows from net addition to stock and losses of toilet paper in sewage (TP) of 0.09 and 0.03 respectively (see Chapter 5).

$$EoL_{discard} = 100 * (1 - NaS - TP) = 88 \qquad \textit{Equation B-7}$$

$$RP_{EoLdiscard_{fulfilled}} = \frac{86}{88} = 0.97 \qquad \textit{Equation B-8}$$

In conclusion, the benchmark for fulfilment of the recovery potential for recycling of E-o-L discards is 0.97.

B-2. Current and ideal material flows

Table B-2. 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	E-o-L discards	88.0	88.0
F25	E-o-L discards	Recycling	48.6	88.0
F26	E-o-L discards	Energy recovery	4.7	0.0
F27	E-o-L discards	Incineration	3.1	0.0
F28	E-o-L discards	Landfill	31.5	0.0
F29	Black liquor	Energy recovery	38.0	17.7
F30	Recycling sludge	Non-energy recovery	5.2	21.7
F31	Recycling sludge	Energy recovery	0.8	3.5
F32	Recycling sludge	Landfill	4.3	0.0
F33	Papermaking waste	Paper for recycling (out)	5.3	5.3
F34	Paper in sewage	Non-energy recovery	1.2	0.0
F35	Paper in sewage	Energy recovery	0.4	3.0
F36	Paper in sewage	Incineration	0.2	0.0
F37	Paper in sewage	Landfill	1.2	0.0
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

Appendix C. Energy flows

C-1. Bottom-up estimate for heat and electricity demand

Table C-1. Bottom-up estimate for heat and electricity demand.

	Material flows	SEC values from IEA (2007a)		Total energy demand	
	Quantity (Mt)	**Heat (GJ/t)**	**Electricity (GJ/t)**	**Heat (PJ)**	**Electricity (PJ)**
Mechanical pulping	32.4	0.00	7.50	0	243
Chemical pulping	150.0	12.25	2.08	1,837	312
Recycled pulp, deinked	130.7	2.00	1.62	261	212
Recycled pulp, not deinked	43.6	0.50	0.36	22	16
Newsprint	30.5	3.78	3.16	115	96
Printing and writing	106.1	5.25	1.80	557	191
Sanitary and household	30.4	5.13	3.60	156	109
Packaging	214.3	4.32	1.80	926	386
Other	17.8	4.88	2.88	87	51
Printing	174.1	2.05	2.47	357	429
Total				**4,318**	**2,045**

C-2. Parameter values and figures for the energy balance

Table C-2. Parameter values and material flow quantities for the energy balance.

Parameter	Explanation	Value	Reference
η_CHP	Total efficiency CHP	0.85	Adapted from Suhr et al. (2015)
η_electric	Electric efficiency CHP	0.25	Adapted from Suhr et al. (2015)
η_heat	Thermal efficiency CHP	0.60	Adapted from Suhr et al. (2015)
H_bl	Heating value black liquor (GJ/t)	12.3	(IEA 2007b)
H_rps	Heating value recycled pulping sludge (GJ/t)	2.8	(Gavrilescu 2008)
H_sr	Heating value sludge and rejects (GJ/t)	4.2	(Gavrilescu 2008)
BL	Black liquor (Mt)	151	Chapter 6, Table 6-2
RPS	Recycled pulping sludge (Mt)	41	Chapter 6, Table 6-2
SR	Sludge and rejects (Mt)	5.6	Chapter 6, Table 6-2
ER_rps	Energy recovery fraction of RPS	0.08	Chapter 6, Table 6-2
ER_sr	Energy recovery fraction of SR	0.25	Chapter 6, Table 6-2

C-3. Energy balance including equations

Table C-3. Energy balance of Figure 7-1. H_tot and E_tot are the sum of heat and electricity flows.

Flow	From	To	Energy (PJ)	Equation
I1	Bought fuels	Fuels and waste	3,846	I4 + I5 - I2
I2	Mill waste	Fuels and waste	1,881	BL * H_bl + RPS * ER_rps * H_rps + SR * ER_sr + H_sr
I3	Market	Electricity use	1,522	(IEA 2007a)
I4	Fuels and waste	Heat generation	3,602	I6 / η_CHP
I5	Fuels and waste	CHP	2,125	(I7 + I8) / η_CHP
I6	Heat generation	Heat use	3,062	H_tot - I7
I7	CHP	Heat use	1,275	I8 / η_electric * η_heat
I8	CHP	Electricity use	531	E_tot - I3
I9	Heat generation	Loss	540	I4 – I6
I10	CHP	Loss	319	I5 - I7 - I8
H1	Heat use	Chemical pulping	1,846	Calculation analogous to Table C-1 but with the scaled SEC values from Table 7-3
H2	Heat use	Recycled pulping (deinked)	263	
H3	Heat use	Recycled pulping (not deinked)	22	
H4	Heat use	Newsprint	116	
H5	Heat use	Printing + writing	560	
H6	Heat use	Sanitary + household	157	
H7	Heat use	Packaging	930	
H8	Heat use	Other	87	
H9	Heat use	Printing	359	
E1	Electricity use	Mechanical pulping	244	
E2	Electricity use	Chemical pulping	313	
E3	Electricity use	Recycled pulping (deinked)	213	
E4	Electricity use	Recycled pulping (not deinked)	16	
E5	Electricity use	Newsprint	97	
E6	Electricity use	Printing + writing	192	
E7	Electricity use	Sanitary + household	110	
E8	Electricity use	Packaging	388	
E9	Electricity use	Other	51	
E10	Electricity use	Printing	429	

Appendix D. Model summary

D-1. Material flow parameters

Table D-1. Summary of material flow parameters.

