Energy use in the paper industry
An assessment of improvement potentials at different levels

Jobien Laurijssen
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PhD thesis with summary in Dutch
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Energy use in the paper industry
An assessment of improvement potentials at different levels

Energiegebruik in de papierindustrie
Een beoordeling van verbeterpotentiëlen op verschillende niveau’s

(met een samenvatting in het Nederlands)

Proefschrift

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Prof.dr. E. Worrell
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1. Introduction

The energy intensive manufacturing industry is an important element of the global economy. It produces goods and materials that are essential for many other sectors in the world, thereby contributing largely to the global GDP (27%) and labour employment (22%) (Bassi et al., 2012). Given the nature of its business, the development of the manufacturing industry is largely dependent on the availability of resources like minerals, wood, water and energy. Fossil and mineral resources have been crucial in the development of the global economy and societies have relied on increasing supplies of energy to meet their need for goods and services. Major changes in current trends are however required if future energy systems are to be affordable, safe, secure, and environmentally sound (GEA, 2012). Increasing scarcity raises the cost of exploiting existing natural resources, while the basic need for a secure supply of raw materials creates incentives to innovate and conserve. In today’s globalised world, resource efficiency and innovation have even become a prerequisite for companies to compete and survive.

The 20th century has been characterised by an unprecedented growth in population and size of the global economy. During the last century, global population quadrupled to 6.4 billion (and further up to 7 billion in 2012), GDP grew more than 20-fold and total global materials extraction (i.e. construction minerals, ores and industrial minerals, fossil energy carriers and biomass) increased 8-fold to approximately 60 billion tons of materials per year (Krausmann et al., 2009). In particular, the period after WWII was characterized by rapid growth of material use, driven by both population and economic growth. Within this period there was a shift from the dominance of biomass use towards the use of mineral resources (Krausmann et al., 2009). Despite strong growth in the world’s population and even stronger growth in GDP, during most of the 20th century resource prices of e.g. food, water, energy and steel declined. Prices fell because of a combination of new low-cost sources of supply and technological innovation (Mc Kinsey Global Institute, 2011). In the early 1970s, the oil crisis drew, for the first time, major attention to the dependency on limited resources such as fossil fuels. Skyrocketing energy prices led companies to significantly improve their energy- and resource efficiency. With the exception of biomass use, which continued to rise at a moderate pace, average annual growth rates of material use declined by 50% or more (Krausmann et al., 2009). Towards the turn of the new millennium, however, global growth rates of all materials accelerated again (Krausmann et al., 2009). Driven by strong global economic growth, particularly in emerging countries such as China, India and Brazil, the first years of the new millennium were marked by a major surge in demand for raw materials and energy. As a consequence, price increases in the last decade erased all price declines of the previous
Commodity markets have started to display increased volatility and unprecedented movements of prices (EC, 2011).

Currently, fossil fuel energy and raw materials are used on such a scale that the resulting consequences in terms of global warming, ecological deterioration and energy insecurity are generating worldwide impacts. Human induced CO\(_2\) emissions (excluding CO\(_2\) emissions due to deforestation) increased by 0.8% on average in the period 1990–2000 and with 3.3% on average over the period 2000–2006 (Boden et al., 2009; Van de Broek et al., 2011). Several studies (e.g. IPCC, 2007a; Climate congress, 2009) underpin the necessity to limit the human induced increase of the mean temperature on earth to maximum 2°C or even stricter. These studies also emphasize the tremendous effort that is needed to reach this goal. Meinshausen et al. (2009) argue that diminishing the annual global CO\(_2\) emissions to 50% of the 2000 level in 2050, is not sufficient to keep global warming below 2°C. According to them, short term actions are needed that limit CO\(_2\) emissions to less than 25% above 2000 levels in 2020.

The high reliance on energy and natural resources, as well as the considerable amount of emissions generated by the manufacturing industries has driven the debate for climate policy, with possible consequences on the short-term economic performance of these industries (Bassi et al., 2012). For example, climate policies imposing costs on carbon-based energy sources are expected to increase the production cost of manufacturing industries and possibly shrink their domestic market shares, which may in turn lead to loss of jobs (Bassi et al., 2009). In order to avoid negative consequences as a result of current trends in the manufacturing industry, well founded strategies that encourage sustainable production while maintaining economic viability of these industries are essential.

Achieving sustainable development requires carefully balancing environmental, societal, and economic interests. For industries, the concept of sustainability has undergone an essential shift, from a distant, environmentally oriented ideology to a model that opens up business opportunities (e.g. reducing production costs, hedging risks, gaining strategic advantages by entering new markets with high value products) (Schönsleben, et al., 2010). Today, many companies are integrating sustainability aspects into their business concepts. A recent survey by KPMG (2011) shows that 95 percent of the 250 largest companies in the world is currently reporting on its Corporate Responsibility activities (KPMG, 2011). Nevertheless, achieving economic and environmental objectives simultaneously remains a major challenge (Schönsleben, et al., 2010).
1.1 Industrial energy use and emissions

Industrial activities contribute directly and indirectly some 37% of the global greenhouse gas emissions (Worrell et al., 2009). Total industrial GHG emissions are currently estimated to be about 12 GtCO\textsubscript{2}-eq/yr. (Bernstein et al., 2007). Globally, the energy-intensive industries still emit the largest share of total industrial GHG emissions (Worrell, 2011; IEA, 2007; IEA 2008a). By far the largest share of GHG emissions in the industry are related to energy use (83%) (Worrell et al., 2009). In 2007, the global manufacturing industry used approximately 127 EJ of final energy (including feedstock use for petrochemicals) (Banerjee et al., 2012). This is equivalent to about one-third of the total global final energy use (which amounts 363 EJ) (IEA, 2012a). The production of energy-intensive industrial goods has grown significantly and is expected to continue to grow as population and per capita income increase. Since 1970, global annual production of cement increased 336%; aluminium, 252%; steel, 95%; ammonia, 353% and paper, 190% (Worrell et al., 2009). International Energy Agency (IEA) projections show that the absolute global industrial energy use will increase by at least 50% until 2050 compared to the 2006 level under the most ambitious climate policy scenario, while it will even double in the baseline scenario (IEA, 2009).

Even though the absolute industrial energy use has been increasing over the years, energy intensity of the industry has steadily declined in most countries since the oil price shocks of the 1970s. Historically, industrial energy-efficiency improvement rates have typically been around 1%/year. However, various countries have demonstrated that it is possible to double these rates for extended periods of time (Worrell, 2011). It is generally believed that large potentials still exist to further reduce energy use and GHG emissions in most sectors and economies. According to the IEA-World Energy Outlook (2012b): “a significant share of the potential to improve energy efficiency – four-fifths of the potential in the buildings sector and more than half in industry – still remains untapped”. Saygin et al. (2011) estimate worldwide improvement potentials of 27% ± 8%, equivalent to 32.5 ± 9.6 EJ, in final energy savings by implementation of Best Practice Technologies. About 64% of the identified energy saving potential (20.9 ± 5.2 EJ/yr) can be found in the energy-intensive sectors: petroleum refineries, iron and steel, non-ferrous metals, non-metallic minerals, chemical and petrochemicals, and pulp and paper, while the remaining potential (36%) is in non-energy-intensive or light industries (Saygin et al., 2011). A wide range of technologies have the potential to reduce industrial emissions, but available mitigation options are often not fully used due to a number of barriers like limited access to capital, lack of management attention and/or insufficient availability of knowledge (Fleiter et al., 2012; Worrell et al., 2009). Industry has almost continuously improved its energy efficiency over the past decades, but energy efficiency still seems to remain the most cost-effective option for GHG mitigation for the next decade (IEA,
2012; Worrell, 2011; IPCC, 2007). Other opportunities include fuel switching and increased material efficiency.

### 1.2 The pulp and paper industry

The pulp and paper industry is the fourth largest industrial user of energy worldwide. The global pulp and paper industry has a turnover of €80 billion a year and contributes annually €18 billion in value and wealth creation (CEPI, 2009). Around 1.8 million jobs depend directly and indirectly on the industry, 63% of which are in rural areas (CEPI, 2009). In 2010, the global production of paper was 394 million ton (FAO, 2011). Asia has the largest share in total paper production (42%), followed by Europe (28%) and North America (23%) (FAO, 2011; Table 1.1). The principal paper producing country in the world is China, followed by the US, Japan and Germany. Despite its significant production capacity, China still relies to a great extent on imports of paper to cover its rapidly growing demand.

#### Table 1.1 Production and consumption of paper and paperboard

<table>
<thead>
<tr>
<th>Region</th>
<th>Amount (million tons)</th>
<th>Average annual change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Projected</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>1990</td>
</tr>
<tr>
<td>Production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Asia and the Pacific</td>
<td>13</td>
<td>58</td>
</tr>
<tr>
<td>Europe</td>
<td>33</td>
<td>76</td>
</tr>
<tr>
<td>Latin America and the Caribbean</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>North America</td>
<td>48</td>
<td>91</td>
</tr>
<tr>
<td>Western and Central Asia</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>World</td>
<td>96</td>
<td>238</td>
</tr>
<tr>
<td>Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Asia and the Pacific</td>
<td>13</td>
<td>63</td>
</tr>
<tr>
<td>Europe</td>
<td>32</td>
<td>73</td>
</tr>
<tr>
<td>Latin America and the Caribbean</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>North America</td>
<td>46</td>
<td>87</td>
</tr>
<tr>
<td>Western and Central Asia</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>World</td>
<td>96</td>
<td>237</td>
</tr>
</tbody>
</table>

Source: FAO state of the world’s forests 2009

Looking at the global division of paper grades, almost half of the paper and board product mix is packaging and wrapping paper and board and about 30% is printing and writing paper, the
remainder is newsprint, household and sanitary paper (IEA, 2008b). Total consumption of pulp and paper products is positively correlated with gross domestic product. The more developed regions of the world have the highest per capita consumptions. Today, North America, Europe and Asia account for more than 90% of absolute paper and paperboard consumption, with almost equal shares amongst them (Szabo et al., 2009; Table 1.1). The global demand of paper and paperboard is expected to grow about 3%/yr in the period 2005-2020 (Table 1.1), with highest growth rates in Eastern Europe, Asia (except Japan) and Latin America (Jaakko Poyry 2006; IPTS, 2006; Table 1.1) and smaller growth rates in the mature markets (North America, EU, Japan).

The pulp and paper industry is a diverse industry, consisting of many different and complex processes, depending largely on the paper grade produced (e.g. tissue, packaging, newsprint or writing paper). The level of integration within a certain company or country can vary. Some companies exclusively produce pulp, while others cover the full production cycle from fibre resources to final paper grades. The industry is very capital intensive and production technologies are mainly based on traditional principles and readily available technology (Szabo et al., 2011; Berends and Romme, 2001). Paper can be produced from virgin pulp (derived from wood) or from recovered paper. The two main virgin pulp types are mechanical and chemical pulps, which are not substitutes but complements in papermaking, because their qualities differ and they are used in different grades of papers. The pulp and paper market is heterogeneous and highly interconnected through international trade. In addition to wood and final paper products, pulp and recovered paper are also traded internationally. The production of chemical and mechanical pulp is concentrated in a few countries, with the United States, Canada, Brazil, Finland and Sweden being most important (IEA, 2008b). Besides wood, recycled paper is also an important raw material input in the paper-making process. Recycled paper has a significant share in the global fibre supply, representing half of the total. In Europe, a leader in recovery, about 70% of the consumed paper is recycled (ERPC, 2011). Recycling combines both economic and ecological benefits, but due to quality reasons, recovered paper is not used in all paper grades. Moreover, fibres deteriorate every time they are used and at some point in time (estimated at 6-7 times (Villanueva and Wenzel, 2007)) they become of too low quality to be used in papermaking. A certain influx of virgin pulp in the paper chain is therefore always needed.

Because of its economic and environmental advantages, demand of recovered paper is expected to grow fast in the future. If this demand growth is not accompanied with an equal increase in paper recovery, this might lead to a continuous price increase of recovered paper. Moreover, the pulp and paper industry faces competition on its virgin raw material (i.e. wood) with markets with enormous growing potential (i.e. biofuels and bio-energy). This demand
growth comes not only from the developing regions, but also from developed countries where climate changes policies are acting as a driver for increased use of biomass.

1.2.1 Energy use in the pulp and paper industry

The pulp and paper industry both uses and produces large amounts of energy. With an absolute energy use of 6.4 EJ (IEA, 2008b), it accounts for about five percent of the total final energy use in IEA member countries, which is about 15% of the final use in the industry sector. Approximately two-thirds of its final energy consumption is fuel that is used to produce heat, while the remaining third is electricity, either from the grid or produced on site (IEA, 2008b). Unlike other industrial sectors, the pulp and paper industry also produces energy as a by-product and currently generates about 50% of its own energy needs from biomass residues (IEA, 2008b). In Europe, the industry has also invested heavily in combined heat and power generation (CHP). The industry has further put major efforts in the improvement of its energy efficiency. As a result, total specific primary energy consumption for the production of pulp and paper decreased from 16.1 GJ/t in 1990 to 13.9 GJ/t in 2010 in CEPI member states\(^1\) (CEPI, 2011).

Energy costs can have a large impact on the performance of pulp and paper companies. Pulp and paper are commodity goods that are traded on an international market. In order to stay competitive, controlling energy costs is therefore a key strategy. In Europe, from 2005 until 2007, energy prices rose drastically by around 40% on average. Even though energy prices declined again in 2009, they are still one of the major cost components of the pulp and paper sector today. On average, energy costs are 16% of the production costs (BREF, 2010) and in some cases up to 30% (CEPI, 2012), making energy the second largest cost factor after raw materials, and indicating the significant challenges that rising fuel prices (including biomass resources) bring to the sector.

1.2.2 Carbon footprint of the pulp and paper industry

Mainly due to increased use of bio-energy and energy efficiency improvements, GHG emission intensity from the pulp and paper industry has significantly reduced over time. Fossil fuel use by the US pulp and paper industry declined by more than 50% between 1972 and 2002 (Bernstein et al., 2007). Since 1990, the CO\(_2\) emission intensity of the pulp and paper industry has also decreased by approximately 20% in Australia and about 40% in Canada (Bernstein et al., 2007). Sustained efforts have reduced specific CO\(_2\) emissions in the European pulp and paper industry from 0.57 t CO\(_2\)/t product in 1990 to 0.34 t CO\(_2\)/t product

\(^1\) 17 European Union members plus Norway
in 2010 (CEPI, 2011); A reduction of almost 40% in 20 years. Despite these achievements, there remain large potentials for GHG emission reduction in the pulp and paper industry. In a business-as-usual scenario, there is still room for improvement because the average values of the 10% of best performers (benchmark levels) have 50% and 30% lower specific CO₂ emissions than the highest values and the average, respectively (JRC, 2011).

The connections between climate change issues and the forest products industry are more complex than for any other industry. Direct emissions from the pulp, paper, paperboard and wood products manufacturing are estimated to be 260 MtCO₂/yr and the industry’s indirect emissions from purchased electricity are estimated to be around 190 MtCO₂/yr (Miner and Perez-Garcia, 2007). The forests that supply the industry’s raw material, however, remove carbon dioxide from the atmosphere and store the carbon in the forest ecosystem and ultimately in forest products. Most of the industry’s manufacturing facilities require fossil fuels, but the pulp and paper industry obtains much of its energy also from biomass fuels. Moreover, the pulp and paper industry is a leader in recycling. Measuring the impact of paper production and the allocation of recycling on climate change is difficult due to a lack of agreement on method, system boundaries and impact indicators. Nowadays, “CO₂ footprint” has become a popular indicator to indicate the climatic impact of manufactured goods. Due to the complex flows of carbon through the paper chain, however, application of this indicator is different and more difficult than in other industrial sectors. Trade-offs between recycling and other waste management options for used paper have been debated in several studies (e.g. Finnveden and Ekval, 1998; Hekkert et al., 1999; Villanueva and Wenzel, 2007) some of them focussing specifically on climate change mitigation effects (e.g. Farahani et al., 2004, Dornburg and Faaij, 2005). Paper has a relatively high heating value, similar to wood, and this energy can be released and utilised via incineration. On the other hand, when more paper is recycled, raw material for virgin paper production could be saved. This releases wood and/or forest area for other uses. Whether this should be accounted for depends, amongst other things, on the scarcity of forest area and biomass (Villenueva and Wenzel, 2007). The outcome of individual life cycle studies depends largely on the choices made regarding accounting rules and system boundaries, most specifically the ones concerning energy use and generation, and the way land use forestry is included within the system boundaries. To assess the consequences of recycling on the life cycle impact of paper, we need a clear approach on how to deal with energy use and generation as well as solid system boundaries regarding the inclusion of carbon stocks and forest management. Moreover, given the diversity of the paper industry in terms of product and feedstock mixes, there is a clear need for further analyses on the life cycle impact of recycling while taking into account different paper grades.
1.3 Energy benchmarks

In order to estimate industrial energy improvement potentials, energy benchmarks can be used. Energy benchmarks can be applied at different levels of aggregation (e.g. sector level, country level, mill level or process level), depending on the typical goal of the benchmarking exercise as well as on the type of data available (Saygin et al., 2011). The level of aggregation determines to a great extent the type of improvement potential that is identified (e.g. from an increasing recycling rate at country level to the adoption of an energy saving technology on the individual mill level). Energy efficiency improvement can be defined as using less energy for producing the same amount of service or useful output without affecting the level of service or useful output itself. For energy efficiency monitoring at high aggregation levels, economic indicators such as turnover or value added are often used to define the service or useful output level. Changes in the ratio of energy use to these economic indicators can tell something about changes in the way energy is used in a certain sector; however, many factors may contribute to such changes. Causes range from a shift in product portfolio within a sector, to a change in cost price structure of the industry, up to ‘real’ energy efficiency improvements where the same products are produced with less energy (e.g. due to better technology). It is widely accepted that for an industrial sector, the use of physical rather than economic indicators of activity offers a better understanding of energy efficiency developments. Physical indicators are more closely related to ‘technical efficiency’ of an industrial sector and are not affected by variations in prices of commodities or product mix changes (Worrell et al., 1997). High quality and detailed data is needed to perform a benchmark based on physical indicators. Despite the important role of energy in the paper and board industry, information on energy use in this industrial sector, as compared to other sectors, is limited. Because of the lack of publicly available data on a detailed process and product level, most studies on industrial improvement potentials in the pulp and paper industry, so far, have been done on a relatively high level of aggregation (Saygin et al., 2011; Worrell et al., 1994; Farla et al. 1997). Given the large diversity of the sector concerning feedstock use and product mixes, benchmarks at this high level of aggregation have only limited use in identifying energy efficiency improvement opportunities at mill level. In order to assess this type of improvement potential, there is a clear need for high quality and detailed industrial data. Since energy use in the paper industry is largely dependent on the feedstock used and grade produced, high quality data should be used to carry out a benchmark that takes into account these inter-sector variations, in order to assess realistic energy improvement potentials at mill level.
1.4 Technological improvements options

Substantial efforts were made to analyse energy efficiency improvement potentials of energy-intensive industries (e.g., chemical and petrochemical, iron and steel, pulp and paper) from a technology point of view. De Beer et al. (1998) studied improvement options in the paper and board industry, identifying and characterizing new technologies that can improve energy efficiency in the long term. Similarly, Worrell et al. (2001), describe opportunities to improve energy efficiency in the U.S. pulp and paper industry. They examined over 45 technologies and measures to reduce energy use. Saygin et al. (2011) estimates energy savings for the pulp and paper industry at 20-25%. Key uncertainties in the projection of mitigation potentials are: the cost of future technology, future energy and carbon prices, future levels of industry activity and the rate of technology development and diffusion within a certain industry. Especially the latter aspect is interesting, since the manufacturing of paper is a very capital-intensive operation. A state-of-the-art paper machine may cost more than US$ 400 million apiece and typically accounts for more than 50% of the total investment costs of a new paper mill (Van Dijk and Szirmai, 2006). Given the large capital expenditure in the paper industry, a major new technology is introduced only once every five to seven years. By far the largest share of energy use in a paper mill takes place in the drying sections (Laurijssen et al., 2012). It is also considered as the process with the highest energy reduction potential (Laurijssen et al., 2010). The paper machine drying section and its operating principal have, however, remained almost unchanged since their initial development; the share of conventional multi-cylinder dryers in paper production is still 95% (Karlsson, 2000). Attempts to develop new drying techniques in the paper industry are known, but most of them are not commercially available yet (Luiten et al., 2006; Mujumdar, 2007). Due to the long life-cycle of drying equipment (20-40 years) (Mujumdar, 2007), large scale implementation of novel dryers is not expected to occur rapidly. Even though several studies (e.g. De Beer et al., 1998; Luiten et al., 2006; Martin et al., 2000; Mujumdar 2007; Manninen et al., 2002) have identified novel technologies that have the potential to reduce energy consumption in paper production, development of these technologies is often hampered by e.g. technical and capital investments barriers. In order to increase energy efficiency of paper production in the shorter term, there is a need to identify retrofit measures of existing technologies, especially in the drying section. This has hardly been covered in available literature.

1.5 Energy conversion technologies

Paper mills have a large energy demand. Since the largest part of their energy demand is heat, most paper mills operate their own heat generation facility. Many studies have investigated the potential of new energy conversion technologies in terms of CO₂ emission reduction and
costs (e.g. Schmidt et al., 2010; Faaij, 2006). Most of these studies, however, deal with energy conversion for electricity production or district heating (e.g. Difs et al., 2010; Basu et al., 2011, Möst and Fichtner, 2010 and Kalina, 2010) Some other studies have evaluated energy conversion strategies in the pulp and paper industry, but most of these studies have an exclusive focus on black liquor gasification (e.g. Eriksson and Harvey, 2011; Joelsson and Gustavsson, 2008; Carlsson et al., 2010; Petterson and Harvey, 2010; Naqvi et al., 2010). To determine an optimal energy conversion route is challenging and complicated, since on-going technological developments have increased the number of applicable energy conversion technologies while the developments in energy and CO₂ prices in the future are very uncertain. Moreover, due to differences in energy demand, energy costs and available biomass and fuel resources, strategic choices might vary by country and location as well as by product and feedstock mix. To assess the improvement potential in terms of primary energy use, efficiency, energy costs, and CO₂ emission reduction that can be achieved by e.g. fuel switches and the uptake of novel energy generation technologies, research is needed that takes into account local circumstances as well as the heat and electricity demand of different paper grades.

Table 1.2 Overview of covering of identified research gaps throughout this thesis for evaluating the life cycle improvement potential of paper

<table>
<thead>
<tr>
<th>Energy efficiency improvement potential</th>
<th>Chapter 4 - Benchmarking at process unit level - Energy efficiency improvement potential per paper grade</th>
<th>Chapter 5 - Energy efficiency improvement in drying section - Retrofit of multi-cylinder dryers - Heat recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological improvement options</td>
<td>Chapter 3 and 4 - Technological improvement options per paper grade - Optimised energy conversion technology at country level, grade specific</td>
<td>Chapter 4 - Technological improvement potential at process level per paper grade</td>
</tr>
<tr>
<td></td>
<td>Chapter 3 - Optimised energy conversion technologies for paper mills in various European countries - Local resources - CO₂, energy costs, primary energy</td>
<td></td>
</tr>
<tr>
<td>Influence of material efficiency (recycling)</td>
<td>Chapter 2 - Paper recycling - System analysis - Life cycle impact per paper grade on energy and CO₂ emissions</td>
<td>Chapter 2 - Opportunities for the paper industry by increased recycling - System analysis - Life cycle impact on energy and CO₂ emissions</td>
</tr>
</tbody>
</table>

17
1.6 Summary of identified research needs

It is obvious that energy and material efficiency as well as GHG emissions are important aspects to the environmental and economic impact of paper production. Several scientific studies have analysed impacts and improvement potentials of the paper industry related to some of these issues. The previous section, however, also underlines the complexity of the sector in terms of e.g. feedstock use, product mix, recycling, capital intensity and local resource availability. To make a rational judgement on the improvement potential of a sector as complex as the pulp and paper industry, comprehensive and detailed approaches are needed that are lacking in current literature. Table 1.2 schematically summarizes how the research gaps, as identified in the previous sections, will be addressed. The combined set of results can be subsequently used to explore the overall possibilities to improve energy efficiency and lower GHG emissions over the life cycle of paper production and use.

1.7 Scope and outline of this thesis

Given the increasing scarcity of fossil resources and an ever increasing global population, it is evident that a transition to more sustainable use of energy and raw materials, as well as energy efficiency improvement in general, is needed. Being already bio-based and with more than 50% of its energy needs already coming from sustainable sources, the pulp and paper sector has a unique position to play in this transition. However, for reasons explained (vulnerability to energy, material and CO₂ prices, pressure on biomass resources), the sector will need to further conserve and innovate. Therefore achievements are needed on all levels (i.e. process, mill, country and sector). The central research question for this thesis is:

What is the improvement potential, at different levels, to reduce the life cycle impact in terms of energy use and GHG emissions of paper and board?