		2012			2050		
Category	**Parameters**	**-**	**0**	**+**	**REF**	**IE**	**W-a-R**
Yields (-)	Yield of mechanical pulping	0.90	0.93	0.95			
	Yield of chemical pulping	0.40	0.48	0.55			
	Yield of recycled pulping	0.73	0.81	0.89	0.77	0.75	0.73
	Yield of production process		0.95				
Fractions (-)	Deinked packaging		0.75		0.81	0.84	0.87
	Printed packaging		0.17				
Waste intensities (kg/t pulp)	Tall oil and other by-products	10	50	75			
	Screening rejects	2	11	20			
	WWTP solids		10				
	Causticizing waste	10	30	60			
Industrial waste treatment fractions (-)	Final product to non-energy recovery	0.04	0.06	0.12			
	Final product to landfill	0.04	0.06	0.11			
	Energy recovery black liquor		1.00		1.00	1.00	1.00
	Non-energy recovery recycling sludge*		0.50		0.62	0.74	0.86
	Energy recovery recycling sludge*		0.08		0.10	0.12	0.14
	Non-energy recovery sludge and rejects*		0.25		0.33	0.42	0.50
	Energy recovery sludge and rejects*		0.25		0.33	0.42	0.50
	Non-energy recovery causticizing waste*		0.25		0.42	0.58	0.75
	Non-energy recovery boiler ash*		0.50		0.67	0.83	1.00
Consumer waste treatment fractions (-)	NaS	0.06	0.09	0.12			
	Paper to sewage		0.03				
	Recycling of E-o-L discard		0.55		0.70	0.85	1.00
	ER Residual*		0.12		0.25	0.37	0.50
	Incineration Residual*		0.08		0.05	0.03	0.00
	Non-ER paper to sewage*		0.40		0.27	0.13	0.00
	ER paper to sewage*		0.12		0.41	0.71	1.00
	Incineration paper to sewage*		0.08		0.05	0.03	0.00
Ash content (-)	Recycling sludge		0.45				
	Sludge and rejects		0.10				

*Historical value grows linearly from 0 in 1970 to the indicated value in 2012.

D-2. Energy parameters

Table D-2. Summary of energy flow parameters

		2012			2050		
Category	**Parameters**	**-**	**0**	**+**	**REF**	**IE**	**W-a-R**
Energy efficiencies (-)	Energy recovery from landfill gas		0.35				
	Electricity from MSW plant		0.25				
	Heat generation		0.85				
	Heat from CHP		0.60				
	Electricity from CHP		0.25				
Heating value (GJ/t)	Paper to sewage		15.00				
	Black liquor		12.29				
	Recycling sludge		2.80				
	Sludge and rejects		4.20				
Fuel (GJ/t)	Forestry	0.156	0.173	0.190			
Heat (GJ/t)	Kaolin	0.95	1.05	1.16			
	Mechanical pulp	0.00	0.00	0.00			
	Chemical pulp	10.55	11.73	12.90			
	Recovered pulp, deinked	1.72	1.91	2.11			
	Recovered pulp, not deinked	0.43	0.48	0.53			
	Newsprint	3.26	3.62	3.98			
	Printing + Writing	4.52	5.03	5.53			
	Sanitary + Hygienic	4.42	4.91	5.40			
	Packaging	3.72	4.14	4.55			
	Other grades	4.20	4.67	5.14			
	Printing	1.74	1.93	2.12			
Electricity (GJ/t)	Forestry	0.049	0.054	0.059			
	Kaolin	0.62	0.69	0.76			
	Mechanical pulp	6.46	7.18	7.90			
	Chemical pulp	1.79	1.99	2.19			
	Recovered pulp, deinked	1.40	1.55	1.71			
	Recovered pulp, not deinked	0.31	0.34	0.38			
	Newsprint	2.72	3.03	3.33			
	Printing + Writing	1.55	1.72	1.90			
	Sanitary + Hygienic	3.10	3.45	3.79			
	Packaging	1.55	1.72	1.90			
	Other grades	2.48	2.76	3.03			
	Printing	2.22	2.47	2.71			
Learning rate	Learning rate for pulp, paper, and print SEC values*				0.065	0.097	0.130
*Based on cumulative production with cumulative production in 1960 being 2.22 Gt.							