Considering the opportunities, constraints and research needs identified in the previous sections, the specific research aims of this thesis are to:

- Assess and evaluate the availability of high quality industrial data and, based on such data, explore the energy efficiency improvement potential of the paper industry, taking into account the diversity of the sector that is reflected in a variety of product and feedstock mixes.
- Assess the potential of technological improvement options to reduce energy consumption and CO₂ emissions in the paper industry, taking into account local circumstances and capital intensity of the sector.
- Develop and apply analysis methods that allow for assessment of the influence of recycling on the life cycle impact of different paper and board grades.

The content of the various chapters is discussed in more detail below.

Chapter 2 assesses improvement opportunities at sector level. Increased demand of wood for energy puts pressure on the availability of pulp wood. This could be overcome by increasing biomass supply or by improving the efficiency with which we use biomass for energy and materials. Recycling of paper could be a key part of such a strategy. An approach is presented that integrates pulp, paper, and energy production over the total life-cycle to assess the impact of paper recycling. The GHG and energy impact of different paper production chains from primary, secondary (recovered) or a combination of fibres is measured. Farahani et al. (2004) already showed that assumptions on the inclusion of land use have significant influence on the result of life cycle analyses of paper production chains. Chapter 2 builds on that analysis, expanding the approach with forestry and energy generation. Moreover, an analysis of different paper grades is included and the effect of different recycling rates on different paper grades and different mixes of paper products is explored.

Chapter 3 assesses improvement opportunities at country level. We analyse which energy conversion strategies can reduce energy costs, primary energy use and CO\textsubscript{2} emissions for paper mills in different European countries. The focus is on inter-European differences, comparing and analysing similarities and differences in cross-country impacts of European policies. Reflecting on domestically available resources in three case study countries, a selection of current and possible alternative energy conversion routes for the paper industry in each country is made. Energy costs, primary energy use and CO\textsubscript{2} emissions of the paper and board industry, associated with each of the selected energy conversion strategies, are calculated, taking into account different paper grades. Special attention is paid to the impact of future CO\textsubscript{2} price levels on the competitiveness of the selected energy conversion routes and the role of European policies in the strategic decision for future energy conversion options in the individual countries is discussed.

In Chapter 4, improvement opportunities are identified at mill and process level. There are large differences between paper mills in e.g. feedstock use and grades produced, but typical processes are similar in all mills. The aim of this study is to benchmark the specific energy consumption (SEC) of similar processes within different paper mills to identify energy improvement potentials. Improvement potentials are identified as measures that can be taken at mill/process level under assumed fixed inputs and outputs. A benchmarking method based on energy and material balances per process is used. We were able to use industrial data on a
detailed level and conducted energy benchmarking comparisons for 23 Dutch paper mills. More than 200 data points have been provided by every single mill. Average SECs per process step for different paper grades are calculated and for each process step in different paper grades improvement potentials are identified.

Chapter 5 identifies improvement opportunities for the drying section. The drying process is with approximately 50% the largest energy consumer in a paper mill. Conventional multi-cylinder dryers still dominate the sector and, due to the high capital intensity and related investment barriers, introduction of novel, more energy-efficient dryers is not expected in the near future. Since energy efficiency is crucial, short-term energy efficiency improvement options in conventional multi-cylinder dryers in the paper industry are evaluated. The focus is on measures that can be taken by retrofitting and/or choosing different processing conditions in existing factories. A thermodynamic optimization of ventilation systems of conventional multi-cylinder dryers is proposed, as well as a selection of measures to reduce evaporation in the first place.

Chapter 6 summarizes the outcomes of the studies described in this thesis. Furthermore, general conclusions are drawn and future prospects are described.
Chapter 1

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2. Paper and biomass for energy?*

The impact of paper recycling on energy and CO2 emissions

Abstract

The pulp and paper industry is placed in a unique position as biomass used as feedstock is now in increasingly high demand from the energy sector. Increased demand for biomass increases pressure on the availability of this resource, which might strengthen the need for recycling of paper. In this study, we calculate the energy use and carbon dioxide emissions for paper production from three pulp types. Increased recycling enables an increase in biomass availability and reduces life-cycle energy use and carbon dioxide emissions. Recovered paper as feedstock leads to lowest energy use (22 GJ/t) and CO₂ emissions (−1100 kg CO₂/t) when biomass not used for paper production is assumed to be converted into bio-energy. Large differences exist between paper grades in e.g. electricity and heat use during production, fibre furnish, filler content and recyclability. We found large variation in energy use over the life-cycle of different grades. However, in all paper grades, life-cycle energy use decreases with increased recycling rates and increased use of recovered fibres. The average life-cycle energy use of the paper mix produced in The Netherlands, where the recycling rate is approximately 75%, is about 14 GJ/t. This equals CO₂ savings of about 1 t CO₂/t paper if no recycled fibres would be used.

* Published in Resources, Conservation and Recycling, Vol. 54 (2010), pp. 1208-1218. Co-authors are M. Marsidi, A. Westenbroek, E. Worrell and A. Faaij.
2.1 Introduction

In the European Union and other regions there is strong interest in the use of biomass for energy; both as fuel for power generation, and as the basis for biofuels. This is enhanced by EU targets of 20% renewable energy consumption and at least 10% of transport fuels from biofuels in 2020. Even though many studies estimate large future potential availability of biomass (Londo et al., 2010; Dornburg et al., 2008) some studies debate that transitional problems with sufficient biomass might cause price increases of selected food crops due to the increased demand for biofuels (Eide, 2008; Mitchell, 2008). The same may hold for the supply of wood, especially on the long term, as woody biomass is used as fuel for power, heat and transportation fuels (the so-called second generation biofuels). Efficient use of the limited volumes of primary energy resources (either fossil or biomass, as land is a constrained resource) is crucial. Moreover, efficient use of energy has potentially the largest contribution to climate change mitigation in the next decades (IPCC, 2007).

Today, about 32% of the industrial roundwood produced around the world is used in the production of pulp for paper (FAOSTAT, 2007). Paper companies are among the largest forest owners in the world. Wood is not only the major feedstock for the global paper industry; it also covers a large part of the energy used in the pulp and paper industry (see e.g. Miner and Perez-Garcia, 2007). This makes the pulp and paper industry the largest producer and user of renewable energy sources in Europe, with 50% of its primary energy consumption coming from these (McKinsey and Poyry, 2007). Its biogenic feedstock makes the paper industry’s end-products both an industrial product, as well as a renewable energy source, as energy production from incineration of biomass is considered to be CO₂ neutral² Therefore, the resource efficiency of paper production might be equally important as the emission of CO₂ over the life-cycle. Increased demand of wood for energy use may affect the price and availability of pulp wood. This could be overcome by increasing biomass supply or by improving the efficiency with which we use biomass for energy and materials. Recycling of paper could be a key part of such a strategy.

Measuring the impact of paper production and hence the allocation of recycling on climate change is difficult due to a lack of agreement on method, system boundaries and impact indicators. Focusing on climate change, the “CO2 footprint” is increasingly attracting attention as an indicator. However, application of this indicator to the paper industry is not fully analogous to other industrial sectors, due to the important role of biogenic carbon in the feedstock, energy use, and emissions. In recent years various Life Cycle Assessment (LCA)

² One should be careful with the concept of CO₂ neutrality: although the primary feedstock is of biogenic origin, the end-product may contain additives that may not be considered CO₂ neutral.
and waste management studies have been published that debate the trade-offs of recycling and other waste management options for used paper, i.e. incineration or landfilling (e.g. Finnveden and Ekvall, 1998; Hekkert et al., 1999; Villanueva and Wenzel, 2007) or focus on this question from the perspective of climate change mitigation (e.g. Farahani et al., 2004; Dornburg and Faaij, 2005). Most of the studies conclude that recycling, in terms of climatic change, is beneficial over incineration and landfilling. The studies also show that assumptions on energy and resource use in papermaking are important factors in determining the results of such analyses. As these might vary for different paper grades, an analysis of the climate impact of choices in the paper cycle should also assess the validity of the conclusions for the different paper grades. Furthermore, the studies vary with respect to the inclusion of land-use (i.e. forestry) in the assessments. In e.g. Hekkert et al. (1999) paper production with incineration and recycling are compared on the basis of equal land-use. Dornburg and Faaij (2005) included land-use in analysing the cost and CO2 emission reduction of biomass cascading chains. Including forestry in the analysis has become even more important considering the increasing pressure on biomass availability, as a tree “saved” due to recycling would most likely contribute to the (sustainable) supply of power and heat using biomass.

The above highlights the need to assess the impact of recycling in the context of CO2 emissions, energy use and land-use in a consistent manner over the total life-cycle of paper. In this paper we present an approach that integrates pulp, paper, and power production (from biomass, pulping by-products and waste incineration) over the total life-cycle to assess the impact of paper recycling. This study aims to measure the GHG and energy impact of different paper production chains from primary, secondary (recovered) or a combination of fibres. We build on the analysis of Farahani et al. (2004) (that showed that assumptions on e.g. excess land usage have significant influence on the result of LCA of paper production chains) but expand the approach with forestry and biomass power production. Moreover, we include an analysis of different paper grades. We use the paper and board industry of The Netherlands as a basis for the analysis. This is an example of a pulp and paper industry that heavily relies on recycling of paper for its feedstock supply, but generates a mix of paper grades (although slated towards packaging grades). In the analysis we explore the effect of different recycling rates on different paper grades and different mixes of paper production, which makes the analysis suitable for exploring other countries’ paper industries as well. In this paper we first introduce the methodology applied, the system boundaries and input assumptions. We have used various scenarios e.g. varying recycling rates, and paper grades, to evaluate the impact of different choices in the model. This is followed by a presentation of the results and a discussion of the main factors that drive the results. Finally, we give directions to further research.
2.2 Methodology

2.2.1. Scope

The life-cycle inventory incorporates all processes which are relevant to providing insights on the goal and scope of the research. All processes using or producing fossil or biomass energy are included in the analysis. In Fig. 2.1 the pulp and paper production processes are depicted together with the material, energy and CO2 emission flows. Note that CO2 sequestration and CO2 emission from biomass growth and energy extraction is not inserted in Fig. 2.1. Following IPCC guidelines, the net CO2 emission from biomass is considered 0. The mass flow in Fig. 2.1 only considers the biomass flows. The user phase of paper is not explicitly modelled, but the recovery and waste phases of paper are linked to paper production.

![Fig. 2.1 Overview of processes which require or produce energy during the paper production process and are included in this analysis.](image)

In order to use life-cycle analysis as a tool to measure GHG emissions and energy use of paper production chains, system boundaries need to be clearly defined. We first explore two system boundary conditions to study the effect of resource efficiency in paper production chains. Moreover, two approaches are used for calculations in Microsoft Excel. The
approaches are based on the same assumptions but vary in level of detail: in the first approach a standard paper grade is produced from three pulp types, we analyse the energy use and GHG emissions of the three pulp types for two system boundaries that vary with respect to the inclusion of surplus biomass. In the second approach, six different paper grades are produced from predefined pulp types. In this approach we analyse the energy use of different paper grades for the different stages of their life-cycle. In both approaches the functional unit by which the different analysis chains are compared is weight of paper in metric tonnes\(^3\). We calculate energy use and GHG emissions of single paper production chains and of a mix of different grades.

2.2.2 Model assumptions

The model assumptions in this study are:

- For pulp production we include the three dominant types of pulp, i.e. chemical (modelled as Kraft pulp), mechanical (modelled as thermo-mechanical pulping, TMP) and recovered pulping.
- The paper mills using chemical pulp are considered to be non-integrated\(^4\) as is the situation in The Netherlands.
- The study focuses on fibre and filler\(^5\) use, other additives (e.g. chemicals) are excluded.
- The energy extracted from biomass streams is assumed to replace energy produced by fossil fuels\(^6\).
- The rejects from recovered pulping also includes plastics; the energy generated from the plastic fractions is included in the (bio)energy generated. We assume that only power is produced from biomass or Municipal Solid Waste (MSW) incineration.
- We assume sustainable yield forestry\(^7\), therefore all processes in which CO\(_2\) emission take place because of biomass decay or incineration, do not add to the net carbon addition to the atmosphere.

\(^3\) Metric ton is a common unit in exploring energy and GHG emission of paper production chains. Putting more emphasis on functionality of papers grades, other units (e.g. m\(^2\)) might be more appropriate.

\(^4\) Integrated mills consist of a pulp mill and a paper mill on the same site. Such mills receive logs or wood chips and produce paper. Non-integrated mills purchase wood pulp, usually as dried baled, known as market pulp.

\(^5\) Fillers are used in paper production to enhance paper characteristics. Fillers are mostly inorganic (calcium carbonates) and contributed to increased printability and opacity of papers.

\(^6\) Although the electricity mix in most countries is not 100% fossil fuel based, we consider electricity production from fossil fuels as the baseline for comparing sustainable energy production.

\(^7\) Sustainable yield forestry means that growth and harvesting rates are balanced. The forest product can therefore be considered CO\(_2\) neutral (meaning that the CO\(_2\) released when the product decays or is incinerated, is equivalent to that taken from the atmosphere by the plants as they photosynthesize).
• The user phase is not incorporated. This phase entails the part in which paper is used e.g. for food packing. While the role of paper as a service provider in society is extremely important, this paper focuses on the paper itself, and not on the service provided.
• All used paper not used by recycling processes is incinerated. In reality not all waste paper would be incinerated, as the mix of incineration in the MSW processing mix varies from country to country. Hence, this assumption gives a relatively high credit to incineration of paper.
• For energy crops and paper production the same type of tree species are assumed to be used, in contrast to an earlier analysis by Hekkert et al. (1999) but in accordance with Dornburg and Faaij (2005).
• Although chemical pulping and resource extraction does not occur in The Netherlands, Dutch conversion and CO₂ emission factors are used for heat and power generation throughout the model.
• All weight is reported in metric tonnes (t) and energy is expressed on Lower Heating Value (LHV)-basis.

2.2.3 System boundaries
In the first modelling approach, energy use and CO₂ emissions are calculated for a reference paper type (newsprint) that is produced from either mechanical pulp, chemical pulp or from recovered paper. Here, we explore the effect of using two different system boundaries for biomass resource use (shown in Fig. 2.2), on energy use and CO₂ emissions of the three pulp types.

**Fig. 2.2** Schematic overview of the influence of using different system boundaries on biomass energy use and bio-energy generation (grey) of three pulp types (e = energy). Dotted processes are included in system boundary B only.
A: feedstock use varies per pulp type. Virgin pulps have higher feedstock use, but the bio-energy produced during pulping is also accounted for. A tree ‘saved’ due to recycling is not accounted for in this approach as there is no limit to the amount of resources that can be used.

B: feedstock use is pre-set. Because of the increasing pressure on biomass, we model a system with resources constraints (wood). Virgin feedstock use is therefore, for all three pulp types, pre-set at the same fixed level (the amount of wood needed when all paper would be produced via chemical pulping). Surplus feedstock not used for paper production is assumed to be converted into bio-energy. This method gives extra CO₂ credits to mechanical pulping and recycling of paper, as surplus biomass is assumed to be converted into bio energy.

2.2.4 Level of detail
In the second approach, six paper grades are included to cover the total Dutch paper and board industry. The different paper grades that are produced in The Netherlands each have specific characteristics which in turn require different processes in order to manufacture them. The total industry is modelled by linking the life-cycles of the paper production of six different paper grades. Each of these paper grades has its own specific values for fibre content, filling percentage of inorganic material and production values for the pulping and papermaking (see Tables 2.1 and 2.3). Moreover, the recycling rate is different for each individual paper grade. We analyse the CO₂ emissions and energy usage of the total paper and board industry in The Netherlands and explore the effects of recycling on the total industries’ CO₂ emissions and energy use. We assume that feedstock use varies per pulp type (system boundary type A from above). The amount of recycled paper that is collected, might not match the amount of recovered fibres needed for paper production. We assume that a recovered paper surplus contributes to a reduced virgin pulp production whereas a deficit creates a push on virgin pulp production and hence forest resources. We further analyse the environmental impact of individual paper grades. For individual paper grades, it is not so straightforward to calculate the impact of recycling. Some paper grades have a high recycling rate, but no recovered fibres are used in the production of the same grade (e.g. printing paper). In our analysis, a credit for recyclability (i.e. the ability of the product to be recycled) is directly included to the life-cycle impact of that grade; also when no recovered fibres are used in the production of the product. This is done by allocating an energy value to the fibres that are recovered after use. We assume that the energy value of recovered fibres is similar to the energy value of wood needed to produce the same amount of virgin fibres (via chemical pulping).
Table 2.1 Description of the six assumed paper grades and their fibre content. Typical composition of the paper grades (virgin and recovered fibre) production volumes and recycling rates in The Netherlands are given. In practice, these figures may be different from product to product and from country to country.

<table>
<thead>
<tr>
<th>Paper type</th>
<th>Description</th>
<th>Fibre Content *</th>
<th>Prod. kt (2007) †</th>
<th>Recycling rate (2007) ‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newsprint</td>
<td>Newsprint paper can be produced from both primary and secondary fibres, and is used to produce newsprints. The primary fibre type is mostly dominated by mechanical pulping. The recovered pulp is deinked and dispersed to obtain a higher brightness of the paper.</td>
<td>80% recovered  20% mechanical</td>
<td>421</td>
<td>80%</td>
</tr>
<tr>
<td>PRINTING AND WRITING PAPER</td>
<td>The high quality of printing and writing paper used in e.g. magazines requires primary fibre pulp. This quality is related to the end product, as consumers demand a certain whiteness and brightness. This type is dominated by chemical pulping because of the requirement for a high level of brightness and good strength.</td>
<td>100% chemical</td>
<td>924</td>
<td>80%</td>
</tr>
<tr>
<td>Sanitary paper</td>
<td>Sanitary paper can be produced from primary fibre or recovered fibre, and is used to produce e.g. toilet paper and tissues. The primary fibre is generally from chemical pulp. Sanitary paper needs to be strong, absorbent and soft.</td>
<td>95% recovered  5% chemical</td>
<td>115</td>
<td>0%</td>
</tr>
<tr>
<td>Corrugated board</td>
<td>Corrugated board can consist of different combinations of layers of sheets produced from recovered pulp, mechanical pulp and chemical pulp. This type of paper has a wide variety of applications but is mostly used for packaging.</td>
<td>100% recovered</td>
<td>859</td>
<td>73%</td>
</tr>
<tr>
<td>Greyboard</td>
<td>Greyboard consists of 100% recovered paper and has multiple applications e.g. book boards and food plates. Because of its applications, it does not require deinking.</td>
<td>100% recovered</td>
<td>740</td>
<td>73%</td>
</tr>
<tr>
<td>Folding boxboard</td>
<td>Folding boxboard can consist of different types of fibres and is typically used for packaging material of various food products. In the Netherlands this paper grade consists of recovered paper and mechanical paper. Because of its application, the outer layer needs to be representative; the layers therefore undergo either deinking steps or bleaching.</td>
<td>66% recovered  34% mechanical</td>
<td>106</td>
<td>73%</td>
</tr>
</tbody>
</table>

a Source: Royal Netherlands Paper and Board Association (2009). Estimation based on real data from Dutch Paper mills. Aggregated per product group for the purpose of this study.

b Source: website Royal Netherlands Paper and Board Association (www.vnp-online.nl).

c Source: website Informatiecentrum Papier en Karton (Informatiecentrum Papier en Karton, 2009).

2.2.5 Calculation method

The amount of CO₂ released for a specific process is calculated by multiplying the energy use for that process with the emission factor for each energy carrier. We use IPCC default emission factors for all fuels (see Table 2.4). We use natural gas as the default fossil fuel, as is used by the paper and board industry in The Netherlands (see also Section 4):

\[
CO₂_{total} = E_{fossil} * \alpha + E_{he} * \beta
\]  

(1)
Chapter 2

Where \( E_{\text{fossil}} \), electricity use from fossil fuels; \( E_{\text{he,fossil}} \), heat use from fossil fuels; \( \alpha = \) conversion factor from electricity from fossil fuels to CO\(_2\) emission; \( \beta = \) conversion factor from heat from fossil fuels to CO\(_2\) emission.

The total amount of energy used (\( E_{\text{primary, total}} \)) in the production chain is the summation of the primary energy used from fossil resources (\( E_{\text{fossil,input}} \)), biomass resources used as feedstock (\( E_{\text{biomass,input}} \)) and energy generated from biomass (\( E_{\text{biomass,output}} \)):

\[
E_{\text{primary, total}} = E_{\text{fossil,input}} + E_{\text{biomass,input}} - E_{\text{biomass,output}}
\]

\[
E_{\text{fossil,input}} = E_{\text{el,fossil}} \times \epsilon + E_{\text{he,fossil}} \times \phi
\]

\[
E_{\text{biomass,input}} = M_{\text{biomass}} \times \delta
\]

\[
E_{\text{biomass,output}} = E_{\text{el,biomass}} \times \epsilon + E_{\text{he,biomass}} \times \phi
\]

Where: \( E_{\text{primary, total}} \) = total required primary energy; \( E_{\text{fossil,input}} \) = total primary energy input from fossil fuels; \( E_{\text{biomass,input}} \) = total primary energy input from biomass; \( E_{\text{biomass,output}} \) = total primary energy output from biomass; \( M_{\text{biomass}} \) = total weight of biomass input; \( \delta \) = energy potential of biomass per ton; \( E_{\text{el,biomass}} \) = Electricity produced from biomass; \( E_{\text{he,biomass}} \) = Heat produced from biomass; \( \epsilon \) = energy conversion factor of primary energy into electricity; \( \phi \) = energy conversion factor of primary energy into heat.

The CO\(_2\) emission of the total paper industry in the Netherlands (CO\(_2\)totalpaperindustry) is the sum of all individual CO\(_2\) emissions of the paper grades, multiplied by their respective (weight) share in the total paper production: the impact factor (\( \lambda_i \)). The total energy use of the paper industry in the Netherlands (\( E_{\text{primary,totalpaperindustry}} \)) is the sum of all individual primary fossil fuel (\( E_{\text{fossil,input}} \)), biomass fuel (\( E_{\text{biomass,input}} \)) and bio-energy (\( E_{\text{biomass,output}} \)) multiplied by their respective impact factor (\( \lambda_i \)).

\[
CO_{2\text{,totalpaperindustry}} = \sum_i (CO_2)_i \times \lambda_i
\]

\[
E_{\text{primary,totalpaperindustry}} = \sum_i E_{\text{fossil,input}}_i \times \lambda_i + \sum_i E_{\text{biomass,input}}_i \times \lambda_i - \sum_i E_{\text{biomass,output}}_i \times \lambda_i
\]

Where: CO\(_2\)total paper industry = CO\(_2\) emission of the total paper industry in the Netherlands; \( E_{\text{primary,totalpaperindustry}} \) = total usage of primary energy of the total paper industry in the Netherlands; \( (CO_2)_i \) = CO\(_2\) emission of individual paper type i; \( E_{\text{fossil,input}}_i \) = individual primary fossil energy input of paper type i; \( E_{\text{biomass,input}}_i \) = individual primary biomass energy input of paper type i; \( E_{\text{biomass,output}}_i \) = individual primary energy extracted from biomass of paper type i; \( \lambda_i \) = impact factor of individual paper type i.
Table 2.2 Overview of key data assumptions on energy use and generation of the different processes.

<table>
<thead>
<tr>
<th>Processes ↓</th>
<th>Energy use</th>
<th>Energy generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electricity</td>
<td>Steam</td>
</tr>
<tr>
<td>Resource extraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chipping</td>
<td>15 kWh/t b</td>
<td>-</td>
</tr>
<tr>
<td>Transport</td>
<td>Truck</td>
<td>-</td>
</tr>
<tr>
<td>Pulping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical pulping</td>
<td>2200 kWh/t d</td>
<td>-</td>
</tr>
<tr>
<td>Chemical Pulping</td>
<td>700 kWh/t d</td>
<td>22.2 GJ/t d</td>
</tr>
<tr>
<td>RP pulping for newsprint</td>
<td>330 kWh/t h</td>
<td>0.6 GJ/t h</td>
</tr>
<tr>
<td>RP pulping for sanitary</td>
<td>375 kWh/t h</td>
<td>0.6 GJ/t h</td>
</tr>
<tr>
<td>RP pulping for corrugated board</td>
<td>100 kWh/t h</td>
<td>0.06 GJ/t h</td>
</tr>
<tr>
<td>RP pulping for greyboard</td>
<td>85 kWh/t h</td>
<td>0.02 GJ/t h</td>
</tr>
<tr>
<td>RP pulping for folding boxboard</td>
<td>500 kWh/t h</td>
<td>0.35 GJ/t h</td>
</tr>
<tr>
<td>Paper-making</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newsprint</td>
<td>550 kWh/t h</td>
<td>4.5 GJ/t h</td>
</tr>
<tr>
<td>Printing/ writing</td>
<td>340 kWh/t h</td>
<td>5.5 GJ/t h</td>
</tr>
<tr>
<td>Sanitary</td>
<td>530 kWh/t h</td>
<td>5.2 GJ/t h</td>
</tr>
<tr>
<td>Corrugated board</td>
<td>180 kWh/t h</td>
<td>4.7 GJ/t h</td>
</tr>
<tr>
<td>Greyboard</td>
<td>200 kWh/t h</td>
<td>4.8 GJ/t h</td>
</tr>
<tr>
<td>Folding boxboard</td>
<td>180 kWh/t h</td>
<td>5.5 GJ/t h</td>
</tr>
<tr>
<td>Production of additives</td>
<td>Inorganic filler production</td>
<td>192 kWh/t j</td>
</tr>
<tr>
<td>Energy conversion processes</td>
<td>Energy generation from coarse rejects</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Energy generation from deinking sludge</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Energy generation from MSW incineration m</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Energy generation from wood incineration n</td>
<td>-</td>
</tr>
</tbody>
</table>

a Worrell et al. (1994).
c Farahani et al. (2004).
d Gullichsen and Fogelholm (2000) (Eds.).
e It is assumed that 3.1 GJ is available as excess heat from the pulping process (Gullichsen and Fogelholm, 2000) and 2.3 GJ from the burning of bark (Holmberg and Gustavsson, 2007).
f Includes 11.7 GJ steam used in process and 10.5 GJ steam used in Back Pressure Steam Turbine (BPST)/Condensing Steam Turbine (CST) (Gullichsen and Fogelholm, 2000).
g It is assumed that 18 GJ is available from black liquor and 4.2 GJ from bark burning.
h Estimation based on real data from Dutch Paper mills. Source: Royal Netherlands Paper and Board Association (2009). Database is confidential. Aggregated per product group for the purpose of this study.
Based on SimaPro data for Kaolin (BUWAL250). Total energy use of fillers is calculated at 1.74 GJ/t. This energy figure for fillers (kaolin) is in accordance with the total energy use 2.0 GJ/t reported by IPPC (European Commission, 2004) and 1.5 GJ/t reported by Joelsson and Gustavsson (2008).

Based on energy content wood (18 GJ/t) (Cleveland, 2004). Assuming an electrical combustion efficiency of 24% for mixed municipal waste and rejects from paper industry (also mixed).

Estimation based on real data from Dutch Paper industry. De-inking sludges are in The Netherlands mostly used as fuel and feedstock for industrial conversion into mineral products (i.e. CDEM facility in Duiven, The Netherlands). Both heat and electricity are produced within the process to convert the used minerals into a new mineral product (in total 4.2 GJ/t of de-inking sludge).

Based on energy content of wood (18 GJ/t) (Cleveland, 2004). Assuming an electrical combustion efficiency of 34%. Mann and Spath (1997) use a conversion efficiency of 37.2%. Dornburg et al. (2006) use 35% for biomass gasification and co-combustion in a coal-fired power plant and even 48–59% for BIG-CC (not commercially).

Table 2.3 Overview of key data assumptions (in %) on fibre furnish, inorganic filler content, rejects from RP cleaning, resource efficiency and recycling rates of the different pulp types and paper grades.

<table>
<thead>
<tr>
<th>Paper grade</th>
<th>Pulp type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mechanical</td>
</tr>
<tr>
<td>Fibre furnish (%)</td>
<td></td>
</tr>
<tr>
<td>Mech. Pulp</td>
<td>20</td>
</tr>
<tr>
<td>Chem. pulp</td>
<td>0</td>
</tr>
<tr>
<td>RP</td>
<td>80</td>
</tr>
<tr>
<td>Inorganic filler content (%)</td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>1.5</td>
</tr>
<tr>
<td>Fine</td>
<td>0.4</td>
</tr>
<tr>
<td>Deinking</td>
<td>10</td>
</tr>
<tr>
<td>Recycle rate (%)</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Resource efficiency (%)</td>
<td></td>
</tr>
<tr>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

a Estimation based on real data from Dutch Paper mills. Source: Royal Netherlands Paper and Board Association (2009). Database is confidential. Aggregated per product group for the purpose of this study.


c Informatiecentrum Papier en Karton (www.papierenkarton.org).

d Mechanical pulping produces a high pulp yield of 85–95% compared to only 45% from chemical pulping Paper Industry Technical Association (PITA, 2009) www.pita.co.uk/factsheets.
2.2.6 Input data

Tables 2.2 and 2.3 provide an overview of the key data assumptions of the various processes. The technologies used in the diverse processes are state-of-the-art technologies. We have distinguished six different paper grades and three different types of pulp. Since the energy use to pulp recovered paper depends on the type of paper product (e.g. de-inking, refining and dispersing steps), we have linked this pulping step to the six different grades. The other two pulping processes are reported separately. The assumptions related to resource extraction, transportation, end-of-life and energy generation from wood and/or waste are the same for all paper grades. Table 2.4 provides an overview of conversion factors for energy conversions, CO₂ emission factors and energy content used in this study.

**Table 2.4** Overview of conversion factors for energy conversion, CO₂ emission factors and energy content used in this study.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Electricity</th>
<th>0.522 kg CO₂/kWh (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat (natural gas)</td>
<td>72 kg CO₂/GJ (^b)</td>
</tr>
<tr>
<td>Energy conversion factors</td>
<td>Electricity</td>
<td>42% (^c)</td>
</tr>
<tr>
<td></td>
<td>Heat</td>
<td>90% (^c)</td>
</tr>
<tr>
<td>Energy content</td>
<td>Biomass</td>
<td>18 GJ/t (^d)</td>
</tr>
</tbody>
</table>

\( ^a\) Average emission factor for Dutch grid is 0.522 kgCO2/GJ (Sevenster et al., 2007).  
\( ^b\) Assuming Natural Gas as boiler fuel, which is common in The Netherlands. The value is calculated by dividing the CO2 value for natural gas (65 kgCO2/GJ) by the efficiency factor of heat boilers (90%). 
\( ^c\) Graus et al. (2007). Based on weighted average electrical efficiencies for 10 countries or region that together generate 65% of worldwide fossil power generation (35% for coal, 45% for natural gas).  
\( ^d\) Based on energy of content wood (18 GJ/t) (Cleveland, 2004).

2.3 Results

We first analyse the influence of the two system boundary conditions on the environmental impact of primary and secondary fibres. We use a reference paper production process (newsprint production), because the values for production processes can vary between paper grades (see Tables 2.2 and 2.3).

2.3.1 No constraints on resource use

In Figs. 2.3 and 2.4, the energy use and CO₂ emissions from the production of paper from three different pulp types is shown. In Fig. 2.3, we have distinguished between the amounts of ‘external’ energy input, biomass input (feedstock) and bio-energy output from the processes. The amount of energy input is lowest in paper from recovered pulp (13.5 GJ/t) and highest in
paper produced from chemical pulp (42.5 GJ/t). The amount of bio-energy output is also highest in paper from chemical pulp (38.6 GJ/t). In fact, the net energy use of this type is close to 0 if we would not account for biomass input (= feedstock energy). Feedstock energy is only accounted for in the two virgin based pulps. Since the yield of mechanical pulp is about twice as high (see Table 2.3) as that of chemical pulp, the required virgin biomass input is about half that of chemical pulping. In mechanical pulping, only a small part of the raw material (mainly bark) is used to produce bio-energy. Fig. 2.4 shows that CO2 emissions are lowest (approx. 300 kg CO2/t paper), for paper produced via chemical pulping. This is because feedstock not used for papermaking (more than 50%) is used as an energy source to the process. Virgin pulps have higher feedstock use, but the bio-energy produced during pulping reduces CO2 emissions. Highest CO2 emissions (approx. 1450 kg CO2/t paper) are in paper production from mechanical pulp. The energy demand in mechanical pulping is a little lower than that in chemical pulping. However, most of the feedstock (95%) in mechanical pulping is used in the papermaking process and only 5% is used for bio-energy production. Although the energy use in recovered paper mills is low, in most cases the energy use is of fossil origin and no bio-energy is produced in the process. This explains the relatively high level of CO2 emissions (approx. 800 kg CO2/t paper) for newspaper production from recovered paper.

![Fig. 2.3 Energy input and output during the production of newsprint paper from three pulp types.](image)

Fig. 2.3 Energy input and output during the production of newsprint paper from three pulp types.

The error bars in Figs. 2.4 and 2.5 indicate results within realistic data ranges for material losses in mechanical (4–6%) and chemical (54–56%) pulping, for electricity (550–650 kWh/t paper) and heat use (4.5–6.5 GJ/t paper) in paper production, for electricity (2100–2900 kWh/t pulp) and heat generation (3.1–5.5 GJ/t pulp) in mechanical pulping, for electricity (550–700 kWh/t pulp) and heat use (15.7–18 GJ/t pulp) in chemical pulping and for electricity (1170–1425 kWh/t pulp) and heat generation (18–22.2 GJ/t pulp) in black liquor energy extraction.
2.3.2 Putting a limit on resource use

Recycling leads to an increase in biomass available when compared to virgin based production chains. Current life-cycle methods often do not incorporate this increase. We investigate the effect of limiting resources on the energy use and CO$_2$ emissions of paper production for the three different pulp types. We expand the system boundaries and assume the same feedstock use for each production chain (i.e. the feedstock use for chemical pulping). Surplus feedstock is assumed to be converted into energy. The inclusion of surplus biomass in our system boundaries leads to a decrease in CO$_2$ emissions in mechanical and recovered pulping (Fig. 2.5). Recovered paper based pulping (−1100 kgCO$_2$/t) is under these assumptions that the most favourable pulp type with respect to CO$_2$ emissions and even outperforms chemical pulping (300 kgCO$_2$/t). Within the current system boundaries, energy use includes both process energy as well as feedstock energy and this figure in both mechanical (48 GJ/t) and recovered pulping (22 GJ/t) increases (Fig. 2.6) even though more bio-energy is produced. This is due to the assumed feedstock use, which is in this approach the same for all pulp types. This assumption makes the figures for the three pulp types better comparable, as for chemical pulping also part of the feedstock is used for energy generation. However, since the total energy use now includes both bio-energy production as well as paper production, the figures do not reflect paper production energy use, but represent total resource consumption. The analysis shows that using a single indicator, CO$_2$ emissions or energy consumption, is not sufficient to determine the sustainability of paper production chains, especially when comparing different chains. One of the reasons for this is the complex relation between these two indicators in bio-based processes. The allocation of surplus biomass for production of bio-energy is of significant influence on the outcome of life-cycle analyses in paper production chains. Recycling of paper leads to more available biomass, which can potentially be used for energy extraction. It can be debated if it is justified to allocate the surplus feedstock to the recycling chain. However, including this resource
limitation into the model makes a fairer comparison between primary fibre chains and chains using recovered fibres possible.

**Fig. 2.5** CO₂ emissions during the production of newsprint paper from three pulp types with two different system boundaries.

**Fig. 2.6** Energy use during the production of newsprint paper from three pulp types with two different system boundaries.

### 2.3.3 Dutch paper and board production life-cycle analysis – country model

Fig. 2.7 depicts the energy use and CO₂ emissions over the lifecycle of an ‘average’ ton paper (Dutch paper and board mix) for different recycling rates. The total average recycling rate in The Netherlands is approximately 75% (PRN, 2009). Fig. 2.7 shows that this indicates an energy use of about 14 GJ/t over the life-cycle. This is equal to CO₂ savings of about 1 t CO₂/t paper as compared to no recycling (see Fig. 2.7). For paper production in The Netherlands (3
Mt per year), this means about 3 Mt avoided CO2 emissions per year, as compared to 0% recycling. This is equivalent to 9% of the total Dutch industrial CO2 emissions in 2007.

![Fig. 2.7 Influence of recycling rate on life-cycle energy use and CO2 emissions of paper production in The Netherlands.](image)

2.3.4 Production life-cycle analysis – individual paper grades

Large variations exist between paper grades in electricity and heat use during production, but also in e.g. fibre furnish, filler content and recyclability (see Tables 1.1 and 1.3). As these parameters influence energy use over the life-cycle, we further investigate individual paper grades. We are not interested in the relative performance of one grade over another as we assume that paper grades cannot be substituted due to differences in product specifications and quality demands. However, assessing different paper grades helps to gain better insight into the impact of improvement options on energy use and CO2 emissions. In this section, we therefore explore the life-cycle energy use breakdowns of six paper grades (Fig. 2.8).

Fig. 2.8 shows that the energy needed for processing (process energy in) varies by more than a factor of 4 between paper grades. Printing and writing papers are more energy intensive than the packaging grades. This is the logical consequence of variations in quality demands. Biomass energy in is only related to paper grades that (at least for some part) use virgin fibres (see Table 2.1). Corrugated board and greyboard are produced from 100% recovered fibres and therefore no biomass energy is allocated to these grades. Only the grades that are (partly)

\[\text{energy use breakdowns of six paper grades (Fig. 2.8).}\]

\[\text{Fig. 2.8 shows that the energy needed for processing (process energy in) varies by more than a factor of 4 between paper grades. Printing and writing papers are more energy intensive than the packaging grades. This is the logical consequence of variations in quality demands. Biomass energy in is only related to paper grades that (at least for some part) use virgin fibres (see Table 2.1). Corrugated board and greyboard are produced from 100% recovered fibres and therefore no biomass energy is allocated to these grades. Only the grades that are (partly)\]

\[\text{According to the Dutch national statistics office (CBS, 2009), 33 Mt CO2 was emitted by the Dutch industrial sector in 2007.}\]
produced from chemical pulp (i.e. printing and writing paper and sanitary paper), show substantial bio-energy output. For the other grades, the share of bio-energy (from mechanical pulp or from recovered paper rejects) is so small that it is hardly visible in Fig. 2.8.

End-of-life energy indicates the energy value of the paper grade at the end of its life-cycle. In our study, two end-of-life options for fibres are modelled: (1) recycling or (2) MSW incineration. If the fibre is recycled, the end-of-life energy of the fibre is assumed to equal the feedstock energy needed to produce the same amount of fibres from chemical pulp. If the fibre is not recycled, it is assumed to be incinerated for energy. From an energy point of view, recycling of the fibre is a more valuable end-of-life option as the energy content of pulpwod replaced is higher than the energy generated by MSW incineration. Not all paper grades, however, consist solely of fibres. In some paper grades the amount of fillers can be up to 50% (Table 2.3). Fillers do not contribute to energy generation in MSW incineration. Moreover fillers cannot be recycled in the process. Therefore, we have not allocated an end-of-life energy value to fillers. In Fig. 2.8, it can be seen that the grades with a high recycling rate and/or low filler use, have the highest energy value at the end-of-life. Sanitary paper has a low end-of-life energy value as it is neither recycled nor incinerated. Printing and writing paper has a high recycling rate (80%), however the amount of fillers is high, which explains its lower end-of-life energy value as compared to e.g. newsprint that has the same recycling rate.
We investigate the effect of the following optimisation options on the life-cycle energy use of printing and writing paper:

- Reduced heat consumption in papermaking with 30%.
- Decreasing filler percentage from 21% to 0%.
- Increased recycled fibre input from 0% to 20%.
- Increased recycling from 80% to 100%.

We have selected printing and writing paper to demonstrate the effect of the changes. Note that in reality not all optimisation options are suited for all paper grades (e.g. for printing and writing paper, increased recovered fibre input will probably not be possible because of quality standards). However, this option might be suited for other paper grades\(^\text{10}\). The results are shown in Fig. 2.9.

Reducing steam use in papermaking with 30% is modelled to reflect improvements in drying technology. Fig. 2.9 shows that reducing drying energy only influences the process energy; all other life-cycle energy impacts remain unchanged. As the energy intensity of chemical pulping is high, the energy impact of papermaking is relatively small. A 30% steam reduction

\(^{10}\) In that case, however, the quantified result would probably change due to large variations in life-cycle energy use between the different paper grades.
in papermaking has a positive impact of approximately 2 GJ/t on the life-cycle energy use of printing and writing paper. Reducing the filler content has an influence on all life-cycle energy parts of printing and writing paper. In this scenario, we have reduced filler content from 21% to 0%. The biomass energy increases with 8.4 GJ/t as fillers will be replaced by virgin fibres. The process energy increases with 6.3 GJ/t since it is more energy intensive to produce fibres than to produce fillers (see Table 2.2). However, since more chemical pulping is needed, also the bio-energy output increases (9.8 GJ/t). A positive impact (7.1 GJ/t) is also seen on the end-of-life energy, as fillers do not contribute to energy generation in MSW incineration and they cannot be recycled for reduced biomass demand. The overall effect of reducing filler content on the life-cycle energy of printing and writing paper is a reduced life-cycle energy use of 2.2 GJ/t. In printing and writing papers often no recovered fibres are used. In the third scenario we explore the effect of using 20% recovered fibres. The result is a decrease in biomass energy in and bio-energy out. Also the process energy use decreases as it is less energy intensive to process recovered fibres than to extract virgin fibres from wood. The end-of-life energy does not change. The overall impact is a reduced life-cycle energy use of 4.1 GJ/t. Finally, the effect of increasing the recycling rate is explored. The recycling rate for printing and writing paper in The Netherlands is about 80% (see Table 2.1). We model the effect of increasing the rate to 100%. The results show that this only impacts the end-of-life energy value of the paper. All other life-cycle stages remain unchanged as we have not changed the fibre furnish of the paper. Since the end-of-life energy value increases, the overall effect of this scenario is a reduced life-cycle energy use of 4.7 GJ/t.

2.3.5 Sensitivity analyses

In Figs. 2.10 and 2.11, sensitivity to the main energy conversion parameters is investigated. These parameters are energy efficiency in bio-energy production, energy efficiency of MSW incineration\(^\text{11}\), emissions of reference electricity production, CO\(_2\) emissions of reference fuels and CO\(_2\) emissions of reference electricity production. Sensitivity to changes in system boundary conditions concerning surplus land have been studied in the first section of this chapter. The influence of technical and technological changes on life-cycle energy use of different paper grades has been studied in Fig. 2.9. In this section the sensitivity analyses focus on overall life-cycle energy use and CO\(_2\) emissions of total paper production in The Netherlands. The recycling rate in The Netherlands is assumed to be 75%. Table 2.5 shows ranges of the main parameters that are varied.

\(^{11}\) Note that this is for demonstration purposes only, it is not realistic to increase the recovered fibre input of printing and writing paper for quality reasons.
**Table 2.5 Ranges of parameters for sensitivity analysis.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW incineration (kWh/t)(^a)</td>
<td>-1200</td>
<td>-600</td>
<td>-2050</td>
</tr>
<tr>
<td>((\eta_e = 24%))</td>
<td></td>
<td>((\eta_e = 12%))</td>
<td>((\eta_e = 41%))</td>
</tr>
<tr>
<td>Energy from wood (kWh/t)(^b)</td>
<td>-1700</td>
<td>-1000</td>
<td>-2500</td>
</tr>
<tr>
<td>((\eta_e = 34%))</td>
<td></td>
<td>((\eta_e = 20%))</td>
<td>((\eta_e = 50%))</td>
</tr>
<tr>
<td>CO(_2) emission factor heat (kg CO(_2)/GJ)</td>
<td>72</td>
<td>0</td>
<td>112(^c)</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Renewables</td>
<td>Lignite</td>
<td></td>
</tr>
<tr>
<td>CO(_2) emission factor electricity (kg CO(_2)/kWh)(^d)</td>
<td>0.522</td>
<td>0</td>
<td>0.960</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Renewables</td>
<td>Lignite</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Faaij et al. (1998). High values are for IG/CC; low values are for low efficiency standalone combustion facilities.

\(^b\) Faaij (2006). High values are for BIG/CC; low values are for standalone combustion.

\(^c\) Lower value is based on heat from CO2 neutral sources e.g. biomass. Higher value is based on a IPPC default CO2 emission factor of 101.2 kg CO2/GJ for lignite and a conversion efficiency of (90%).

\(^d\) Lower value is based on electricity from CO2 neutral sources e.g. wind or biomass. The high value is based on IPPC default CO2 emission factor of 101.2 kgCO2/GJ for Lignite and a conversion efficiency of 42%.

Fig. 2.10 presents the sensitivity of life-cycle energy use of paper production in The Netherlands (14.1 GJ/t) to changes in energy efficiency in bio-energy production and in MSW incineration. The results show that the maximum MSW incineration efficiency considered in the sensitivity analysis, leads to the lowest lifecycle energy use (12.4 GJ/t) (assumed recycling rate of 75%). With lower recycling rates, the impact of MSW incineration efficiency increases. The impact of increased wood conversion efficiency is smaller (13.8 GJ/t). The reason is that in the current system, using applied system boundaries, only a few surplus wood is converted to electricity.
**Fig. 2.10** Sensitivity of life-cycle energy use of paper production in The Netherlands (75% recycled fibre) to changes in energy efficiency in bio-energy production and in MSW incineration.

The sensitivity of life-cycle CO\(_2\) emissions from paper production (210 kg CO\(_2\)/t paper) is presented in Fig. 2.11. The lowest CO\(_2\) emissions (−110 kg CO\(_2\)/t paper) are found for minimum CO\(_2\) emission factors for heat generation. The life-cycle CO\(_2\) emissions of paper production could be reduced with 150% if all heat needed, would be provided via CO\(_2\) neutral energy sources. Steam is nowadays mainly provided via natural gas. CO\(_2\) emissions do not only drop to 0, but even become negative due to CO\(_2\) credits at the end of paper life. The influence of CO\(_2\) emissions of reference electricity production is smaller. A low emission factor for electricity production leads to higher life-cycle CO\(_2\) emissions (320 kg CO\(_2\)/t paper). This is because energy extracted from biomass streams (e.g. via black liquor) replaces energy produced by the grid. In general, the sensitivity of life-cycle energy use of paper production to the main energy conversion parameters is found to be relatively small (<13%). The impact increases in systems where more energy is generated from surplus biomass or from MSW incineration. Compared to the results in previous sections, the choice of system boundaries, recycling rate and the pulp/paper mix produced have highest impact on the results. The sensitivity of life-cycle CO\(_2\) emissions to CO\(_2\) emission factors of heat and electricity production is found to be larger (up to 150%).
2.4 Discussion

Various LCA’s and waste management studies have been published that discuss the trade-offs of recycling and other end-of-life options for used paper. Although, in this study, we have not focused on different waste management alternatives, findings are in-line with most of these studies. Recycling is beneficial regarding CO$_2$ emissions and (feedstock) energy use over the paper life-cycle. Moreover, we found that the choice of system boundary has large impacts on the results. Especially regarding the in- or exclusion of surplus biomass that becomes available via increased recycling. This study provides new insights with respect to the pulp and paper production of a whole country and the relative impact of individual paper grades. Therefore, we were able to find not only the differences in paper grades but also the effects of recycling of different paper grades and of a mix of paper grades. It is important to emphasise that although we compared the environmental impacts of three different types of pulp, we do not intend to suggest that using one type of pulp is better over another because:

- The choice for a certain type of pulp is above all affected by the specific characteristics of the end product. Not every type of pulp is suited for every type of paper.
- The choice also depends on the feedstock availability. Where some countries have abundant forests, other more densely populated countries (like The Netherlands) have better opportunities for recovered paper collection.
- An input of virgin fibres in the paper cycle will always be needed to ensure continuation of the recycling loop. This is because not all fibres can be recovered (e.g. tissue, cigarettes, archives) and a single fibre has a finite life after which strength and quality degenerates.
- A focus on energy and CO$_2$ alone should not be used as the basis for decision making. From sustainability point of view, other environmental indicators (e.g. water use, chemical use etc.), economic and social indicators should be taken into account. From a business perspective, indicators on quality, costs and added value should be involved.