D-3. Emissions parameters

Table D-3. Summary of emissions parameters.

		2012			2050		
Category	**Parameters**	**-**	**0**	**+**	**REF**	**IE**	**W-a-R**
Ratios	Ratio CO_2/C		3.67				
	Ratio CH_4/C		1.33				
CI (kg CO_2/GJ)	Coal		95				
	Peat		106				
	Oil		78				
	Natural gas		56				
	Diesel oil	70	74	78			
	Fuels (excluding industrial waste)	58	61	64			
	Electricity and heat sector	191	201	211			
	Growth rate (all fuels)				0.99	0.98	0.97
Landfill gas	Half-life factor	0.04	0.05	0.06			
	Methane Correction Factor	0.50	0.75	1.00	0.80	0.90	1.00
	Degradable Organic Carbon content paper	0.32	0.40	0.48			
	Degradable Organic Carbon content industrial waste	0.090	0.145	0.200			
	Fraction Degradable Organic Carbon dissimilated	0.42	0.50	0.60			
	Share of CH_4 in landfill gas	0.476	0.500	0.525			
	Oxidation factor for CH_4 in top layer**	0.10	0.05	0.00			
	Rate of CH_4 capture* **	0.30	0.25	0.20	0.50	0.75	0.85
	Factor for CH_4 in CO_2 equivalents		28				

*Historical value grows linearly from 0 in 1970 to the indicated value in 2012. **The upper boundary is a lower value because the lower parameter value leads to higher emissions from landfill.

Appendix E. Greenhouse gas targets

Table E shows the calculation of the four variables listed in Table 4-2. The absolute cumulative target range is calculated by multiplying the upper and lower global carbon budget for 2013-2050 with the variable A. The absolute annual targets for 2050 are calculated by multiplying the upper and lower global targets for 2050 with the variable X. It should be noted that the table reflects the calculation of the targets for the REF scenario only. The value for A is affected by parametric uncertainty. The values for B, X, and Y are affected not only by parametric uncertainty but also by uncertainty regarding fuel use and by the choice of scenario.

Table E. Calculation of variables for emission targets (modelled estimates for REF scenario).

Variable	Component	Quantity	Sources
A	Paper life cycle CO_2 in 2012 (Mt CO_2)	488	Modelled (REF)
	Global CO_2 in 2012 (Gt CO_2)	33.9	(Olivier et al. 2015)
	Value for A	1.4%	
B	Cumulative paper life cycle CO_2 2013-2050 (Gt CO_2)	19.3	Modelled (REF)
	Global CO_2 budget 2011-2050 (Gt CO_2)	870-1240	(Clarke et al. 2014)
	CO_2 Emissions 2011 (Gt CO_2)	34.7	(Olivier et al. 2015)
	CO_2 Emissions 2012 (Gt CO_2)	33.9	(Olivier et al. 2015)
	Global CO_2 budget 2013-2050 (Gt CO_2)	801-1171	
	Value for B	1.6-2.3%	
X	Paper life cycle GHG in 2012 (Mt CO_2e)	721	Modelled (REF)
	Global GHG in 2012 (Gt CO_2e)	53.9	(JRC 2017)
	Value for X	1.2%	
Y	Paper life cycle GHG in 2050 (Mt CO_2e)	735	Modelled (REF)
	Reduction from 2010 for a 44-68% chance of staying below 2 degrees	-0.42 to -0.57	(Clarke et al. 2014)
	GHG Emissions in 2010 (Gt CO_2e)	49	(IPCC 2014)
	Global GHG in 2050 (Gt CO_2e)	21.1-28.4	
	Value for Y	2.3-3.2%	

Appendix F. Comparison of emission estimates

Table E. Comparison of global GHG estimates from the global paper life cycle.

	(Subak and Craighill 1999)	**(Miner and Perez-Garcia 2007)**	**(Allwood et al. 2010)**	**(FAO 2010a)**	**This thesis**
Emissions year	1990s	Early 2000s	2006	2006/2007	2012
Consumption (Mt)	213**	339*	382	387***	399
Pulp, paper, print (Mt CO_2e)	290	370	686	390.4	618
Intensity (kg CO_2e/kg paper)	*1.36*	*1.09*	*1.80*	*1.01*	*1.55*
Landfill gas (Mt CO_2e)	278	-	-	200	233
Intensity (kg CO_2e /kg paper)	*1.30*	-	-	*0.52*	*0.58*
Landfill stock (Mt CO_2e)	-	-	-	-67	-102
Intensity (kg CO_2e /kg paper)	-	-	-	*-0.17*	*-0.26*
Product stock (Mt CO_2e)	-	-	-	-20	-53
Intensity (kg CO_2e /kg paper)	-	-	-	*-0.05*	*-0.13*

*Based on FAO (2016) for the year 2003.

**Consumption in major countries only as listed in Table 1 in the publication.

***Average value between 2006 and 2007 based on FAO (2016).