This study focused on the effect of increasing pressure on biomass availability (see also Holmberg and Gustavsson (2007))$^{12}$. We have analysed this by applying two different boundary conditions for surplus biomass. Recycling of paper leads to increased biomass availability, which can potentially be used for energy generation. It can, however, be

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$^{12}$ Holmberg and Gustavsson (2007) investigated the total biomass used for chemical and mechanical pulping under the assumption that all energy required – including external electricity and transportation fuel – is based on forest biomass (which is the same principal, but calculated exactly the other way around, as chosen in this study). They did not consider recycled fibres.
questioned if it is justified to allocate the surplus biomass to the recycling chain. A similar approach has been chosen by Dornburg and Faaij (2005) who studied costs and CO\textsubscript{2} emissions of biomass cascading. In our system boundary analysis, we investigated the impact of: (a) allocating recycling benefits solely to recovered pulp (e.g. accounting the energy input by feedstock use only to virgin based pulps) and allocating benefits of virgin fibres (e.g. negative CO\textsubscript{2} emissions due to bio-energy production) solely to these types and (b) of allocating surplus biomass to the more efficient chains. Both methods have advantages and disadvantages and this study has shown, that one should be careful selecting system boundaries in a system where the virgin and recycling chains are so dependent. A debate is also on-going in the LCA community on the allocation of recycling benefits. Due to the unique nature of the pulp and paper industry, this debate could have different impacts than that of other materials (e.g. steel, glass).

In our individual paper grade analysis, we tried to compromise on the allocation issue by directly transferring the benefits of recyclability to the life-cycle of that grade. This method gives the paper grade not only credits for the recovered fibre input, but also for the recovered fibres that can be extracted from it after use. Therefore, this approach also allocates recycling benefits to the virgin paper grades that are crucial in continuing the recycling loop. However, since biomass energy input for recovered fibres is assumed to be 0, the life-cycle energy use of paper products from recovered fibres can become negative. This is because the benefits of recycling are counted for both at the cradle as well as the grave for these grades. On the other hand, the approach chosen gives best insights in the impact of paper production during the various phases of its life-cycle.

One of the assumptions in our model is that chemical pulp is produced in non-integrated mills. This assumption might result in relatively high energy use for this type of pulp. Not only is an extra transport step required in chains with non-integrated mills, also the pulp needs an extra drying step. Other differences may appear depending on the type of integrated mill. The impact of transport on the total results is assumed to be small, but the heat use for drying pulp might be considerable. In our analysis, we have modelled a scenario with reduced heat consumption in the production of printing and writing paper. The results show that process energy decreased with less than 2 GJ/t over the life-cycle. This is a decrease of only 5% of and does not qualitatively change our results. Given the diverse types of integrated mills, however, results cannot be adopted to integrated mills without further analysis.

One of the unique elements of this study has been to distinguish between different paper grades. This takes the analysis on this aspect further than the study of Dornburg and Faaij (2005). We found large differences in life-cycle energy use between paper grades. Although recycling was found to have a positive impact on life-cycle energy use of all grades, the size
of the impact differs from grade to grade. This is for example due to differences in filler content. Even though the energy use of filler production is smaller than that of fibre extraction, the life-cycle impact of filler use is larger. This example illustrates that it is important to consider total life-cycle impacts and not only focus on process energy inputs. Differences in biomass input and bio-energy output between grades are related to difference in virgin or recovered fibre input. The impact of these differences depends largely on the modelling approach chosen (e.g. system boundaries and allocation method) as described above.

The impacts of energy conversion efficiencies and CO₂ emission factors have been analysed in our sensitivity analysis. Here, we assumed that the recycling rate is 75%. The impact under these assumptions was found to be rather small. In systems with lower recycling rates, the influence of MSW incineration efficiency increases as more paper is assumed to burned for energy. In systems where more biomass is incinerated to generate energy, the impact of both the biomass conversion efficiency as well as the emission factor of the grid increases. The latter is because the electricity generated from extracted biomass streams is assumed to replace energy produced from the grid.

2.5 Conclusions

This study has shown that paper recycling has a positive impact on energy intensity and CO₂ emissions over the total life-cycle. Assuming no constraints on resource availability, the paper production life-cycle from chemical pulping has the best score on CO₂ emission (300 kg CO₂/t) and the worst score on energy intensity (44 GJ/t). This is explained by the high feedstock use for energy generation. Paper production from recovered paper has lowest energy use (13 GJ/t). Assuming constraints on biomass availability (i.e. if biomass is also used for energy generation), recycling op paper has the lowest energy intensity (22 GJ/t) and CO₂ footprint (−1100 kg CO₂/t).

The life-cycle energy use of the current paper and board mix produced in The Netherlands is about 14 GJ/t. The recycling rate in The Netherlands is approximately 75%. The leads to CO₂ savings of about 1 t CO₂/t paper compared to no recycling. For paper production in The Netherlands (3 Mt per year), this equals about 3 Mt avoided CO₂ emissions per year. This is equivalent to approximately 9% of the total Dutch industrial CO₂ emissions in 2007.

Large variations exist between paper grades in e.g. electricity and heat use during production, fibre furnish, filler content and recyclability. These parameters were found to influence energy use over the life-cycle. The process energy needed for pulp and paper production
varies by more than a factor of 4 between paper grades (8–34 GJ/t), due to variations in quality demands. Differences in biomass input (0–32 GJ/t) and bio-energy output (0–38 GJ/t) between grades are related to differences in virgin or recovered fibre input. The impact of these differences depends further on the modelling approach chosen (e.g. system boundaries and allocation method). We found that grades with a high recycling rate and/or low filler use, have the highest energy value at the end-of-life (27–34 GJ/t). Even though the energy use of filler production is smaller than that of fibre extraction, the life-cycle impact of filler use is larger. Recycling was found to reduce life-cycle energy intensity of all grades.

Reduced heat consumption in papermaking (30%), decreased filler percentage (0%), increased recycled fibre input (20%) and increased recycling (100%) were all found to reduce life-cycle energy intensity of printing and writing paper production. The effects were found in different parts of the life cycle and together amount to savings of 15 GJ/ton. Also in this study, the allocation of recycling benefits between virgin and recovered fibres is found to be a difficult question. In our study, we tried to compromise on the allocation issue by directly transferring the benefits of recyclability to the life-cycle of that grade. This method gives the paper grade not only credits for the recovered fibre input, but also for the recovered fibres that can be extracted from it after use. Since biomass energy input for recovered fibres is assumed to be 0, the life-cycle energy use of paper products from recovered fibres can become negative. However, this approach gives better insights in the impact of paper production during the various phases of its life-cycle. This study has shown that it is important to consider total lifecycle impacts and not only focus on process energy inputs. The choice of allocation depends largely on the purpose of the study and our results have shown that one should be very careful on this issue; especially in a system where the virgin and recycling chains are so dependent.
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3. Energy conversion strategies in the European paper industry*

A case study in three countries

Abstract

The pulp and paper industry both uses and produces large amounts of energy and rising fuel prices bring along significant challenges to the sector. Several strategies can be applied in order to remain competitive e.g. an increase in energy efficiency, a switch in fuel and/ or a novel energy conversion technology. In this study, we investigate if improved energy conversion strategies can reduce energy costs, primary energy use and CO$_2$ emissions of paper mills within different European countries (the Netherlands, Poland and Sweden). Our results show that differences in history and availability of resources has led to different conversion strategies in the three countries. We found that a natural gas combined cycle, which is largely implemented in The Netherlands due to long term domestic availability of natural gas, has the lowest primary energy demand. Due to a long history of low electricity prices, CHP has not been common in Sweden. Many Swedish mills use biomass as an energy source and due to low CO$_2$ emissions of the national grid the CO$_2$ emission profile of the Swedish paper industry is very low. Our results imply that future conversion routes for the Swedish paper and board industry are again wood based; in case of increasing electricity prices these would be biomass gasification based CHP solutions. With a reduction of 800 kgCO$_2$/ t paper on average, a switch from coal to biomass would reduce CO$_2$ emissions in the Polish pulp and paper industry with approximately 0.6 Mton/year. A carbon price of 20-25 €/ton would, according to our results, be enough to provoke this switch. Due to the high share of natural gas, the CO$_2$ emission reduction potential of the Dutch paper industry (1.5 Mton/year) is even larger than in Poland. Due to high biomass prices and relative low CO$_2$ emission profile of natural gas, a carbon prices of more than 60 €/ton CO$_2$ would be needed to provoke a switch in The Netherlands. Provided with few alternatives, the most effective strategy in The Netherlands would be an increase in energy efficiency.

* Published in Applied Energy, Vol. 98 (2012), pp. 102-113. Co-authors are A. Faaij and E. Worrell.
3.1 Introduction

The pulp and paper industry both uses and produces large amounts of energy. It accounts for about 5% of the total final energy use in IEA member countries, which is about 15% of the final use in the industry sector (IEA, 2011). The European pulp industry, in 2008, produced 26% of the world’s total pulp production (CEPI, 2009a). Paper exports in 2008 accounted for nearly 17 Mton of Europe’s production total of some 99 Mton. Less than 6 Mton of Europe’s paper needs (87.9 Mton) were imported (CEPI, 2009a). The European paper and board industry needs to stay competitive with emerging centres of the paper industry in e.g. Asia and South America. Energy costs have a large impact on the performance of pulp and paper companies, resulting in a drive to reduce energy consumption. The total specific energy consumption for the production of pulp and paper decreased from 16.1 GJ/t in 1990 to 13.8 GJ/t in 2008 in CEPI member states (CEPI, 2009b). Moreover, the European paper and board industry is a leader in the use of renewable energy sources, with a fraction of 55% biomass in its total fuel use (CEPI, 2009b). The industry has also invested heavily in combined heat and power generation (CHP), and sustained efforts have reduced specific CO$_2$ emissions with almost 40% from 1990 (0.57 t CO$_2$/t product) to 2009 (0.35 t CO$_2$/t product) (CEPI, 2009b).

Despite these efforts, energy has become one of the major cost components with a share of over 30% for some mills (CEPI, 2011) and rising fuel prices (including biomass sources) bring along significant challenges to the sector. Rising energy prices have increased the importance to control energy costs in industries’ strategies. The on-going efforts in improving energy efficiency only partly compensate for this effect. Even though the increase in energy prices is a global phenomenon, large differences in energy costs exist, even between different European countries and even for paper mills with similar energy efficiencies. Reasons are diverse and include differences in energy sources available, types of energy conversion, local electricity prices, and taxation or subsidy schemes. The type of fuel used is strongly related to the local availability of raw material, historic development and government policies (Ecofys, 2009). Pulp and paper are commodity goods that are traded on an international market. Increased energy costs in a paper mill’s cost structure can weaken the competitive position of paper mills that face high energy prices. This might even be true for mills with a relatively low specific energy use and a good CO$_2$ emission profile in countries where the available energy is expensive.

Many studies have investigated the potential of new energy conversion technologies in terms of CO$_2$ emission reduction and costs (e.g. Schmidt et al., 2010); most of these studies deal with energy conversion for electricity production or district heating (e.g. Basu et al., 2011; Möst and Fichtner, 2010; Difs et al., 2010 and Kalina, 2010). Several studies evaluate energy
conversion strategies in the pulp and paper industry, but most of these studies have an exclusive focus on black liquor gasification (e.g. Eriksson and Harvey, 2004; Joelsson and Gustanvsson, 2008; Carlsson et al., 2010; Petterson and Harvey, 2010 and Naqvi et al., 2010). To our knowledge, no studies are known that focus on a comparison of current paper industries’ energy conversion strategies in different countries or on the impact of future energy conversion strategies on cross-country differences in energy cost, primary energy use and related CO2 emissions.

The European paper industry operates on a world market where a level playing field is hard to be secured. Energy prices have been rising and, with the adoption of emission trading, so are the costs for CO2 emissions. In order to stay competitive, for paper mills, controlling energy costs is a key strategy. Part of this strategy is the choice for an efficient energy conversion technology and a low cost energy source (including CO2 emission related cost). The developments of energy and CO2 prices in the future are, however, insecure and on-going technological developments have increased the number of applicable energy conversion options. Therefore, to determine an optimal energy conversion route is challenging and complicated. The aim of this study is to analyse which energy conversion strategies can offset energy price differences and reduce primary energy use and CO2 emissions for paper mills within different European countries. Three case study countries have been selected (the Netherlands, Poland and Sweden), all countries having a thriving paper industry (> 2 Mton paper production/year) and individually having a large variation in available natural resources. We focus on inter-European differences, so that we can compare and analyse similarities and differences in cross-country impacts of European policies.

At first, an overview of the Dutch, Swedish en Polish pulp and paper industries’ structure is given, including an overview of the domestically available resources for pulp and energy production. We further make a selection of current and possible alternative energy conversion routes for the paper industry in each case study country. We then calculate energy costs, primary energy use and CO2 emissions of the paper and board industry, associated with each of the selected energy conversion strategies. We take into account different paper grades as their heat and electricity demand ratios vary (Laurijssen et al., 2010), which can influence the choice for a certain type of technology. We put special attention to the impact of future CO2 price levels on the competitiveness of the selected energy conversion routes. Finally, results are discussed, which includes a cross country comparison of different alternatives. We reflect on the role of European policies in the strategic decision for future energy conversion options in the individual countries.
3.2 Paper industry structure and related energy conversion routes in three case study countries

In the following section a description of the Dutch, Swedish and Polish pulp and paper industries’ structure is given, including the dominant industrial energy conversion routes. We also discuss the countries’ main energy sources and electricity mix. Table 3.1 summarizes the main characteristics in the selected countries.

3.2.1 The Netherlands

The Dutch paper and board industry consists of 23 production locations that provide direct employment to about 4300 employees. Together, the Dutch paper and board mills were responsible for a production of 3 Mton paper in 2008 with a turnover of 1.8 billion Euros (VNP, 2008). About 74% of the produced paper is exported. The Dutch paper industry mainly uses recovered fibres as feedstock and (domestic) biomass is hardly available. More than 80% of the fibre raw material input is recovered paper. All Dutch paper mills are non-integrated mills, including those mills that use virgin fibres as feedstock.

The Netherlands is a significant producer (and exporter) of natural gas. It is the second largest producer of natural gas in the EU and it depends on energy imports for oil and hard coal. The Dutch electricity mix is mainly based on natural gas (63%) and hard coal (23%) (EC, 2007a). Electricity prices are almost 10% above European average (Eurostat, 2010). The Dutch paper industry runs for approximately 97% on natural gas (Ecofys, 2009). Its total annual energy use is about 31 PJ. Approximately 75% of the production locations have a CHP installation installed, the other mills produce heat in boilers and buy electricity from the grid.

3.2.2 Sweden

The Swedish paper and board industry consist of 41 paper mills and 41 pulp mills. Together, the Swedish pulp and paper mills produced 3.8 Mton market pulp and 11.4 Mton paper and board in 2010 (Swedish Forest Industries Federation, 2010). Sweden is the 2nd largest pulp producer of Europe (after Finland) and the 3rd largest producer of paper in Europe (after Germany and Finland). About 85% of the market pulp and 88% of the produced paper is

---

13 The wording with respect to integration is not used uniformly throughout literature and discussions. In this report, following the definition of (Ecofys, 2009) an integrated mill is defined as a mill where virgin pulp making is integrated with paper making on the same site. The term non-integrated mill is used for mills using recycled fibre and mills that buy pulp from the market. Market pulp mills only produce pulp for sale to the market. In Europe about 18% of all mills in the pulp and paper industry are integrated mills although different degrees of integration occur (Ecofys, 2009).
exported (Swedish Forest Industries Federation, 2010). Biomass resources are widely available and the Swedish paper industry is mainly virgin fibre-based. Only 17% of the fibre raw material input is recovered paper, 50% is chemical pulp, 30% is mechanical pulp and 3% is semi-chemical pulp. About 68% of the pulp produced in Sweden is processed in integrated mills (Swedish Forest Industries Federation, 2010). In integrated mills, the exhaust heat of the pulping process (from incinerating black liquor) is used in the papermaking process, which reduces the need for steam production via current energy conversion routes.

Table 3.1 Main characteristics of Dutch, Swedish and Polish pulp and paper industries with regard to production and energy conversion routes.

<table>
<thead>
<tr>
<th></th>
<th>NL</th>
<th>SE</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production (Mton) Paper</td>
<td>Market pulp</td>
<td>0 4 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paper</td>
<td>3 11 3</td>
<td></td>
</tr>
<tr>
<td>Fibre share Virgin</td>
<td>Recycled</td>
<td>80% 17% 37%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Virgin</td>
<td>20% 83% 63%</td>
<td></td>
</tr>
<tr>
<td>Integrated mills (%)</td>
<td>+/-0% 68%</td>
<td>Unknown</td>
<td></td>
</tr>
<tr>
<td>Main domestic energy source</td>
<td>Natural gas</td>
<td>Biomass</td>
<td>Coal and Biomass</td>
</tr>
<tr>
<td>Dominant energy conversion routes in P&amp;P industry</td>
<td>CHP (gas)</td>
<td>Recovery heat</td>
<td>Boiler (coal/bio)</td>
</tr>
<tr>
<td></td>
<td>Boiler (gas)</td>
<td>Boiler (biomass)</td>
<td>Recovery heat</td>
</tr>
<tr>
<td>Grid electricity mix (%)</td>
<td>63% gas 50% nuclear 92% coal</td>
<td>23% coal 50% hydro</td>
<td></td>
</tr>
</tbody>
</table>

More than a third of the energy supply in Sweden depends on imports. Energy imports are mainly oil from Russia and Norway with some small quantities of hard coal imports. Domestic energy production is mainly limited to electricity generation. About half of the electricity generated in Sweden is produced from nuclear energy, the other half from renewables (where hydropower plays a substantial role) (EC, 2007b). Due to the low presence of fossil fuel resources, CO₂ emissions related to Swedish electricity production are very low (+/- 0.4 kg CO₂/kWh). Electricity prices have been more than 20% lower than European averages (Eurostat, 2010) over the last years, and a substantial amount of electricity in the Swedish paper industry is purchased from the grid. In some mills, exhaust steam from black liquor recovery is used in a steam turbine to produce electricity. On average, however, paper producers in Sweden produce only approximately 25% of their power demand (Swedish Forest Industries Federation, 2010). Heat demand is mostly covered by black liquor recovery and by additional heat boilers. Heat boilers in the Swedish paper and board industry are mainly fuelled with biomass (89%) or oil (9%) (Ecofys, 2009).

14 Currently, electricity prices are historically high in Sweden, although not 20%, they are still well below European averages.
3.2.3 Poland

In Poland, 39 paper and board mills and 5 pulp mills of various sizes are in operation. Their total annual production is approximately 1 Mton pulp and 3 Mton paper. From the 39 paper mills, 21 are smaller than 10,000 ton a year and the 2 largest paper mills (with production capacities above 500,000 tons a year), together contribute to over 50% of the total paper production in Poland (Malinowski and Michniewicz, 2007). The production of pulp in Poland is taking place at 5 companies. In 3 companies chemical pulp is produced by the Kraft method, the 2 others produce mechanical pulp (Malinowski and Michniewicz, 2007).

Coal is the dominant fuel in Poland and accounts for around 65% of the total primary energy consumption in 2006 (Nilsson et al., 2006). Poland has the largest coal reserves of Europe; it is the 9th largest coal producing country in the world and the 5th largest coal exporting country. About 38% of natural gas consumption is produced in Poland. Russian imports cover about 47% of the domestic consumption of natural gas in Poland (EC, 2007c). Poland is also dependent on the import of oil, since its domestic production only covers about 8% of its domestic consumption. Due to large coal reserves, electricity in Poland is for over 90% produced from coal, including both hard coal and lignite. The remaining electricity is mainly produced by oil, gas and renewables. Electricity prices are almost 10% below European averages (Eurostat, 2010). Energy sources used in the Polish pulp and paper industry are mainly biomass (69%) and coal (25%) (Ecofys, 2009). Several Polish paper mills are integrated and have relatively cheap steam from black liquor recovery. Most non-integrated mills produce steam with a boiler on biomass and/or coal. Electricity is bought from the grid or produced on location by means of a steam turbine.

3.3 Methodology

First, we describe the approach to calculate energy costs, primary energy use and CO₂ emissions for current and several alternative energy conversion routes in the three case study countries. The heat and electricity demand ratio of a paper mill depends for a large part on the paper grade produced (Ecofys, 2009; Laurijssen et al., 2010). This ratio might affect the choice for an energy conversion technology as the heat to power ratio of the conversion technology is adapted to either the heat or the power demand ratio of the mill. Since the focus in this study is on energy conversion, and also because of data availability, we assume a fixed and equal energy demand, for three paper grades, in all three countries. The assumption of equal energy intensities for paper mills in different countries is not realistic. Different mill sizes and differences in cross-country energy prices can largely influence energy-efficiency. Therefore, we explore the impact of differences in energy intensities on our results in a
sensitivity analysis. Table 3.2 shows our assumptions for corrugated board, graphical paper, and tissue. We further assume a reference capacity of 150 kton paper production/year for all paper mills.

<table>
<thead>
<tr>
<th>Table 3.2 Typical heat and electricity demand by paper grade (Laurijssen et al., 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper grade</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Corrugated Board</td>
</tr>
<tr>
<td>Printing Paper</td>
</tr>
<tr>
<td>Tissue</td>
</tr>
</tbody>
</table>

Energy conversion technologies are assessed using the following parameters: capital cost, O&M cost, thermal efficiency, electrical efficiency, estimated lifetime, fuel type(s), capacity and scaling factor. Energy sources are assessed by: current price, price volatility and carbon content. Energy conversion routes (combination of conversion technology and energy source) are evaluated according to energy costs, primary energy use and CO₂ emissions. For each conversion route the energy costs are calculated according to formula (1):

\[
\text{CoE} = (\alpha \times I) + \text{O&M} + F - B + \text{CO}_2
\]

(1)

\[
\text{CoE} = \text{Cost of Energy (€/year)}
\]

\[
\alpha = \text{Annuity factor (year}^{-1}\text{)}
\]

\[
I = \text{Initial investment (€)}
\]

\[
\text{O&M} = \text{Operation and Maintenance costs (€/year)}
\]

\[
F = \text{Fuel and electricity costs (€/year)}
\]

\[
B = \text{Benefits of energy delivery (€/year)}
\]

\[
\text{CO}_2 = \text{Carbon emission costs (€/year)}
\]

To annualize costs the annuity factor is used:

\[
\alpha = \frac{r}{(1 - (1 + r)^{-L})}
\]

(2)

\[
L = \text{Lifetime (year)}
\]

\[
\alpha = \text{Annuity factor}
\]

In order to derive installation costs at capacities other than for which prices are provided by literature or by other sources, the costs at the capacities under consideration are calculated (3):
In chemical pulp mills, black liquor is generated during a process in which cellulose is separated from lignin. Black liquor is used as an energy source in the mill. Since it is not a product that is traded on the market (except for some situations where the pulp mill’s energy plant is outsourced (Holmberg et al., 2011), there is no market price for lignin and there are on-going discussions about how it should be valued (Svensson et al., 2009). Some studies assume that no price should be accounted to black liquor, as it is a left-over stream from the pulping process (Karlsson, 2011). In Svensson et al. (2009) it is assumed that the price of lignin is 50% higher than the price of by-products. Other studies even propose that lignin should possibly be valued at a price equivalent to oil (e.g. Axelsson, 2011 and Axelsson and Berntsson, 2011). In this study, we value black liquor at a price equivalent to the price of pulpwood. In order to reflect the different approaches found in literature, we take into account a price range of black liquor in our calculations (Table 3.4).

Primary energy use is the energy content of the fuel needed to generate the required heat and electricity for paper production. We assume that on-site fuel use is determined by heat demand of the process in combination with thermal efficiency of the respective conversion route. Depending on electrical efficiency of the conversion route and electricity demand of the process, there is either a shortage or excess of electricity produced on site. In case of shortage, we add primary energy use from grid based electricity, assuming 40% efficiency\(^{15}\), to the on-site fuel use. In cases of excess electricity production, electricity delivered is assumed to replace grid electricity produced with 40% efficiency, and a consequent amount of primary energy is deducted from on-site fuel use. Financial revenues for surplus electricity production are assumed to be 90% as compared to the price of buying electricity.

\(^{15}\) The efficiency of grid based electricity varies per country and per region in Europe. At this moment, there is a rapid increase in interconnectivity of national grids in Europe. Moreover, we observe an increasing share of renewable energy sources and de-centralised electricity production in Europe. Given these trends, we were unable to find country-specific grid efficiencies for our case study countries. We therefore assume 40% efficiency for electricity generation as a European average.
In cases where there is a shortage of electricity produced on-site, CO₂ emissions are calculated as the CO₂ emissions from on-site fuel use plus CO₂ emissions related to the electricity that is purchased from the grid. For conversion routes with excess electricity produced on site, we calculate total CO₂ emissions as the CO₂ emissions from on-site fuel use minus CO₂ emissions related to avoided production of grid electricity. In both cases we assume the average CO₂ figures of the national grid. We will discuss on the impact of this assumption in the discussion section.

3.4 Conversion routes and data

3.4.1 Selected energy conversion routes

Several technologies are able to fulfil the energy needs of paper and board producing plants. Table 3.3 gives an overview of selected current and alternative energy conversion routes in the three case study countries. Current energy routes in the Dutch paper industry are: a gas-heated boiler in combination with electricity from the grid, a gas-heated boiler with steam turbine, a gas turbine and a combined cycle (CC) on natural gas. As alternatives routes we have selected several biomass-based options in combination with current technologies. In some of these routes, a gasification step is needed. In this study, we distinguish biomass gasification (BIG) and black liquor gasification (BLG).

Current energy conversion routes in the Swedish paper industry include a biomass boiler, an oil boiler and a recovery boiler, all in combination with electricity from the grid. In some cases a steam turbine is used to produce electricity for own usage. As alternative energy conversion routes for Sweden, we have selected different types of combined heat and power technologies. Current energy conversion routes in the Polish paper industry are diverse. We include boilers fuelled by coal and biomass in combination with electricity from the grid. We further consider a boiler on coal in combination with a steam turbine and recovery heat in combination with electricity from the grid. As alternative energy conversion routes for Poland, we have selected several natural gas and biomass based combined heat and power technologies.

---

16 We have included two alternative energy conversion routes in Sweden that are based on natural gas. It is important to mention that Sweden has no known large natural gas resources and has not built any nation-wide gas grid. A high pressure gas grid only exists in western Sweden where a gas pipes transport the gas from Malmo to Gothenburg and further North up to Stenungsund. Only a small share of the Swedish pulp and paper industry operates in this area.
Table 3.3 Overview of selected current and alternative energy conversion routes in the three case study countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Current routes</th>
<th>Alternative routes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technology</td>
<td>Fuel</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Boiler</td>
<td>Natural Gas</td>
</tr>
<tr>
<td></td>
<td>Steam Turbine</td>
<td>Natural Gas</td>
</tr>
<tr>
<td></td>
<td>Gas Turbine</td>
<td>Natural Gas</td>
</tr>
<tr>
<td></td>
<td>Combined Cycle</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>Sweden</td>
<td>Boiler</td>
<td>Biomass</td>
</tr>
<tr>
<td></td>
<td>Boiler</td>
<td>Oil</td>
</tr>
<tr>
<td></td>
<td>Recovery Boiler</td>
<td>Black Liquor</td>
</tr>
<tr>
<td></td>
<td>Steam Turbine</td>
<td>Biomass</td>
</tr>
<tr>
<td>Poland</td>
<td>Boiler</td>
<td>Coal</td>
</tr>
<tr>
<td></td>
<td>Boiler</td>
<td>Biomass</td>
</tr>
<tr>
<td></td>
<td>Recovery Boiler</td>
<td>Black Liquor</td>
</tr>
<tr>
<td></td>
<td>Steam Turbine</td>
<td>Coal</td>
</tr>
</tbody>
</table>

3.4.2 Price and cost data

Table 3.4 gives an overview of CO₂ emissions factors and fuel prices in the different countries. Some prices (e.g. oil) are similar for the three countries under consideration, whereas other prices (e.g. electricity) vary largely from one nation to the other. We have indicated current fuel and electricity prices, as well as price ranges. Price ranges are based on fuel price histories and future energy price predictions (IEA, 2009). The price of CO₂ is assumed to be 15 euro/t CO₂. We apply a CO₂ price range of 10-50 euro/t CO₂.
### Table 3.4 Applied fuel price (ranges) and CO₂ emissions factors in the case study countries

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Country</th>
<th>Price Ranges Unit</th>
<th>Emissions Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>NL</td>
<td>6.0&lt;sup&gt;a&lt;/sup&gt; 3.5 – 10 €/GJ</td>
<td>56.7&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>9.6&lt;sup&gt;a&lt;/sup&gt; 6.2 – 14 €/GJ</td>
<td>56.7&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>7.1&lt;sup&gt;a&lt;/sup&gt; 3.7 – 11 €/GJ</td>
<td>56.7&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td>Oil</td>
<td>EU</td>
<td>13.5&lt;sup&gt;b&lt;/sup&gt; 2.3 – 16.6 €/GJ</td>
<td>77.4&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td>Coal</td>
<td>NL</td>
<td>2.3&lt;sup&gt;c&lt;/sup&gt; 1.0 – 2.7 €/GJ</td>
<td>94.0&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>2.3&lt;sup&gt;c&lt;/sup&gt; 1.0 – 2.7 €/GJ</td>
<td>94.0&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>2.0&lt;sup&gt;c&lt;/sup&gt; 1.0 – 2.5 €/GJ</td>
<td>94.0&lt;sup&gt;h&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td>Biomass (pellets)</td>
<td>NL</td>
<td>7.6&lt;sup&gt;d&lt;/sup&gt; 5.3 – 9.4 €/GJ</td>
<td>0&lt;sup&gt;i&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td>Biomass(chips)</td>
<td>SE</td>
<td>4.5&lt;sup&gt;e&lt;/sup&gt; 4.0 – 6.7 €/GJ</td>
<td>0&lt;sup&gt;i&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>3.3&lt;sup&gt;f&lt;/sup&gt; 2.5 – 5.0 €/GJ</td>
<td>0&lt;sup&gt;i&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td>Black liquor</td>
<td>SE</td>
<td>4.5&lt;sup&gt;g&lt;/sup&gt; 0 – 13.5 €/GJ</td>
<td>0&lt;sup&gt;i&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>3.3&lt;sup&gt;g&lt;/sup&gt; 0 – 13.5 €/GJ</td>
<td>0&lt;sup&gt;i&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td>Electricity</td>
<td>NL</td>
<td>75&lt;sup&gt;a&lt;/sup&gt; 60 – 90 €/MWh</td>
<td>405&lt;sup&gt;j&lt;/sup&gt; kgCO₂/GJ</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>69&lt;sup&gt;a&lt;/sup&gt; 30 – 75 €/MWh</td>
<td>40&lt;sup&gt;j&lt;/sup&gt; kgCO₂/MWh</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>76&lt;sup&gt;a&lt;/sup&gt; 40 – 85 €/MWh</td>
<td>668&lt;sup&gt;j&lt;/sup&gt; kgCO₂/MWh</td>
</tr>
</tbody>
</table>

<sup>a</sup> Eurostat, 2010. Prices industrial consumers: 1-4 PJ gas; 20-70 TWh electricity.

<sup>b</sup> IEA, 2011. 116 $/bbl; 6.1 GJ/barrel; 0.71 €/$ (Oct 2010). Applied range: 20-150 $/bbl

<sup>c</sup> E-coal.com, 2010. 94$/ton (EU-ARA); 84$/ton (Poland); 29.3 GJ/ton; 0.71 €/$ (Oct 2010). Applied range: 30-110 $/ton

<sup>d</sup> Price of industrial wood pellets for the Dutch market, traded at the Endex ([www.endex.nl](http://www.endex.nl)) is 130 euro/ton (April 2011). Lower heating value of pellets is assumed to be 17 GJ/ton. Applied range: 90-160 €/ton

<sup>e</sup> Price of saw-mill by-products in Sweden (Olsson et al., 2010) 160 SEK/MWh; Conversion rate: 1Euro = 10 SEK (2009). Range assumes a price increase of maximum 50%. 

<sup>f</sup> Price of willow wood chips in 2009 is 56.7 euro/ton and lower heating value of willow wood chips is 16 MJ/ton (Stolarski et al., 2010); prices are for residential building, for industrial users they are probably lower. Range assumes a price increase of maximum 50%. Wit and Faaij, 2010 estimate a cost price range of 2.5-4.0 €/GJ for forest residues, our range is somewhat higher as we consider prices, not costs.

<sup>g</sup> There is no market price for lignin at the moment, but there are on-going discussions about how it should be valued. Here, we assume lignin prices equivalent to pulpwood prices. The price range is chosen in order to reflect discussions on lignin price valuation between zero and oil price levels

<sup>h</sup> Vreuls and Zijlema, 2009.

<sup>i</sup> We assume sustainable yield forestry, therefore CO₂ emission related caused by the incineration of biomass, do not add to the net carbon addition to the atmosphere.

<sup>j</sup> IEA, 2007.

Table 3.5 gives an overview of estimated investment costs of the different technologies at indicated reference capacities. For the combined cycles based on biomass and black liquor gasification, we have applied a range of 20% in investment costs as these are immature
technologies and investment costs figures are therefore insecure. For each technology also estimated operation and maintenance costs and applied thermal and electrical efficiencies are shown. For all technologies, we assume a scaling factor of 0.7, a technical life time of 25 years and an interest rate of 10%. All costs are related to our reference paper production capacity of 150 kton per year.\textsuperscript{17}

\begin{table}
\centering
\caption{Assumed investment costs and energy efficiencies of conversion technologies}
\begin{tabular}{lccccc}
\hline
Conversion & Ref. & Inv.costs & $\eta$ heat & $\eta$ elec & O&M costs & O&M costs \\
technology & capacity & (at ref. capacity) & & & Fixed & Variable \\
\hline
NG Boiler\textsuperscript{[a]} & 30 & 100€/kWh & 90\% & - & 2\% & 0.7 \\
Bio boiler\textsuperscript{[a]} & 30 & 360€/kWh & 85\%\textsuperscript{[c]} & - & 2\% & 2 \\
Oil Boiler\textsuperscript{[a]} & 30 & 170€/kWh & 90\% & - & 2\% & 0.7 \\
Coal Boiler\textsuperscript{[a]} & 30 & 330€/kWh & 89\% & - & 2.5\% & 2.7 \\
RecovBoil+ST\textsuperscript{[b]} & 64MWe & 1500€/kWe & 44\% & 13\% & 4\% & - \\
NGST\textsuperscript{[c]} & 1.6 MWe & 1305€/kWe & 69\% & 15\% & 2\% & 2\textsuperscript{[44]} \\
BioST\textsuperscript{[a]} & 10 MWe & 2300€/kWe & 61\%\textsuperscript{[1]} & 21\%\textsuperscript{[1]} & 2\% & 2.6 \\
CoalST\textsuperscript{[a]} & 10 MWe & 2200€/kWe & 62\% & 27\% & 2.5\% & 3.3 \\
Gas turbine\textsuperscript{[d]} & 8 MWe & 1470€/kWe & 64\% & 25\% & - & 2.75 \\
NGCC\textsuperscript{[d]} & 60 MWe & 1199€/kWe & 34\% & 41\% & - & 4.1 \\
BIGCC\textsuperscript{[a][e]} & 100 & 1040-1560 & 51\%\textsuperscript{[g]} & 32\%\textsuperscript{[g]} & 2.5\% & 3.3 \\
BLGCC\textsuperscript{[b]} & 114MWe & 1080-1620€/kWe & 42\% & 24\% & 4\% & - \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a} Borjesson and Ahlgren, 2010.
\textsuperscript{b} Larson et al., 2009.
\textsuperscript{c} Fritzon and Berntsson, 2006.
\textsuperscript{d} Marel, van der et al., 2008.
\textsuperscript{e} Gustavsson et al., 2007.
\textsuperscript{f} Joanneum Research, 2010.
\textsuperscript{g} Stahl, 2004.

\textsuperscript{17} Since Poland has many smaller sized mills, capacities of these mills may be lower, resulting in increased investment costs. This effect will be discussed later.
3.5 Results

3.5.1 Primary energy demand

Figure 3.1 shows primary energy demand and current energy costs for production of printing paper, with assumed fixed final energy demand, via selected current (C) and alternative (A) energy conversion routes in the three European countries. Conversion routes, in Figure 3.1, are ranked according to primary energy use.

![Figure 3.1: Primary energy use (left hand axis) and energy costs (right hand axis) for production of printing paper for current and alternative energy conversion routes in Poland, Sweden and The Netherlands.](image)

Primary energy use is lowest for natural gas combined cycle (5.0 GJ/t) and gasified biomass based combined cycles (7.4 GJ/t), followed by gas turbines and steam turbines (8.0-9.9 GJ/t). All combined heat and power (CHP) options, besides black liquor recovery boilers, are more efficient in terms of primary energy use than the non-combined options (heat only boilers). The most efficient conversion route in terms of primary energy use (NGCC) is common technology in the Dutch paper and board industry. Due to high natural gas prices and relatively low electricity prices, NGCC is not a promising technology for Sweden. This is further emphasised by the fact that natural gas is only available in the far south and west coast in Sweden, where only a small share of the pulp and paper mills are located. BIGCC is found to be an alternative technology with relatively high efficiency in terms of primary energy input. Due to the necessary gasification step, the energy efficiency of this technology is
somewhat lower than that of the natural gas based combined cycle. Heat only boilers have a high thermal efficiency (Table 3.5). The total primary energy demand of these conversion routes is however high, due to the lower efficiency of standalone electricity production. The least efficient conversion types are black liquor recovery boilers that are well-known in integrated mills in both Poland and Sweden. The least efficient routes have a 2.6 times higher primary energy demand than the most efficient routes.

3.5.2 Energy costs

To evaluate the competitiveness of the selected energy conversion routes, energy costs for corrugated board production (Figure 3.2) as well as for tissue production (Figure 3.3) have been calculated. These two paper grades are shown since they show the largest variation in heat-to-power ratio. Energy cost calculations for printing paper production have been shown in Figure 1 and were found to show similar patterns as the two paper grades shown in Figures 3.2 and 3.3. Figure 3.2 shows energy costs for corrugated board production, taking into account energy and CO₂ price ranges as well as price ranges in investment costs for BIGCC and BLGCC. Conversion routes are ranked according to energy costs, but the current and alternative routes are grouped separately.

![Energy costs for the production of corrugated board via different energy conversion routes in Poland, Sweden and The Netherlands. Bandwidths indicate minimum and maximum energy costs within applied fuel price and CO₂ price ranges and investment cost ranges for BIGCC and BLGCC (see Tables 3.4 and 3.5).](image)
Regarding current energy conversion technologies, and assuming equal energy efficiencies, Polish mills have lowest energy costs for corrugated board production. A coal-fuelled steam turbine is, at current price levels, the most efficient energy conversion route (36€/t) from an economic point of view. Due to the relatively low pulpwood prices in Poland, and our assumption that the black liquor price equals the pulpwood price, recovery boilers are also competitive. The range is energy costs (18-158 €/t) is however high, due to the chosen bandwidth in black liquor pricing (Table 3.4). At current (historically) high electricity prices, the most competitive current conversion route in Sweden is a steam turbine on biomass (51€/t). Heat boilers become an economically better alternative at lower electricity price levels. At assumed reference energy prices, the natural gas combined cycle (52€/t) is the most competitive technology in The Netherlands. Its large cost range (2-130 €/t) shows that this conversion route is highly sensitive to i.e. changes in gas and electricity prices as well as scale.

![Energy costs for tissue production via different energy conversion routes in Poland, Sweden and The Netherlands. Bandwidths indicate minimum and maximum energy costs within applied fuel price and CO2 price ranges and investment cost ranges for BIGCC and BLGCC (see Tables 3.4 and 3.5).](image-url)
Figure 3.2 shows that some of the identified alternative conversion routes are competitive at current price levels. The biomass fed steam turbine and black liquor gasification in Poland are most competitive (41€/t). Biomass gasification in Sweden is, according to our results, also an economically viable option (38-92€/t). The alternatives for the Dutch corrugated board industry seem less promising. This is because all of our selected alternatives are based on biomass, and the prices of imported biomass pellets in The Netherlands are relatively high (Table 3.4). The heat-to-power ratio in energy demand varies between different paper grades. This can affect the choice for a certain energy conversion route. Figure 3.3 shows energy costs for tissue production, according to the selected energy conversion routes. The heat-to-power demand ratio of tissue is much lower (1.2) than the heat-to-power ratio for corrugated board production (3.6). We compare Figures 3.2 and 3.3 to see how this affects the competitiveness of different energy conversion routes.

Figure 3.3 shows that energy costs for tissue production, in general, are a factor two to three higher than for corrugated board production due to higher energy consumption. For tissue production, a coal-fuelled steam turbine in Poland (116€/t) is, at assumed price levels, again the most efficient energy conversion route from an economic point of view. The biomass fed steam turbine (121€/t) is the most economic Swedish route. Apart from the biomass boiler in Sweden, heat only boilers are the least economic choices among the current options. This can be explained by the high electricity use in tissue production. The Swedish biomass boiler is least affected due to the relatively low electricity prices in Sweden. Even though current Swedish electricity prices are well above their average of the last ten years, they still belong to the lowest of Europe. At current price levels a natural gas combined cycle (125€/t) is the most competitive technology in The Netherlands, but the energy costs range (74-221€/t) is, also in this case, very large.

Considering the selected alternative conversion routes, it appears that several of them are able to generate energy at competitive costs. Most economical alternative routes, are the Swedish (115€/t) and Polish (120€/t) routes that are based on (gasified) biomass or black liquor. The biomass fed steam turbine, which was found to be the most economic option for corrugated board production, has slightly higher energy costs (123€/t) than the gasification routes, but is still an economically viable alternative. It can further be seen that most combined cycles rank a little better, in terms of energy production costs, than in the case of corrugated board production because of a better match in heat-to-power ratio between tissue production and combined cycle technology.
3.5.3 \(\text{CO}_2\) emissions

In Figure 3.4, \(\text{CO}_2\) emissions from printing paper production for the selected conversion routes are plotted against energy costs. Figure 3.4 shows that the coal-fuelled steam turbine in Poland, that was found to be the most efficient technology in terms of economics, is one of the worst in terms of \(\text{CO}_2\) emissions (0.75 ton \(\text{CO}_2/t\) paper). Only the Polish heat only boiler on coal and the NGCC in Sweden have higher \(\text{CO}_2\) emissions. The NGCC route in Sweden has an almost two times higher \(\text{CO}_2\) emission profile as compared to the same conversion route in The Netherlands. The reason is that due to its electricity production, the NGCC replaces grid-based electricity, which in the Netherlands has a much higher \(\text{CO}_2\) profile than in Sweden (Table 3.4). In this study, we assume that average grid mix electricity is replaced. We will discuss the impact of this assumption, as compared to the replacement of marginal electricity production, later. Several of the analysed conversion routes are found to have negative \(\text{CO}_2\) emissions. All of these are bio-based technologies with combined heat and power production. The reason for these negative \(\text{CO}_2\) emissions can be found in the assumption that \(\text{CO}_2\) emissions from the incineration of biomass are zero. Due to power production, \(\text{CO}_2\) emissions from grid-based electricity are avoided.

Among current energy conversion routes, the Swedish ones (except for the oil boiler) perform by far better than the routes in The Netherlands and Poland (apart from the Polish recovery boiler). Due to its current good performance, the \(\text{CO}_2\) emission reduction potential in the Swedish paper industry is low. \(\text{CO}_2\) emissions of the Dutch paper and board industry are, compared to the other countries, average to high, even though the \(\text{CO}_2\) emission factor of natural gas, as compared to other fossil fuels, is rather low. This is due to the large share of bio-based energy already present in the European pulp and paper industry.

Most of the selected alternative conversion routes perform better in terms of \(\text{CO}_2\) emissions than the current routes. From these routes, the ones that appear to be economically competitive are the BLGCC and biomass-based steam turbine routes in Poland and the BIGCC and BLGCC routes in Sweden, although these technologies are not commercial yet. A switch from coal-based to biomass-based combined heat and power routes in Poland would reduce \(\text{CO}_2\) emissions by approximately 800 kg \(\text{CO}_2/\text{t paper}\) on average. The share of coal in the energy mix used in the Polish pulp and paper industry is approximately 25% (Ecofys, 2009). With an annual paper production of 3 Mton, the \(\text{CO}_2\) emission reduction potential in the Polish pulp and paper industry is therefore approximately 0.6 Mton/year. A switch from natural gas to biomass based CHP in The Netherlands would reduce \(\text{CO}_2\) emissions with approximately 500 kg \(\text{CO}_2/\text{t paper}\) depending on the type of CHP. With a share of 97% of natural gas in the energy mix of the Dutch paper and board industry and an annual paper production of 3 Mton, the \(\text{CO}_2\) emission reduction potential in the Dutch pulp and paper industry is approximately 1.5 Mton/year. The bio-based conversion routes that are necessary
to establish this reduction are, however, under current conditions in The Netherlands not economically viable.

3.6 Sensitivity analysis

3.6.1 CO₂ prices

In order to study the impact of future CO₂ price levels on the competitiveness of selected energy conversion routes, we have calculated energy costs of printing paper production for all selected conversion routes at different carbon prices (Figures 3.5, 3.6 and 3.7). In Figure 3.5, results are shown for the Dutch conversion options. Results show that a biomass boiler outcompetes a natural gas boiler at a price of 60€/ton CO₂ or higher. A steam turbine on biomass is more cost effective than a steam turbine on natural gas at a price of 45-50€/ton CO₂. The BIGCC route, due to its negative CO₂ emission profile, is the only conversion route where energy costs decrease with increasing CO₂ prices. At a price of €40/ton CO₂ or higher, BIGCC energy costs are lower than energy costs for a natural gas steam turbine. BIGCC is the most cost-effective option in The Netherlands at a carbon price of 65-70€/ton or higher. The total energy costs in that scenario (all other assumptions being equal) are calculated at 90€/ton paper, which is almost 30% higher than current energy costs.

In Figure 3.6, energy costs of printing paper production for selected conversion routes in Sweden are calculated at different carbon prices. Figure 3.6 shows that energy costs for all fossil fuel based conversion routes increase rapidly with increasing carbon prices. The bio-based conversion routes are, under our assumptions, hardly affected by changes in carbon prices. Energy costs of the bio-based combined heat and power options, just slightly decrease due to electricity generation replacing grid based electricity that also has a low carbon profile. Under the new carbon emission trading system period (2013-2020), where CO₂ emission credits are allocated based on the paper grade produced, the effect on increasing CO₂ prices will, however, have a positive impact on the economics of the paper mill. This effect will be discussed later. The impact of carbon prices on energy costs of printing paper production in Poland is shown in Figure 3.7. Results show that BLGCC is the most economic conversion route at a carbon price of approximately 20 €/ton CO₂ or higher. Also the steam boiler on biomass is competitive at relatively low CO₂ prices (+/- 25 €/ton CO₂). Energy costs for both conversion routes are for all carbon prices scenarios competitive, also when compared to the other case study countries (Figures 3.5 and 3.6).

18 At such high carbon prices, electricity prices will be affected as well. We have not taken into account the effect of carbon price related electricity price increases on our results, but we will discuss this later.
Fig. 3.4: CO$_2$ emissions and energy costs related to the production of printing paper via different current and alternative energy conversion routes in Poland, Sweden and The Netherlands. Black dots indicate current technology routes. White dots refer to the selected alternative conversion routes.
Figure 3.5: Energy costs of printing paper production in The Netherlands for selected conversion routes at different carbon prices.

Figure 3.6: Energy costs of printing paper production in Sweden for selected conversion routes at different carbon prices.
Chapter 3

Figure 3.7: Energy costs of printing paper production in Poland for selected conversion routes at different carbon prices

3.6.2 Energy efficiency

As described in the methodology section, we have assumed fixed and equal energy intensities for the individual paper grades produced in all three case study countries. This assumption is not realistic as differences in mill sizes and differences in cross-country energy prices can strongly influence energy-efficiency developments in the paper industry. In order to investigate the effect of this assumption on energy costs of printing paper production, especially with regard to cross-country differences, sensitivity analyses are shown in Figures 3.8 and 3.9. Electricity and heat demand of printing paper production as shown in Table 3.2 are assumed to be representing the Dutch situation. We explore the effect of differences in energy intensity in Poland and Sweden on the competitiveness of conversion routes in Figure 3.8 (current routes) and Figure 3.9 (alternative routes). The results from the sensitivity analyses in Figures 3.8 and 3.9 show that energy intensity has a large absolute effect on energy costs. A 20% increase in energy intensity increases energy costs with almost the same percentage in all conversion routes. The relative effect of changes in energy intensity is found to be rather similar for different conversion routes and different countries. In the discussion section, we will further elaborate on the impact of energy efficiency in relation to energy strategies, energy policies and cross-country differences in energy costs.
Figure 3.8: Energy costs of printing paper production for current conversion routes: sensitivity analysis on effect of differences in energy efficiency in Sweden and Poland

Figure 3.9: Energy costs of printing paper production for alternative conversion routes: sensitivity analysis on effect of differences in energy efficiency in Sweden and Poland
3.7 Discussion & Conclusion

The importance to control energy costs has become increasingly important for the European paper industry. In order to reduce energy costs in paper production, several strategies can be applied, for example an increase in energy efficiency of production, a switch in fuel and/ or the uptake of a novel energy conversion technology. The efficiency of the applied strategy is for a certain part dependent on country-specific factors. The aim of this research has been to investigate whether improved energy conversion strategies can offset energy price differences and reduce primary energy use and CO$_2$ emissions for paper mills within different European countries. In this final section, we will draw conclusion based on our results. We will consider the reliability of data used and assumptions made throughout this study and discuss the possible impact of EU Emission Trading Scheme III (EU ETS III). We will conclude with recommendations for further work.

3.7.1 Conclusion on results

Our results show that differences in history and availability of resources has led to clearly different conversion strategies in the three European countries. We found small differences in the ranking of most promising conversion routes for the three different paper and board grades. This is the results of variations in heat-to-power demand ratios between the selected paper and board grades. In Figure 3.1, it was shown that the most energy efficient conversion technologies are based on natural gas. We found that a natural gas combined cycle has the lowest primary energy demand and the highest sensitivity to energy (gas and electricity) prices. This technological route is most economic when electricity prices are high and gas prices are low (large spark spread). The fact that the Dutch paper industry has a low primary energy use can be considered almost a direct result of Dutch history and current availability of gas. Figure 3.1 shows that CHP is a very suitable conversion technology for the paper industry as it leads to low primary energy demands. Due to a long history of low electricity prices, CHP has not been so common in Sweden. Most Swedish paper mills produce only heat and therefore have a relatively high primary energy demand. However, due to the large abundance of wood, many Swedish mills use biomass as an energy source (either as black liquor in integrated mills, or as wood residues in stand-alone paper mills). Because of this and due to low CO$_2$ emissions related to national electricity production, the CO$_2$ emission profile of the Swedish paper industry is very low (Figure 3.4). Our results imply that the most promising future conversion routes for the Swedish paper and board industry are again wood based. Depending on future electricity prices, these would either be heat only options, or biomass gasification based CHP solutions.
The Polish paper and board industry faces relatively low energy costs, due to the availability of both coal and biomass at low prices. These fuels are mostly used in heat only boilers, which results in relatively high primary energy demand for Polish mills. Figures 3.2, 3.3 and 3.7 have shown that at current CO$_2$ prices, both biomass- and coal-based technologies offer competitive conversion routes in Poland. With a reduction of 800 kgCO$_2$/t paper on average, a switch from coal to biomass would reduce CO$_2$ emissions in the Polish pulp and paper industry with approximately 0.6 Mton/year. A carbon price of 20-25 €/ton would, according to our results, be enough to provoke this switch in Poland. If CO$_2$ prices would increase, the coal-based energy conversion strategies will become more expensive. The Polish industry should therefore increase their use of biomass. Since the electricity mix in Poland is also dominated by coal, the on-site production of electricity (CHP) from biomass would, in the case of high CO$_2$ prices, be a beneficial strategy.

A switch from natural gas to biomass in the Dutch paper industry would reduce CO$_2$ emissions by approximately 500 kg CO$_2$/t paper. Due to the high share of natural gas, the CO$_2$ emission reduction potential of the Dutch paper industry is, with approximately 1.5 Mton/year, even larger than in Poland that has a comparable annual paper production. Energy costs for Dutch mills are high as compared to the other case study countries. Due to the lack of domestically available biomass, most of the biomass based alternatives do not seen promising alternatives in the near future, unless prices for imported biomass decrease. A Dutch switch to biomass would therefore not be an effective energy strategy (Figure 3.4). Due to high biomass prices and given the relative low CO$_2$ emission profile of natural gas, a carbon prices of more than 60 €/ton CO$_2$ would be needed to provoke a switch in The Netherlands. At such high carbon prices, however, Dutch mills would be outcompeted by the Swedish and Polish bio-based mills that benefit from stable or decreasing energy costs at increasing carbon prices (Figures 3.6 and 3.7). Provided with few alternatives, the most effective strategy in The Netherlands would be an increase in energy efficiency.

3.7.2 Discussion of data quality, methodology and assumptions

One of the main uncertainties in our results is related to the quality of data on prices and costs. Fuel prices are highly volatile which increases uncertainty of results. We have tried to reduce uncertainties by working with data-ranges, based on historic price figures, current price levels and future price predictions. Error bars in Figures 3.2 and 3.3 indicate the impact of assumptions and chosen price-ranges on calculated energy costs. Band widths of some conversion routes (especially the combined cycle routes) are so large that they can be the cheapest or most expensive conversion option, depending on e.g. specific gas and electricity prices.
In order to simplify our analysis, we did not differentiate between marginal and average electricity production from the grid. In cases where electricity produced on site replaces electricity from the grid, however, it is actually the marginal production that is replaced, not the average. Especially in the Swedish case studies (and to a smaller extent the Dutch case studies), this might have led to underestimations of the CO\textsubscript{2} avoidance potential of certain routes. Although the average CO\textsubscript{2} emissions from the Swedish grid are very low due to large contributions of hydropower and nuclear energy, cogeneration is under normal circumstances the marginal generation in Sweden. In the Nordic and North European power markets it is mainly coal-fired condensing power plants that have the highest variable cost and thus work as the marginal source of electricity. As Sweden is a part of this larger electricity market, and exchanges electricity with its neighbouring countries, coal condensing could be considered the marginal source in Sweden as well as in the rest of the EU when considering a fully deregulated European electricity market with no restrictions on transfer capacity (Trygg and Amiri, 2007). Our assumption of national average grid mix replacement probably influences the Polish results the least, as their national grid is mainly coal based. Another important issue is that we did not take into account the effect of carbon prices on the price of electricity. In our sensitivity analysis we discuss carbon prices of more than 50 €/ton. Such high carbon prices will also affect the prices of electricity from the grid, but the extent to which prices are affected depends on the fuel used to produce the electricity. In the case of Sweden, for example, the average price of electricity will only be partly affected while the marginal electricity price will largely increase. With increasing carbon prices and resulting increasing electricity prices, the cost effectiveness of bio-based CHP options will most certainly increase. We have also not taken into account differences between day and night tariffs of electricity. Especially in the case of CHP this is an important issue. Due to increased base load capacity in e.g. The Netherlands electricity prices during night are declining which affects the competitiveness of CHP. Flexibility in CHP (e.g. the possibility to increase or decrease the amount of electricity production while remaining the required steam production) is becoming an increasingly important conversion strategy (see also Marsman et al., 2010). Another uncertainty lies in investment cost estimates of selected conversion technologies. Cost data were taken from literature. Especially for biomass and black liquor gasification technologies, there appeared to be large variations in investment cost figures found in literature; also when taking into account scaling factors. We have assumed a 20% uncertainty range for these technologies.

A crucial assumption within this study concerns equal energy efficiencies in paper production in all case study countries. This assumption is partly caused by lack of data and partly by the need to reduce the amount of variables in order to focus on differences in energy conversion technologies. The impact of this assumption has been studied in a sensitivity analysis and was found to be high: a 20% reduced energy efficiency results in an energy cost increase of almost...
Our relative outcomes give good insights, but absolute energy cost figures and resulting cross-country differences in energy costs should be interpreted with care. Especially since in practice, it is likely that paper mills facing high energy prices (e.g. The Netherlands) have a more energy efficient production process in order to stay competitive. Moreover, the paper industry structure in the different countries varies largely with regard to scale. It is expected that large paper mills in e.g. Sweden have been able to increase energy efficiency to a higher degree than the smaller paper mills in e.g. Poland, due to increased cost effectiveness of energy reduction measures at larger scale. Similar scale-effects can be expected in the uptake of novel energy conversion technologies.

3.7.3 EU Emission Trading Scheme (EU ETS)

In the past, European policies have focused mainly on CO\(_2\) emission reduction and sustainable energy production while less on energy efficiency. Our results show that there are, in many cases, trade-offs between the three. The EU ETS is a key instrument in European climate policy. Based on experiences from the first years of the EU ETS the design has been changed for period 2013-2020 (EU ETS III). Two major changes compared to the first two trading periods are a) the EU-wide allocation plan instead of national allocation plans and b) auctioning (instead of grandfathering) as the dominating allocation method. From 2013 on, the power sector will need to buy all carbon credits via auctioning. Other industrial sectors (without potential carbon leakage) will start with 80% free allocation in 2013 which is reduced to 30% in 2020. CO\(_2\) allowances for the European pulp and paper industry will be based on benchmarks. As the sector is recognised as globally operating and prone to international competition (carbon leakage), mills will receive a volume representing 100% of the identified benchmark values for free. These benchmarks represent the emissions from heat consumption in the mills per tonne of pulp and paper produced; they are based on CO\(_2\) emissions of the top 10% installations in every pulp and paper grade. The chosen reference fuel is natural gas. Remaining emissions for heat and electricity production will have to be matched by credits bought at the CO\(_2\) market or government auctions.

In previous allocation periods, the allocation of CO\(_2\) emission credits was decided for by the individual countries according to their national allocation plans (NAPs). Although the NAPs differed per country (in terms of allocation method, base year etc.), most member states allocated allowances (for free) based on historic emissions, projected emissions or business as usual (BAU) scenarios. With the new European allocation method, all paper mills will be allocated based on natural gas based benchmark values (tCO\(_2\) / t paper). This means that paper mills with biomass based conversion routes will most likely be rewarded with more CO\(_2\) credits than before, whereas the coal fired paper mills will see a large reduction in emission credits. For the natural gas based paper mills the impact of the new allocation method depends
mainly on the mill’s energy efficiency as compared to the energy efficiency of the top 10% mills that have set the benchmark value. Moreover, since free allowances are allocated to heat use only, mills will have to buy emission credits for electricity production (also in the case of CHP). This means that mills with a low heat-to-power ratio (e.g. tissue mills) will is most cases be affected harder than mills with a relative high heat-to-power ratio (e.g. corrugated board mills). Mills with an outsourced CHP plant will receive emission credits for the heat used in the process (according to the benchmark value). Mills that deliver heat to non ETS (and non CL) sectors will receive emission credits for the heat produced. The latter brings good opportunities for paper mills with a biomass based CHP to deliver excess heat to e.g. district heating. For mills with a CHP plant, the consequences of the new trading system can also be negative. They have to buy emission credits related to the electricity produced on site. Although the same is true for electricity producers, it is not a given that grid based electricity prices will rise as a consequence of the auctioning. Several electricity production companies already have included these types of costs (wind fall profits) in the current electricity prices. Since the production of electricity will put extra costs to paper mills, the competitive position of CHP might, in that case, decline.

3.7.4 Recommendations

The European Pulp and Paper industry is an energy intensive industry. Surprisingly there is only limited research done on the energy intensity of this industry especially when taking into account possible differences between European countries. Due to lack of data, we were not able to include cross country differences in energy-efficiency in this study. Our results indicated a high impact of energy efficiency on energy conversion strategies and competitiveness of the industry in general, and we therefore recommend further research in this field. Moreover, the effects of an increasingly deregulated and interconnected electricity market on the conversion strategies in the European pulp and paper industry could be further explored, especially by taken into account more explicitly the differences between marginal and average grid based electricity as well as the effect of increasing carbon prices on the competitiveness of CHP.
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4. Benchmarking energy use in the paper industry*

*Published in Energy Efficiency, Vol. 6 (2013), pp. 49-63. Co-authors are A. Faaij and E. Worrell.*

A benchmarking study on process-unit level

Abstract

There are large differences between paper mills in e.g. feedstock use and grades produced, but typical processes are similar in all mills. The aim of this study is to benchmark the specific energy consumption (SEC) of similar processes within different paper mills in order to identify energy improvement potentials at process level. We have defined improvement potentials as measures that can be taken at mill/process level under assumed fixed inputs and outputs. We were able to use industrial data on detailed process level and we conducted energy benchmarking comparisons in 23 Dutch paper mills. We calculated average SECs per process step for different paper grades and we were able to identify ranges in SECs between mills producing the same grade. We found significant opportunities for energy efficiency improvement in the wire and press section as well as in the drying section. The total energy improvement potential based on identified best practices in these sections was estimated at 5.4 PJ (or 15% of the total primary energy use in the selected mills). Energy use in the other processes was found to be too dependent on quality and product specifications to be able to quantify improvement potentials. Our results emphasize that even a benchmark on detailed process level does not lead to clear estimations of energy improvement potentials without accounting for structural effects and without having a decent understanding of the process.
4.1 Introduction

The production of paper and board is an energy intensive process. With an energy use of 6.4 EJ in 2005, the pulp and paper industry was responsible for about 6% of the total world industrial energy use (IEA 2008), being the fourth largest industrial energy user worldwide. Energy prices rose drastically from 2005 until 2008 by around 40% on average in Europe (CEPI, 2007). Even though energy prices declined in 2009, they are still one of the major cost components of the pulp and paper sector today. Energy accounted for 19% of total operating costs of the European pulp and paper industry in 2005, compared to 15% in 2001 (CEPI, 2007). For selected mills, the 2008 share of energy in production costs was up to 30% (CEPI, 2008b). Most of the pulp and paper mills have become part of the Emission Trading System and the industry’s vision is to further improve its performance in terms of greenhouse gas emissions (CEPI, 2008a) and energy efficiency.

4.1.1 Defining energy improvement potentials

Energy consumption in an industrial sector is determined by the activity level, sector structure and energy efficiency (Phylipsen et al., 1997). In order to identify the potential to reduce energy consumption, it is important to differentiate energy efficiency effects from other effects. Phylipsen et al., 1997 describe an approach to separate structural effects from efficiency effects in international comparisons of industrial sectors. According to them, the sector structure can be defined as being determined by the mix of activities or products within a sector. The choice for a definition based on ‘mix of activities’ or ‘mix of products’ can in some cases make a significant difference in determining what can be considered an energy efficiency effect or a structural effect. If the mix of products is used as definition of structure, printing paper produced from virgin fibers and printing paper produced from recycled fibers can be considered two different processes to produce the same product. The switch from virgin to recycled fibers could in this approach be seen as an energy efficiency measure. Defining structure as the mix of processes, one might argue that the two process routes are different activities and differences in energy consumption between the two are then to be considered structural effects.

4.1.2 Benchmarking at different levels of aggregation

In order to estimate industrial energy improvement potentials, energy benchmarks can be used. Energy benchmarks can be applied at different levels of aggregation (e.g. sector level, country level, mill level or process level), depending on the typical goal of the benchmarking exercise. The extent to which structural differences influence the energy improvement potential also depends on the aggregation level (Phylipsen et al., 1997). On country level, an
energy efficiency improvement potential could for example be found in the substitution of plastic by paper. Whereas this is not a measure that can be taken at the individual mill or process level.

### 4.1.3 Energy efficiency indicators

Energy efficiency is defined as the amount of human activity provided per unit of energy used (Martin et al., 1994). In practice, indicators often measure the inverse of energy efficiency (Phylipsen et al., 1997). A frequently used quantitative indicator at a high level of aggregation is energy intensity, which measures activity in economic terms (e.g. Freeman et al 1997; Eichhammer and Mannsbart 1997; Farla and Blok 2000; Ramirez et al. 2005; Neelis et al. 2007; Tanaka 2008). At lower level of aggregation, an often used indicator is Specific Energy Consumption (SEC), which reflects the amount of energy required to produce one physical unit of product (e.g. tons of product) (e.g. Worrell et al 1994; Patterson 1998; Rafiqul 2005; Salta et al. 2009). SEC is mostly determined at country/sector level (e.g. Farla and Blok, 2000; Neelis et al. 2007) or at product level (Farla et al. 1997, De Beer et al., 1997). A specification into feedstock use and product quality is seldom made (Lazarus et al. 1999; Ruth et al. 2001).

### 4.1.4 Energy efficiency at process level in the paper industry

In the first Reference Document of the European Commission on Best Available Techniques in the Pulp and Paper Industry (BAT/BREF) (EIPPCB, 2001) some (best practice) figures on energy demands of different process units for different pulp and paper types are documented. Although many processes are taken into account, a drawback of the report is that data comes from a variety of sources, and calculation methods are not always identified. Worrell et al., (1994), calculate the SEC of different industrial sectors by adding the individual SECs of different industrial activities within a sector. They define SECs for processes with a well described input (feedstock) and output (product) and aggregate these to calculate the SEC of an industrial sector in a country. With regard to the paper industry, they included SECs of 3 pulp types and 5 paper grades. Different processes within paper production are not explicitly taken into account. The same is valid for a study by Francis et al. (2006), who collected energy consumption and production data for processes in 49 pulp and paper mills. The processes chosen in this study are mainly pulping processes, whereas the paper making process is considered as a whole. Manufacturing of paper is however not a single process but a series of unit processes, often linked and interdependent. Although there are large differences between different paper mills, using different types of feedstock and producing different paper grades (and qualities), the typical processes involved in paper production could be broken down in a number of activities that are similar in all mills.
4.1.5 Aim and outline

The aim of this study is to benchmark the specific energy consumption of similar processes within different paper mills in order to identify energy improvement potentials at process level. We define improvement potentials as measures that could be taken at mill/process level under assumed fixed inputs and outputs. If we compare this with the approach described in Phylipsen et al., (1997), we define structure as a mix of activities, but we also take into account the product mix. We first describe the paper making process in general. Then, the data collection methodology is explained. Next, the results are presented in a benchmarking study on process unit level and energy improvement options at process level are identified when possible and/or relevant. This is followed by a discussion of the results. Conclusions are drawn in the final section.

4.2 General process description paper making

In Figure 4.1, a schematic overview of different processes in paper production is shown. Paper is made from pulp, which can be produced from wood fibres (via mechanical pulping or chemical pulping), from recovered paper or in particular cases from non-wood fibres\(^{19}\) (e.g. straw, jute, synthetic). Since we focus on the paper making processes only, we exclude the pulping processes and assume that fibres are already disclosed. Raw materials included are virgin pulp and recovered paper.

Before pulp enters the paper machine, some treatment steps may be necessary. Stock preparation consists of several processes (e.g. fibre disintegration, cleaning, fibre modification and storage and mixing steps) that are adapted to one another. These systems differ considerably depending on the raw stock used and on the quality of furnish required (EIPPCB 2001). Pulp from recovered fibres needs to be cleaned in several cleaning steps to remove impurities e.g. staples, plastics and glue. Sometimes, this type of pulp is also de-inked, depending on product specifications. Ink removal is necessary in plants manufacturing paper grades where brightness and cleanliness is important e.g. for newsprint, tissue or light topliner of recovered paper based carton boards. Another process step that is sometimes applied in stock preparation of recovered fibres is dispersion. During this step, impurities that could not be removed are reduced to a size small enough not to harm paper quality. Dispersion can be performed after de-inking in order to achieve improved fibre-to-fibre bonding (better strength characteristics) in the paper produced and to reduce visible dirty specks in size (EIPPCB 2001). Before dispersion, the dry solids content of the pulp has to be increased from around 5-12% % to 25-30% because dispersion requires strong friction forces and high temperatures

\(^{19}\) The use of non-wood fibers is outside the scope of this paper.
of around 95°C or more (EIPPCB 2001). Paper grades produced from virgin fibres sometimes require a refining step, where fibres are beaten to roughen their surface in order to enhance fibre properties. Refining is carried out in refiners equipped with e.g. a rotating disk that is pressed on a stator. The order of the operation of stock preparation may vary from mill to mill and some of the steps may be repeatedly performed. Finally, pulp is stored and blended.

Fig. 4.1 Schematic overview of different process steps in paper production.

After pulp has undergone all necessary process steps in stock preparation, it is spread on a screen in the former/wire section. In this section, a large share of water is removed by gravitational forces and a vacuum. In the former/wire section, the dry matter content of the paper web increases from about 1% to approximately 20-25%. In the press section, the dry matter content of the paper web is further increased to about 50% by means of press cylinders. Although some thermal energy is used in the press section, most of the dewatering takes place via mechanical work. Thermal dewatering (drying section) requires more energy per removed ton of water than mechanical dewatering and it is therefore beneficial to remove as much water as possible in the press section. After the former section, the paper web enters the press section where further water is removed mechanically. Remaining water is removed thermally in the drying section. In the drying section, the dry matter content of the paper web increases from approximately 50% to around 95%. In many paper and board mills, the drying section is divided into a pre-drying and an after-drying section (Figure 4.1). In between these sections there is often a size press or coating machine for surface property adaptations. In some board mills, this section is used for gluing of additional surface papers. Since these processes add additional moisture to the paper or board, an after drying section is needed to remove the added water.
4.3 Methodology

The Dutch paper industry is for approximately 80% recovered paper based (VNP 2010). Dutch paper mills that are virgin fibre based, purchase pulp on the market while two produce thermo-mechanical pulp (TMP). In several cases there is a mixture of raw materials. The Dutch paper and board industry produces a great variety of products. Products range from newsprint, corrugated board, solid board, printing papers and tissue to various types of specialty papers (VNP 2010).

4.3.1 Data used for this study

To monitor the energy housekeeping of Dutch paper and board mills, The Royal Netherlands’ Paper and Board Association (VNP) together with Gasunie/MPI have developed a product/energy management system (MPI-PEMS). MPI-PEMS has been implemented in all paper and board mills in The Netherlands. The system is used for annual monitoring of energy efficiency developments in the industry and several mills use it to manage energy within the mill. In this study we use data from the MPI-PEMS model to develop a benchmarking study for the Dutch paper/board industry on process unit level. The MPI-PEMS system is based on a product and an energy balance. For each process operation, the incoming and outgoing materials (e.g. intermediate products and process wastes) are determined, together with the dry matter content of the flows. Energy consumption (heat, electricity and fuel) of each individual process unit is measured. As both production and energy consumption data are available, it is possible to generate specific energy consumption figures on process level. The total amount of gas and electricity use is reported as well as the efficiencies of their energy conversion installation. Also, data on electricity, heat and gas use per process operation are measured and reported. Material flows are reported starting from the fibre raw material input, additions of additives and ending with the amount of saleable product produced. Process waste is reported per unit operation and in total. Dry matter content of the paper web is reported before and after the wire, after the press, in between the drying sections. Data are mills’ annual totals and are not specified per product produced within the mill.

The raw data is confidential and of a very high quality. Data is provided by the paper mills themselves. Although each mill has used its own measuring devices, the process of data collection has been guided by a single expert for all mills and a uniform format for data management was used by all mills. The same system and process boundaries were therefore used throughout the sector. More than 200 data points were provided by every single mill, which makes this industrial data collection effort unique in itself.
4.3.2 System boundaries

In the year 2005, 25 paper and board mills were in operation in The Netherlands. In this report we will report (2005) data for 23 mills. Two mills have very specific production processes and for reasons of confidentiality and lack of representativeness, energy figures from these two mills are excluded from the analysis. For the purpose of this study, we present aggregated (electricity, heat and fuel) energy data for the specific energy consumption of the following processes:

- De-inking
- Dispersion
- Stock preparation
- Forming and press section
- Pre-dryer section
- After dryer section

Often when energy consumption in the paper industry is analysed, only main equipment is included whereas e.g. pumps, agitators and peripheral sub-systems for water are not part of the system considered. These processes do not improve pulp or paper quality but are nevertheless relevant in terms of electricity demand. The contribution of pumps and agitators to the total installed power may even vary from 20 up to 30% (EIPPCB 2001). In this study, the energy use of e.g. pumps is included as long as it can be contributed directly to a specific process. There is a difference between installed power (main equipment) and average power demand that is actually used. In this study we have used actual energy consumption figures. The energy use related to site utilities (e.g. water treatment plant, own energy use of boiler house etc.) has been excluded in this study.

Heat recovery is a common feature in paper mills. In 2005, only internal heat recovery was established in Dutch paper mills; no heat was sold to external parties. In our approach, the effects of internal heat recovery are not explicitly taken into account, but they implicitly lead to a reduced energy consumption of the process that uses the recovered heat. The energy figures we use are enthalpy values. An exergy analysis would give further insight in the potentials of heat cascading plant, such as paper mills.

The yield of a process is dependent on raw material quality (EIPPCB 2001). Especially in recovered paper, raw material qualities can vary considerably. Recovered paper can be collected from offices, households, retailers or other places. This results in different grades of recovered paper (e.g. office waste, mixed waste and old corrugated containers (OCC). The country and area where recovered paper is collected can also affect the raw material quality. This is mainly due to differences in collecting and sorting practices (Stawicki and Read 2010).
Because of varying recovered paper quality, some mills may have to take additional efforts in the stock preparation as compared to comparable mills in different areas. In this study, we take into account differences in feedstock (i.e. virgin or recovered fibers), but we do not specify differences in raw material qualities.

4.3.3 Approach to calculate SEC of processes

The final energy used for paper production can be calculated back into primary energy, by multiplying the consumption of heat and electricity with standard conversion efficiencies. We call the primary energy use calculated as such end use energy (Fig. 4.2). End use energy can be distinguished from site use energy (Fig. 4.3). Dutch paper mills use natural gas as their primary source of energy. They have their own steam production and the majority of the mills also produce their own electricity by combined heat and power production (CHP). Therefore, primary energy consumption could also be calculated as total fuel intake plus purchased electricity and steam, diminished with electricity, steam and fuel sold (site use energy). The difference between these two determines the efficiency of on-site energy generation of the mill as compared to standard conversion efficiency. At site level, the indicator site use energy can be preferred over end use energy as it takes into account the efficiency of energy conversion on site and is a good indicator for actual costs. Comparison of both site use energy and end use energy gives better insights into the efficiency of on-site energy generation. To compare energy efficiencies at paper production process level, however, the efficiency of the conversion installation (e.g. CHP installation) should not play a role. Therefore, in this study, we use end use energy (Fig. 4.2) and we thus exclude the efficiency gains related to for example CHP. The total annual end use energy of a process unit is calculated with eq. 1.

\[
E_{\text{process}} = \frac{\text{Elec}_{\text{process}} \times 3.6}{\eta_{\text{elec}}} + \frac{\text{Steam}_{\text{process}} (\text{GJ})}{\eta_{\text{steam}}} + \text{Fuel}_{\text{process}}
\]  

(1)

Where: \(E_{\text{process}}\) = total annual end use energy in the process (GJ/yr); \(\text{Elec}_{\text{process}}\) = annual process electricity consumption (MWh/yr); \(\text{Steam}_{\text{process}}\) = annual process steam consumption (GJ/yr); \(\text{Fuel}_{\text{process}}\) = annual process fuel consumption (GJ/yr); \(\eta_{\text{elec}}\) = conversion factor for electricity into primary energy (42%); \(\eta_{\text{steam}}\) = conversion factor for steam into primary energy (90%)

The specific primary energy consumption of a process unit can be calculated with eq. 2.

---

20 We assume the following conversion factors: for electricity 42% and for heat 90% (LHV).
\[ SEC_{pr} = \frac{E_{process}}{P} \]  

(2)

Where: \( SEC_{pr} \) = the specific primary energy consumption of a process unit; \( E_{process} \) = total annual end use energy in the process (GJ/yr); \( P \) = annual amount of product that is processed in the specific process (t/yr)

During paper production, internal waste is generated, for example when the paper web breaks or during a shift in production from one grade to another. Often, the internal waste can be pulped again internally to avoid material losses. The energy that already has been used to produce the paper, on the other hand, is lost. Eq. 3 describes the total energy loss by internal waste production:

\[ E_{waste} = Waste \times SEC_{waste} \]  

(3)

Where: \( E_{waste} \) = total energy loss by internal waste production (GJ/yr); \( Waste \) = annual amount of waste (t/yr); \( SEC_{waste} \) = specific energy use (GJ/t) of paper production excluding the energy use during paper finishing.

4.3.4 Methodology to analyse results

Mills are clustered based on the dominant paper grade they produce: B = Board; G = Graphical papers; T = Tissue; O = Other grades. Mill numbers refer to the same mill throughout all graphs. All graphical mills use 100% virgin fibre as feedstock; all other mills (B, T and O) have at least 85% of recovered fibres in their total feedstock. Input (feedstock), output (dominant grade) and process are defined as the structural indicators that influence SEC (Phylipsen et al., 1997). For each process, the average SEC per grade is calculated in order to identify the impact of structural indicators. We further calculate the ranges in SEC within each of the four identified grades. We review literature in order to identify the main aspects or explanatory indicators (Phylipsen et al., 1997) that might influence this range and that could be seen as energy improvement measures.
Fig. 4.2 Overview of end use energy in schematic Sankeydiagram (source: VNP)

Fig. 4.3 Overview of site use energy in schematic Sankeydiagram (source: VNP)
4.4 Results

4.4.1 Energy use in de-inking and dispersion

The specific energy consumption of de-inking and dispersion is shown in Figure 4.4. From the 23 mills, only the tissue and other grade mills have dispersion units. Table 4.1 shows the average SEC and the range in SEC per paper grade. The average SEC of dispersion is with 0.4 GJ/t pulp higher in tissue production as compared to other grades. De-inking is applied in the tissue mills and in two of the other grade mills. The average de-inking SEC of tissue is 0.7 GJ/t pulp lower than the average SEC of two other grades mills (Table 4.1). For tissue, the ranges in SEC of the individual dispersion (1.2 GJ/t pulp) and de-inking processes (0.9 GJ/t pulp) are high; the range becomes significantly narrower (0.7 GJ/t pulp) if we combine the SECs of the two processes (Table 4.1). This could be an indication that there is a trade-off between the two. According to Göttscbing and Pakarinen (2000), the tasks of dispersion vary considerably depending on recycling fibre furnish quality and final product (structural indicators). Apart from the different tasks of dispersion, energy use also depends on stock viscosity, temperature, type of fillings and peripheral speed (Göttscbing and Pakarinen 2000). The latter aspects could be considered as key parameters in order to improve the energy efficiency of this process. Selective flotation is used for removing ink particles. Energy consumption of flotation depends largely on the amount of flotation cells, which is in its turn closely related to the end product requirements (structural effect). Process related energy improvement measures in de-inking could be found in the design of piping and the types of air injectors applied (EIPPCB 2001).

![Fig. 4.4 Specific energy consumption for de-inking and dispersion processes (in GJ per ton of absolute dry processed product (adpp)).](image)
Table 4.1. Dispersion and de-inking: average SECs and ranges in SEC for four different paper grades

<table>
<thead>
<tr>
<th>SEC (GJ/t pulp)</th>
<th>Dispersion</th>
<th>De-inking</th>
<th>Dispersion &amp; de-inking combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
<td>Average</td>
</tr>
<tr>
<td>Board</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Graphical</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tissue</td>
<td>1.6</td>
<td>1.0 - 2.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Other</td>
<td>1.2</td>
<td>0.8 - 1.6</td>
<td>1.7*</td>
</tr>
</tbody>
</table>

*Including only mills O1 and O2

4.4.2 Energy use in stock preparation

In Figure 4.5, SEC of stock preparation (excluding deinking and dispersion) is shown. We can distinguish mills with virgin fibre input (G) and mills with (over 85%) recovered fibre input (B, T, O) Table 4.2 summarizes the average SEC per grade as well as the ranges in SEC per grade. The latter can be considered an indication of the energy improvement potential. From Table 4.2 it can be seen that there are large differences in SEC between grades. The average SEC of stock preparation in board mills is only 0.7 GJ/t stock, whereas SEC of the same process in tissue and graphical mills is 2.3 GJ/t stock. The high SEC of stock preparation in graphical paper production can be explained by their use of refiners. Refining equipment is used in all of the graphical mills and in none of the recovered based paper mills. Unfortunately, our data does not allow for reporting the SEC of refining separately. The relatively high SEC of tissue can be explained by a relatively high fibre loss in stock preparation of tissue as well by a low consistency level of the stock.

Fig. 4.5 Specific primary energy consumption during stock preparation, excluding TMP production, deinking and dispersion (in GJ per ton of absolute dry processed product (adpp)).
Table 4.2 Stock preparation: average SECs and ranges in SEC for four different paper grades

<table>
<thead>
<tr>
<th>Stock preparation</th>
<th>SEC (GJ /t stock)</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board</td>
<td>0.7</td>
<td>0.7 - 1.0</td>
<td></td>
</tr>
<tr>
<td>Graphical</td>
<td>2.3</td>
<td>1.5 - 3.0</td>
<td></td>
</tr>
<tr>
<td>Tissue</td>
<td>2.3</td>
<td>1.7 - 2.3</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0.8</td>
<td>0.4 - 1.7</td>
<td></td>
</tr>
</tbody>
</table>

The SEC range in stock preparation for graphical papers was found to be 1.5-3.0 GJ/t stock. As mentioned before, most of the energy in stock preparation of virgin fibres goes to refining. Refining is needed to improve the bonding ability of the individual fibers in the finished paper. The energy needed for refining is to a large extent related to quality specification of end product (EIPPCB 2001; Paulapuro 2000). With our data we are not able quantify the difference between this structural effect and other energy efficiency effects. The SEC range of board mills is relatively small, but still indicates an improvement potential of 0.3 GJ/t stock for the mill with highest SEC (B4). The energy efficiency improvement potential of tissue mill T1 is approximately 0.6 GJ/t stock when compared to mill T3.

4.4.3 Energy use in forming and press section

Fig. 4.6 Specific primary energy consumption, decomposed in electrical and thermal energy use, in the combined forming and press section (in GJ per ton of absolute dry processed product (adpp)).
An overview of the SEC in the combined forming and press section is shown in Figure 4.6. From Table 4.3 it can be seen that differences in average SEC between the grades are small, indicating a limited effect of structural indicators. At the same time, the individual ranges in all grades are very high (up to a factor 6), indicating a large energy improvement potential within this process.

Table 4.3 Forming and press section: average SECs and ranges in SEC for four different paper grades

<table>
<thead>
<tr>
<th>Forming and press</th>
<th>SEC (GJ / t paper)</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board</td>
<td>1.3</td>
<td>0.7 - 2.4</td>
<td></td>
</tr>
<tr>
<td>Graphical</td>
<td>1.5</td>
<td>1.0 – 2.5</td>
<td></td>
</tr>
<tr>
<td>Tissue</td>
<td>1.6</td>
<td>0.8 – 3.0</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>1.3</td>
<td>0.5 – 2.8</td>
<td></td>
</tr>
</tbody>
</table>

We have decomposed the specific primary energy use in electrical and thermal energy use (Fig. 4.6). Given the limited impact of structural effects in this process, we compare SECs of all paper grades. Figure 4.6 shows a large range in specific electricity use (0.3 - 3.0 GJ/t paper) between mills, which indicates a large energy improvement potential in this area. Differences in electricity use can be explained by differences in e.g. pump, compressor and/or vacuum capacities and efficiencies as well as machine speed. The energy potential of optimisations in the vacuum system is considered to be large, but unfortunately this aspect has not gained too much attention in many paper mills (Paulapuro 2000). A considerable energy saving potential in this section could further be found in over-dimensioned pumps and compressors (Wikström et al. 2007; Möllersten et al. 2003). Ranges in specific steam use (0.0 - 1.1 GJ/t paper) are somewhat smaller than ranges in specific electricity use, and could be explained by e.g. the presence/absence of steam boxes and/or differences in process water temperature levels. Increased process water temperatures are often beneficial for mills as these lead to increased production (Cutshall et al. 1988; Patterson and Iwamasa 1999). As compared to the other grades, board mills have a relatively high thermal energy use in this section (Fig. 4.6). Board mills do not use refiners or dispersion units, which both increase process temperatures. Therefore their thermal energy demand might be higher than that of others in this section. Some mills use steam for process water heating (Breedveld et al. 1998), whereas heat could also be gained via heat recovery from the drying section. Such a measure would considerable improve energy efficiency in these types of mills (Laurijssen et al. 2010).
4.4.4 Energy use in drying section

Figure 4.7 shows the SEC in the pre- and after dryer sections of the 23 paper and board mills. Here, values are expressed per ton of absolute dry end product (adep) and not per ton of absolute dry processed product (adpp). This is because the results of both dryers are combined and there are mass differences due to differences in material losses and additives (coatings, paper, starch). Mill G8 has an unrealistically low SEC in the pre-dryer and a very high SEC in the after-drying section. We assume that the SEC figures for this mill are not correct and we have excluded these figures from the results in Table 4.4.

![Graph showing specific primary energy consumption in pre-and after drying section (in GJ per ton of absolute dry end product (adep)).](image)

Fig. 4.7 Specific primary energy consumption in pre-and after drying section (in GJ per ton of absolute dry end product (adep)).

Table 4.4 shows that the differences in average SEC between grades are large. The average SEC of the drying process in board mills is only 4.8 GJ/t paper, whereas the SECs of the same process in tissue and graphical mills are 7.0 and 7.6 GJ/t paper respectively. From Figure 4.7, it can be seen that the high SEC of graphical grades is largely due to a high SEC in the after dryer, which is caused by relatively large water additions in the coating process of graphical papers. The SEC ranges within the four grades indicate considerable energy efficiency improvement potentials for all grades. In order to gain more insight in this improvement potential, we reduce the influence of an important structural indicator: amount of water removal. To do so, we split SEC of drying into the amount of water removal per ton of paper production (Figure 4.8) and the energy use per ton water evaporation (=dryer efficiency) (Figure 4.9).
Table 4.4 Drying sections: average SECs and ranges in SEC for four different paper grades

<table>
<thead>
<tr>
<th>Drying sections</th>
<th>SEC (GJ/t paper)</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board</td>
<td>4.8</td>
<td>4.0 – 5.8</td>
<td></td>
</tr>
<tr>
<td>Graphical</td>
<td>7.6*</td>
<td>5.2* – 9.5</td>
<td></td>
</tr>
<tr>
<td>Tissue</td>
<td>7.0</td>
<td>6.0 – 7.6</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>5.3</td>
<td>4.6 – 6.2</td>
<td></td>
</tr>
</tbody>
</table>

The amount of water removal (Fig. 4.8) varies from 0.9-2.0 t water / t paper. Water removal depends on e.g. dry matter content after the press, water additions in between the drying sections, paper weight and moisture content of the end-product. Most of these aspects largely depend on product (quality) requirements and are considered to be structural effects.

Fig. 4.8 Water removal in the drying section per ton of absolute dry end product (in GJ per ton of absolute dry end product (adep)).

Fig. 4.9 shows that the energy use per ton of water evaporation is less product-specific. Only the energy use in the tissue mills is slightly higher as compared to the other grades. A reason for this could be found in the different type of dryer that used in tissue production (Yankee) as compared to the other grades (multi-cylinder dryers). Energy use in Yankee dryers is in most cases slightly higher than in multi-cylinder dryers (Karlsson 2000). In general, the range in drying energy between all mills (3.6 - 6.2 GJ/t water removal) indicates a large energy-efficiency improvement potential. The main aspects that can influence dryer efficiency are dryer section closure (open, partly open or closed hood), the dryer dew point and the presence
or absence of a heat recovery system. Energy efficiency is highest when the dryer is fully closed, the dryer dew point is high and heat is maximally recovered (Laurijssen et al. 2010).

![Graph showing energy use in GJ per ton of water removal in the drying section.](image)

**Fig. 4.9** Energy use (in GJ per ton of water removal) in the drying section

### 4.4.5 Total primary energy intensity

![Graph showing breakdown of total primary energy intensity per process, including total energy loss due to internal waste production (in GJ per ton of absolute dry end product (adep)].(image)

**Fig. 4.10** Breakdown of total primary energy intensity per process, including total energy loss due to internal waste production (in GJ per ton of absolute dry end product (adep)).
In Figure 4.10, the total primary energy intensity per ton of final paper production, broken down in different processes, is shown for the 23 mills analysed in this study. Also, the total energy loss due to internal waste production (see methodology) is indicated in this figure. The absolute energy loss due to internal waste production is highest for the graphical grades (2.4 GJ/t paper on average) and lowest for the other grades (1.0 GJ/t paper). The share of waste related energy losses, as compared to the total energy use, varies largely from 2% (B4) to 33% (G4). Waste related energy losses can be caused by differences in general operational efficiency of the paper machine, but also by frequent shifts from one grade to another within a certain paper mill.

Table 4.5 Average SEC per process in GJ/t paper (adep) for four different paper grades

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Board</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.5</td>
<td>4.5</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Graphical</td>
<td>0.0</td>
<td>0.0</td>
<td>2.8</td>
<td>1.5</td>
<td>4.7</td>
<td>0.2</td>
<td>2.6</td>
<td>0.7</td>
<td>12.5</td>
</tr>
<tr>
<td>Tissue</td>
<td>0.8</td>
<td>1.5</td>
<td>3.3</td>
<td>1.9</td>
<td>6.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>14.7</td>
</tr>
<tr>
<td>Other</td>
<td>0.6</td>
<td>0.4</td>
<td>1.1</td>
<td>1.5</td>
<td>4.9</td>
<td>0.1</td>
<td>0.5</td>
<td>0.4</td>
<td>9.4</td>
</tr>
</tbody>
</table>

The total primary energy intensity is largely dependent on the grade produced, as can be seen from Fig. 4.10. In Table 4.5, for each of the four defined grades, the average SEC per process (in this case based on the amount of final product produced, not on the amount of product processed in the respective unit operation as done before) and the total average SEC per grade are calculated. Table 4.5 shows that energy use in the pre-dryer section is the process unit with the highest specific energy use in all grades. The share of drying energy (pre- and after drying sections combined) in the total specific energy consumption, varies from 47% for tissue production to 64% in board production. SEC in stock preparation processes is highest in tissue production (5.6 GJ/t stock) and lowest in board production (1.0 GJ/t stock). Average specific energy use in the wire and press section is most comparable for all paper grades, although the individual differences between mills can be large (as we have seen in Fig. 4.6).

4.5 Discussion

Data used in this study were collected by the mills themselves. More than 200 data points were provided by every single mill, which makes this industrial data collection effort unique.
in itself. Data are based on mills’ annual averages, meaning that data were not available for every single type of product produced in every different mill, although this level of detail would be preferred. The available dataset does, unfortunately, not allow a quantified uncertainty analysis in terms of measurement errors. All mills have used their own measuring devices, but the process of data collection has been guided by a single expert for all mills. Moreover, a uniform format for data management (MPI-PEMS) was used by all mills and the same system and process boundaries were therefore used throughout the sector. We therefore consider the data to be reliable and representative. Two Dutch paper mills were excluded from the analysis. In reality the ranges in energy usage in the Dutch Paper and Board industry would therefore be larger. With the described method, it should be possible to perform a similar analysis in another country or in another industrial sector. For such an analysis, participation of the industry seems crucial because the required level of data is mostly not available in public data sources and/or statistics.

Besides their use in scientific studies, energy efficiency indicators and benchmarks are also found in policy making. Several policies in place today rely on measures of energy efficiency performance, primarily to evaluate regulatory performance (Tanaka 2008). Given the number and the complexity of industrial processes and product end-uses, designing consistent and comparable efficiency indices for use in policy-making/implementation processes is extremely difficult (Tanaka 2008). Gielen and Taylor (2009) add that taking account of different product categories is of key importance as various products in a single category may require considerably different amounts of energy for their production. This is confirmed by the results from our study. From a policy making point of view, the results of our study support the view that there is a need for better quality industrial data, especially when benchmarks are to be used in industrial target settings. However, even when data on a detailed level would be available, knowledge of and insight in the specific production processes is needed in order to identify realistic improvement potentials at mill level, if that is the goal of the benchmark.

Looking at our results, we found that even a benchmark on the detailed process unit level, in most cases does not lead to realistic estimations of energy improvement potentials (defined as measures that can be taken at mill/process level) without accounting for structural effects (e.g. inputs and outputs). However, when different product grades and processing routes are taken into account, estimations of energy improvement potentials could, in some cases, be made. Moreover, an energy benchmark on process unit level provides a good insight into the level of variation in energy use between different mills producing similar grades. A limitation of benchmarking on process unit level is that, with a focus on individual processes, an overview on the efficiency of the total process is lost. Sometimes, higher energy intensity in a specific unit operation is needed to enable an energy saving in the total production process. Also,
energy losses related to internal waste generation are not taken into account when analysing energy use on process level only. Our results show that the impact of waste related energy use can be considerable. It is therefore recommended to look at the whole process and use sub-processes as diagnostics to locate problems or to identify energy saving opportunities for processes with comparable inputs and output.

4.6 Conclusion

The aim of this study has been to benchmark the specific energy consumption of similar processes within different paper mills in order to identify energy improvement potentials at process level. We defined improvement potentials as measures that can be taken at mill/process level under assumed fixed inputs and outputs. We have used a benchmarking method based on energy and material balances per process and we were able to use industrial data on detailed process level.

The energy efficiency improvement potential, calculated as the gap between the lowest and highest value, in the combined de-inking and dispersion processes was found to be 0.7 GJ/t pulp for the least efficient tissue mill. In stock preparation (excl. deinking and dispersion) the improvement potential was found to be low for board mills (0.3 GJ/t stock) and tissue (0.6 GJ/t stock). The highest range in SEC was found in graphical grades (1.5-3.0 GJ/t paper), although this range is not an indication for an improvement potential per se, given the large contribution of refining to the energy use in this section and the fact that refining energy largely influences product specifications. The large range in SEC in the forming and press section (0.5-3.0 GJ/ t paper) together with the fact that the average SEC in this section was found to be comparable between grades (1.3-1.6 GJ/t paper) indicates a significant energy efficiency improvement potential in this section. We found that water removal in the drying section is rather grade specific, while differences in energy consumption for evaporation indicate significant improvement potentials in the drying section (up to 2.6 GJ/t water removed).

Despite the detailed data we were able to use in this study, it is still delicate to draw some firm conclusions on the available energy efficiency potential in the Dutch paper and board industry. On a more general level we can state that there are significant opportunities for energy efficiency improvement in the wire and press section as well as in the drying section. The total energy improvement potential based on identified best practices in these sections is estimated at 5.4 PJ (or 15% of the total primary energy use in the selected mills). Energy efficiency improvement potentials can also be found in stock preparation, de-inking and dispersion but we consider energy use in these processes too dependent on quality issues and product specifications to quantify this.
There are various measures of industrial energy efficiency performance, with different purposes and applications. The results of this study have contributed to the discussion of the roles, advantages and risks of some of these measures. This paper emphasizes the importance of a decent understanding of the underlying principles in assessing energy efficiency and in comparing different mills within a benchmark. Given the expressed need for better industrial data, especially in paper production, this paper further contributes to increased data availability of industrial process data.

Acknowledgements:

We thank The Royal Netherlands’ Paper and Board Association and its members for being able to use their data and F. J. de Gram for his efforts to make monitoring within the Dutch paper industry possible. Without them this study would not have been possible.
References


Benchmarking energy use in the paper industry


5. Optimizing the energy efficiency of conventional multi-cylinder dryers in the paper industry*

Abstract

The paper industry is, with about 6% of the total worldwide industrial energy use, an energy-intensive industry. The drying section is with approximately 50% the largest energy consumer in a paper mill, energy use in this section is mainly heat use. Several options to decrease heat use in conventional multi-cylinder drying sections are investigated, calculating the effect on energy use. Optimization measures include a) decreasing the amount of water evaporation by applying additives in higher consistencies and by lowering the water viscosity, b) decreasing the heat use of water evaporation by increasing the dew point temperature of the dryer and c) increasing the amount of heat recovery by using exhaust air to not only pre-heat the incoming air but also to increase process water temperatures. These could all be achieved by retrofitting and/or choosing different processing conditions in existing factories. The combined thermal heat saving potential due to the optimization actions is 1.3GJ/t paper (or 32% of the drying section’s heat use) as compared to the reference situation.

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5.1 Introduction

Globally, the pulp and paper industry is the fourth largest industrial energy user. With 6.4 EJ in 2005 it is responsible for about 6% of total world industrial energy use (IEA, 2008). Approximately two-thirds of the final energy consumption is fuel used to produce heat, while the remaining third is electricity, either purchased or self-generated (IEA, 2008). Unlike most other industrial sectors, the pulp and paper industry also produces energy as a by-product and currently generates about 50% of its own energy needs from biomass residues (IEA, 2006). The significant use of biomass means that the CO$_2$ intensity is lower than other energy intensive industries (IEA, 2008). Since energy prices have risen drastically by around 40% between 2004 and 2007 in Europe (CEPI, 2007), energy has become one of the key cost components of the pulp and paper sector. Energy accounted for 19% of total operating costs of the European pulp and paper industry in 2005, compared to 15% in 2001, which is a difference of more than 10 billion euro (CEPI, 2007). In 2008, the share of energy in the total production costs was up to 30% for some mills (CEPI, 2008).

The pulp and paper industry is composed of two interconnected sub-sectors: pulp and papermaking, which can either be integrated within a single mill or separated into two. In pulp production, the raw material, mainly wood, is transformed into pulp. Paper production basically consists of 5 steps:

1. *Stock preparation* where pulp is mixed with water and additives and is prepared (e.g. cleaned, de-inked, refined) to obtain the right properties.
2. In the *former (or wire) section* the first water is removed by gravitational forces and vacuum.
3. After the former section, the wet paper web enters the *press section* where further water removal takes place mechanically. Dry solid content after the press section is 33%-55% depending on paper grade and press section design (Karlsson, 2000).
4. Remaining water is removed thermally in the *first drying (or pre-drying) section*. Depending on end product specifications, paper is mostly treated further with a sizing step e.g. coating, glue or starch.
5. In this case a *second drying (or final drying) step* is needed. A small amount of moisture (5-9%) remains in the paper even after drying (Karlsson, 2000).

Although the basic principle of all paper machines is similar (i.e., wire, press, and dryer sections) there are differences in the design of individual components, mainly associated with the type of paper produced (Van Dijk and Szirmai, 2006). By far the largest share of energy
use in a non-integrated paper mill\textsuperscript{21} is in the drying sections (see Figure 5.1). Thermal drying is often responsible for more than 80\% of the total steam use. The paper machine drying section and its operating principal have remained almost unchanged since their initial development; contact drying with steam heated cylinders is still the dominant method for drying paper and board (Karlsson, 2000). Attempts to develop new drying techniques with reduced energy intensity in the paper industry are, however, known. Among these novel drying techniques are impulse, impingement, through-air and condensing belt drying. Table 5.1 compares the distribution of different drying methods in paper and board drying applications, energy consumption of the methods, evaporation intensities and effect on paper qualities. In a study by De Beer et al., (1998) several of these technologies are discussed. Most of these technologies are, however, not available commercially yet (e.g. De Beer et al., 1998; Luiten et al., 2006; Martin et al., 2000 and Mujumdar, 2007).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.1.png}
\caption{Distribution of total primary energy use in a specific paper mill.}
\end{figure}

Impulse drying improves mechanical dewatering by applying high temperatures in the press nip, thereby reducing water evaporation in the drying section and hence energy consumption. The paper is pressed between a very hot rotating roll and a static concave so that web consistency can be increased to 55-78\%. The impulse dryer can be retrofitted into an existing machine or incorporated into new ones. The technology was invented by Wahren in 1970, and was further developed together with a paper machine manufacturer (Beloit) in the 80s and 90s. In between 1989 and 1999 four attempts to commercialize the technology failed (Luiten et al., 2006). Under Swedish governmental support a major R&D program was started at the end of the 90s. The main argument for developing the technology further became the increased machine capacity and reduced capital intensity in new mills. The original claim of

\textsuperscript{21} Non-integrated paper mills are paper mills without a pulp production facility. These mills use market pulp to produce paper. Integrated mills have a pulp mill on-site. These mills use logs or chips to produce paper.
increased dewatering lost strength over time (Luiten et al., 2006). After more than 25 years of R&D activities and 15 years of government R&D support impulse drying is still no proven technology (Luiten et al., 2006).

In impingement drying, heat is carried into the web using hot, dry air. Due to the high temperature difference between air and web, there is a high heat flux and consequent high drying rate. Gas burners heat up the air in commercial installations. It is also possible to combine power production with the production of hot gas for the drying unit (Manninen et al., 2002). Air impingement dryers (Yankee cylinders) are commercial available and are largely used in e.g. tissue production (84% see Table 5.1). The advantage of this technology is the large increase in drying (evaporation) rate (see Table 5.1). Total energy requirement for air impingement drying is more or less similar to conventional multi-cylinders (Manninen et al., 2002 and Karlsson, 2000).

Next to air impingement, also steam impingement dryers are known. They are comparable to air impingement dryers but differ in drying medium, as superheated steam is used instead of hot air. Energy use is more or less similar to conventional multi cylinder drying (De Beer et al., 1998). However, since the exhaust air is (low pressure) steam, it is possible to recover all latent heat which creates large potential for heat recovery. In order to compensate for pressure drops, a compressor or fan is required which causes an increase in electricity use. Even though the concept of superheated steam drying is more than 100 years old, and the technology is already used in other industries, the technology is still not commercial in the paper industry (Mujumdar, 2008) as implementation requires a major adaptation to the paper making process (De Beer et al., 1998).

Through-air drying (TAD) is a commercially available technology that has significant market share (11% see Table 5.1) in tissue drying. In the TAD process, hot process air flows through the sheet past each individual fibre. This makes the process much more efficient than conventional drying techniques (Karlsson, 2000). However, because there is no wet pressing in a TAD machine, increased water evaporation is needed in the dryer. TAD machines need to remove about two times more water per unit of fibre by thermal energy than conventional machines. Even though the drying process itself is more efficient, energy intensity increases (Karlsson, 2000). The main advantages of the technology are enhanced sheet properties of softness, bulk and absorbance.

In condensing belt (Condebelt) drying, paper is dried in a drying chamber by contact with a continuous hot steel band, heated by gas or steam. Vapour travels through wire gauzes and condensates on a cooled steel band on the other side. The technology has been developed by Valmet and R&D has been conducted since 1975. Its main advantage is the increased drying
rate (5-15 times) and the potential to completely replace the drying section of conventional machines. Only three commercial installations have been built: the first one in Finland in 1996, the latest two in South Korea in 1999 and 2003. After all these years, the technology is still in early commercialization phase. Steam savings are expected to be 10-20% while electricity use is expected to remain the same (Martin et al., 2000).

Table 5.1 Paper industry dryer distribution by application (Source: Karlsson, 2000)

<table>
<thead>
<tr>
<th>Dryer application</th>
<th>Industry share (%)a</th>
<th>Grades</th>
<th>Distribution (%)</th>
<th>Energy use (MJ/kg H₂O)</th>
<th>Drying rate (kg H₂O/hm²)</th>
<th>Paper quality (+, ~,-)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-cylinder Printing, base papers &amp; boards</td>
<td>85-90</td>
<td>Tissue Paper Board Coating</td>
<td>5 95 95 35</td>
<td>2.8-4.0 2.8-4.0 2.8-4.0 3.0-4.5</td>
<td>20 20 15 5-10</td>
<td>~ + + ~</td>
</tr>
<tr>
<td>Yankee Soft tissues &amp; boards</td>
<td>4-5</td>
<td>Tissue Paper Board Coating</td>
<td>84 0 3 0</td>
<td>4.0-5.0 2.8-3.5</td>
<td>200 30-50</td>
<td>+ +</td>
</tr>
<tr>
<td>Infrared Sizing &amp; coating</td>
<td>3-4</td>
<td>Tissue Paper Board Coating</td>
<td>0 1 1 15</td>
<td>5.0-8.0 5.0-8.0 5.0-8.0</td>
<td>10-30 10-30 70-120</td>
<td>~ ~ ~</td>
</tr>
<tr>
<td>Impingement Increased capacity</td>
<td>2-3</td>
<td>Tissue Paper Board Coating</td>
<td>0 4 0 50</td>
<td>2.8-3.5 3.0-5.0</td>
<td>50-120 40-140</td>
<td>~ ~ ~</td>
</tr>
<tr>
<td>Through Soft tissues, filter fabrics</td>
<td>1-2</td>
<td>Tissue Paper Board Coating</td>
<td>11 0 0 0</td>
<td>3.4-4.5</td>
<td>170-550</td>
<td>+</td>
</tr>
<tr>
<td>Condebelt In production scale</td>
<td></td>
<td>Tissue Paper Board Coating</td>
<td>1</td>
<td>2.6-3.6</td>
<td>200</td>
<td>+,-</td>
</tr>
<tr>
<td>Impulse Pilot stage</td>
<td></td>
<td>Tissue Paper Board Coating</td>
<td>0 0</td>
<td>0.55-1.4 0.55-1.4</td>
<td>500-8000 500-8000</td>
<td>+,- +,-</td>
</tr>
</tbody>
</table>

a Pulp dryers excluded
b ~ indicates that quality might improve or worsen depending on paper grade

It is not expected that large scale implementation of novel dryers will be rapid, as the need for new drying hardware is limited due to the long life-cycle of drying equipment (20-40 years) (Mujumdar, 2007). Paper manufacturing is very capital-intensive and presently, state-of-the-art PMs may cost more than US$ 400 million apiece and typically account for over 50% of the total investment costs of new paper mills (Van Dijk and Szirmai, 2006). A major new technology is introduced only once in five to seven years and in order to stay cost-competitive, a paper machine has to be rebuilt on average once every 15 years (Haarla, 2003). Summarizing, the share of conventional multi-cylinder dryers is 85-90%, and in paper production even 95% (see Table 5.1). Only a few novel drying technologies are commercial
and the energy-efficiency of those technologies is often worse than the efficiency of conventional dryers. Since energy efficiency is crucial, the goal of this study is to identify short-term energy improvement options in conventional multi-cylinder dryers in the paper industry. Few studies are known that focus on improvements of conventional dryers in the paper industry (e.g., Kilponen et al., 2002; Lindell and Stenström, 2004; Sivill et al., 2005 and Petterson and Söderman, 2007), though most of them focus solely on improvements in the heat recovery system. In this study, we perform a thermodynamic optimization of ventilation systems of conventional multi-cylinder dryers. Moreover, we identify measures to reduce evaporation in the first place. We calculate the net energy savings that can be achieved. We will not focus on economic aspects of the optimization options. Calculations are based on data from Dutch paper mills. The study concerns a modeling exercise based on thermodynamic principles, no real time experiments have been performed. In the next section, we describe the paper drying process in multi-cylinder dryers. We then present the methodology, including the theory behind energy use of water evaporation. In the following section, we calculate the effect of several optimizations to increase the energy efficiency of paper drying. Finally, results will be discussed and conclusions will be drawn.

5.2 Paper drying in multi-cylinder dryers

In thermal drying of a product, we can distinguish three steps: separation of liquid from the product, transition of liquid from a fluid to a gaseous phase and removal of the produced vapor. The manner and temperature at which these steps occur, largely determine the energy efficiency of the drying process. Nowadays, most paper mills have multi-cylinder drying sections with closed hoods. In the hood, ventilation air can be largely controlled and is supplied to those places where evaporation is highest. In Figure 5.2, a schematic overview of a multi-cylinder dryer is shown. The dryer consist of two drying sections and a size press. The paper machine cylinders are heated with steam. For removal of moisture, air of approximately 95°C is supplied to the paper hood. Outside air is pre-heated in the first heat recovery unit (HRC I) and further heated with steam. The evaporated water diffuses in the air surrounding the cylinders. This air needs to be replaced continuously in order to maintain a difference in vapor concentration between vapor at the surface of the paper web and vapor in the air. The difference in vapor concentration is proportional to the water vapor pressure at the paper web surface and the partial water vapor pressure in the air, which also determines the speed of diffusion. The hood exhaust air has a high moisture content and a temperature of 80-90°C. About 90-95% of the heat used in the process ends up in the exhaust air (Karlsson, 2000) partly in the dry air and mostly in the diffused vapor. The remaining heat is lost by radiation and convection in the hood, and by heating up the paper web. The high energy content of the exhaust air makes this stream very suitable for heat recovery. The recovered heat is often used
to heat supply air (HRC I), but also the process water (HRC II) and the machine room heating circuit (HRC III) can be supplied with heat from the exhaust air.

An important variable in paper drying is the dew point. Hood manufacturers typically give guaranteed design values for paper hood dew points. This means that no condensation within the hood takes place at temperatures above the dew point. The higher the dew point the easier condensation occurs which is a phenomenon paper producers want to avoid. On the other hand, the higher the dew point, the more vapour the drying air can contain. Which means that less drying air is needed to remove evaporated water. Moreover, at higher dew point temperatures, it is possible to recover more heat from the exhaust air.

Figure 5.2 Schematic overview of an example multi-cylinder dryer including heat recovery

5.3 Methodology

In this study, we focus on optimization options for state-of-the-art multi-cylinder dryers with closed hoods. We further assume that the hood is in good condition, has proper insulation and is equipped with proper ventilation, air distribution and frequency controlled fans. The energy use for paper web heating and the heat loss due to convection and radiation (together approx.
5-10%) (Karlsson, 2000) is not taken into account. This means that about 90-95% of the steam consumption of the dryer is covered in this study.

The energy needed for paper drying can be determined by a combination of:
1) the amount of water that needs to be removed in the drying sections
2) the amount of energy needed for water evaporation
3) the amount of recovered heat from the exhaust air

5.3.1 Amount of water evaporation
The amount of water evaporation in the two drying sections can be calculated as follows:

\[
P_{\text{WE}_{pd}} = \left( \frac{100}{d_{m_i}} - \frac{100}{d_{m_{apd}}} \right) x P_{\text{bdry}}
\]

\[
P_{\text{WE}_{fd}} = \left( \frac{100}{d_{m_{ifd}}} - \frac{100}{d_{m_o}} \right) x P_{\text{bdry}}
\]

Where:
- \(P_{\text{WE}_{pd}}\) = Product Water Evaporation pre-dryer section (ton)
- \(P_{\text{WE}_{fd}}\) = Product Water Evaporation final-dryer section (ton)
- \(d_{m_i}\) = Dry matter content paper web in (%)
- \(d_{m_{apd}}\) = Dry matter content paper web after pre-dryer section (%)
- \(d_{m_{ifd}}\) = Dry matter content paper web in final dryer section (%)
- \(d_{m_o}\) = Dry matter content paper web out (%)
- \(P_{\text{bdry}}\) = Bone dry mass of paper web (ton)

5.3.2 Amount of energy needed for water evaporation
The energy needed to evaporate a kg of water can be determined with a Mollier chart for humid air. The Mollier chart can be used to make calculations on humid air conditions for processes at a constant (atmospheric) pressure. A schematic overview of the basic principles of the Mollier chart is shown in Figure 5.3. The diagram shows, by means of continuous lines, the relationship between the following parameters (all expressed per kg dry air) of a changing mixture of dry air and water vapor:

- Absolute humidity \(w_{\text{VAP}}\) in kg vapor/ kg dry air
- Enthalpy \(h\) in kJ/kg dry air
- Dry-bulb temperature \(\theta\) in °C
Optimizing the energy efficiency of conventional multi-cylinder dryers in the paper industry

Wet-bulb temperature \( (\theta_{wb} \, ^{\circ}C) \)
Dew point temperature \( (\theta_{dew} \, ^{\circ}C) \)
Relative humidity \( (\varphi \, \%) \)
Partial vapor pressure \( (p_{vap} \, \text{in kPa}) \)
Specific volume \( (v \, \text{in m}^3/ \text{kg dry air}) \)

If two of the 8 parameters are known, the other 6 are given by the Mollier chart.

The energy use of the drying process can be extracted from the Mollier chart for humid air by plotting the conditions of supply \((i_1)\) and exhaust air \((u_1)\) of the dryer. The energy use of water evaporation is the product of the energy input per kg dry air and the amount of dry air needed to remove the water (eq. 3). The energy input per kg dry air is equal to the difference in energy content of supplied and exhaust air (eq. 4). The amount of air needed for 1 kg of product water evaporation (PWE) is given by the difference in absolute water content of the two streams (eq. 5).

Energy use (kJ/kg PWE) = Energy input (kJ/kg dry air) * Air use (kg dry air/ kg PWE)  (3)

Energy input (kJ/kg dry air) = \( h_{\text{exhaust}} - h_{\text{supply}} \)  (4)

Air use (kg dry air/ kg PWE) = \( \frac{1000 \, g}{w_{VAP_{\text{exhaust}}} - w_{VAP_{\text{supply}}}} \)  (5)

Where:

\( w_{VAP_{\text{exhaust}}} \) = absolute humidity exhaust air (g water/ kg dry air)
\( w_{VAP_{\text{supply}}} \) = absolute humidity supply air (g water/ kg dry air)

5.3.3 Heat recovery

An important measure to increase energy efficiency in drying is to optimize heat recovery from exhaust air. In this study we account for two applications to use recovered heat directly into the process: preheating incoming air and heating process water. Another option is to use the heat for space heating (excluded here).
Figure 5.3 Principle of the Mollier chart for humid air
Energy from the exhaust air can be recovered to preheat the supply air. The heat recovery efficiency is determined by the temperature efficiency of the (air-air) heat exchanger. The temperature efficiency gives the temperature change in each stream as compared to the maximum temperature difference that could be achieved if the exchanger had an infinite size. Temperature efficiency values are used to calculate the amount of heat transferred in air to air heat recovery equipment:

Where:

\[ \eta_\theta = \text{temperature efficiency of the heat exchanger} \]
\[ m = \text{mass (kg)} \]
\[ \theta = \text{temperature (°C)} \]
\[ w_{\text{VAP}} = \text{moisture content (g/kg dry air)} \]
\[ h = \text{enthalpy of the humid air (kJ/kg dry air)} \]
\[ c = \text{specific heat (kJ/(kg.°C))} \]

\[ \eta_\theta = \frac{m_a \cdot c_a \cdot (\theta_{a2} - \theta_{a1})}{m_a \cdot c_a \cdot (\theta_{a1} - \theta_{a1})} \]

\[ \eta_\theta = \frac{m_o \cdot c_o \cdot (\theta_{o2} - \theta_{o1})}{m_o \cdot c_o \cdot (\theta_{o1} - \theta_{o1})} = \frac{\theta_{o2} - \theta_{o1}}{\theta_{a1} - \theta_{o1}} \]

Pre-heating of the incoming air with exhaust air is already common practice, the temperature efficiencies of heat exchangers in the paper industry are in practice seldom higher than 60% because of economic reasons (the costs of heat exchangers increase with size).

**Heating process water**

If enough energy is available, energy from the exhaust air can be further used to heat the process water. Increasing process water temperature could lower gross energy use since it lowers the viscosity of water. A lower viscosity leads to increased drain velocity in the wire.
and press section, resulting in higher dry matter content after the press section. A widely quoted rule of thumb for web heating is that for every 10°C increase in entry web temperature a 1% increase in dry matter content of the web can be expected (Cutshall et al., 1988). According to Patterson and Iwamasa (1999) this is usually quoted in combination with a second rule of thumb; for every 1% increase in solids out of the press section a 4% energy savings or production increase can be expected because of the reduced drier load. The 10°C rule of thumb is often thought to be linear (within a specific range) for all incoming solids and does not vary significantly across furnishes and pressing conditions. However, in practice these rules may not hold (Patterson and Iwamasa, 1999). A review by Patterson and Iwamasa (1999) indicates, that for a 10°C change in web temperature the change in outgoing solids ranges from 0.13 to 1.92 points. Moreover, this relationship changes as the solids content change. The interaction between incoming solids, temperature increase, and resultant change in web solids is not consistent. Furnish, peak pressure, and pressure impulse have an effect on the interaction. In general, for a given incoming temperature rise the outgoing web solids increases as the temperature increases, although sometimes the change is extremely small or the opposite is true (Patterson and Iwamasa, 1999).

In this study we use the following assumptions:

Process-water from 40 °C to 50 °C, increase d.m. 1.5%, (steam saving 6.0 %)
Process-water from 50 °C to 60 °C, increase d.m. 1.3%, (steam saving 5.2%)
Process-water from 60 °C to 70 °C, increase d.m. 1.1%, (steam saving 4.4%)
Process-water from 70 °C to 80 °C, increase d.m. 0.9%, (steam saving 3.6%)

Prerequisite for this assumption is that process water temperature should be kept constant. With increasing process water temperatures, the spontaneous water evaporation at the (open) wire section increases. Therefore, with increased temperatures, there is an increased cooling of water (by evaporation). This heat loss should be compensated in order to keep the process water temperature constant. The heat loss by spontaneous water evaporation can be calculated as follows (see Eq. 8 and 9):

\[
\text{Heat loss (MJ/h)} = \text{wirewidth (m)} \times \text{spon\_evap (t/h \times m)} \times \text{evap\_heat (MJ/t)} \\
\text{Evaporation heat (MJ/t)} = 2501.6 - (2.4 \times \text{process\_water\_temp (°C)})
\]

Where: Heat loss = energy loss by evaporation on the wire in MJ/hour  
Wirewidth = wirewidth in (m)  
spon\_evap = amount of water evaporation on wire in t water per hour per m wire  
evap\_heat = evaporation energy in MJ / t evaporated water  
process\_water\_temp = temperature of the process water (°C)
5.3.3 Approach

In order to study the energetic optimization of ventilation systems of conventional multi-cylinder dryers, we have used a model based on thermodynamic principles. The model builds on mass and energy balances of the paper web and the drying air (Eq. 8 and 9). We have modeled a model paper mill using standard technology to calculate energy use in the reference situation. Data for the model paper mill are assumptions based on data from Dutch paper mills. No real time experiments have been performed. We calculate net energy use for drying a ton paper by multiplying water evaporation (kg PWE/ t paper) with energy use of water evaporation (MJ / kg PWE). The energy savings by heat recovery are also accounted for. Preheating supply air lowers the energy use for water evaporation, heating process water increases the dry matter content after the press section and thereby decreases water evaporation per ton paper. Several improvement options are identified that reduce the amount of water evaporation, increase the efficiency of water evaporation or increase the amount of heat recovered. The effect of the improvement options on net energy use is calculated. We further calculate total net energy savings that can be achieved by combining all options.

Figure 5.4: Process conditions in the reference drying section
5.4 Results

5.4.1 Reference situation energy use

The process conditions for the reference situation are given in Figure 5.4. We assume that the reference paper mill drying sections operates at a dew point of 59°C, which is a common dew point temperature in modern mills. The process water is not heated in the reference situation. Due to pumps and other equipment the process water temperature is higher than the outside water temperature; it is here estimated at 40°C. The reference mill adds starch to the paper in a size press. The starch comprises 3.5% of the final end weight (bone dry). The starch has an 8% consistency. In the reference situation, only heat recovery for supply air heating is installed, which is common in most mills. No heat recovery of process water is installed.

The drying process is schematically depicted in the Mollier-chart in Figure 5.5. The exhaust air (u1) condition, (temperature of 80°C and relative moisture content is 40%) is plotted in Figure 5.5. During drying, the temperature of the air decreases (sensible heat) and at the same time the moisture content of the air increases (latent heat). The sum of sensible heat and latent heat does not change; this means that the enthalpy stays constant during the drying process.

The drying process follows the line of constant enthalpy. Heating of the supply air is a process that follows the line of constant absolute moisture content. Outside supply air (i1) is first heated in HRC I. Assuming supply air (i1) is 10°C, exhaust air (u1) is 80°C and temperature efficiency of the heat exchanger is 45%. Preheating of the supply air (i1-i2) can be calculated with equation 7): \[ 0.45 = \frac{x - 10°C}{80°C - 10°C}. \]

\[ x = 41.5°C. \]

The temperature increases from 10°C to 41.5 °C while the absolute moisture content remains unchanged (i2). The Mollier-chart shows that about 32 kJ/kg is transferred from the exhaust air to the supply air. It is assumed that all exhaust air (100%) is used to heat all supply air (100%). The supply air is further heated in heat exchangers and by the cylinders. At the point of junction between the line of heating and the line of drying, point i4 is plotted, which indicates the required conditions of the drying air. The process water temperature is higher than 0°C; this means that between i3-i4 no heating is required.

\[ ^{22} \]

To describe the drying process in the Mollier-chart it is assumed that the process takes place on one cylinder which can be heated till a very high temperature (e.g. in “i4” the temperature is 430 oC). In reality the drying section of a multi-cylinder dryer is composed of several cylinders, and is therefore actually a sequence of several smaller drying processes. However, this does not influence the results for energy calculations.
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Moisture increase per kg dry air: \( \Delta w_{\text{w1}-\text{w11}} = 138 \text{ g moisture/kg air} \)

Required air per kg PWE: \( 1000 \text{ g} \)

\( \Delta w \text{ g/kg} = 7.23 \text{ kg air/kg PWE} \)

Consumption with HRC supply air: \( 7.23 \times (h_{i3} - h_{i2}) = 2765 \text{ kJ/kg PWE} \)

HRC when cooling exhaust air till 60°C \( = 8\% \text{ of heat consumption} \)

\[ u_2 = u_2 \]

\[ 144 = u_2 \]

\[ \text{Figure 5.5 the reference drying process in the Mollier-chart} \]
**Table 5.2 Total drying energy in the reference situation: input values and calculated results**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unit</th>
<th>Reference assumption</th>
<th>Calculated input values</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{mi}$</td>
<td>%</td>
<td>48</td>
<td>60.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>$d_{adj}$</td>
<td>%</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{ifd}$</td>
<td>%</td>
<td>60.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{oa}$</td>
<td>%</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{bdry}$</td>
<td>t paper</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{WPE_{pd}}$</td>
<td>kg PWE/t dry paper</td>
<td>833&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{WPE_{fd}}$</td>
<td>kg PWE/t dry paper</td>
<td>592&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{WPE_{total}}$</td>
<td>kg PWE/t dry paper</td>
<td>1425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h_{exhaust}$</td>
<td>kJ/kg dry air</td>
<td>440&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h_{supply}$</td>
<td>kJ/kg dry air</td>
<td>58&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{VAP_{exhaust}}$</td>
<td>kg vapor/kg dry air</td>
<td>144&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{VAP_{supply}}$</td>
<td>kg vapor/kg dry air</td>
<td>6&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy input</td>
<td>kJ/kg dry air</td>
<td>382&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air use</td>
<td>kg dry air/kg PWE</td>
<td>7.23&lt;sup&gt;f&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy use</td>
<td>GJ/t PWE</td>
<td>2.8&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drying energy</td>
<td>GJ/t paper</td>
<td></td>
<td></td>
<td>3.9&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

- It can be calculated that 402 kg of water is used to add starch to 1 t paper. The dry matter content after the size press decreases from 80% to 60.8%.

- $P_{WPE_{pd}} = \frac{100}{d_{mi}} - \frac{100}{d_{adj}} \times P_{bdry}$

- $P_{WPE_{fd}} = \frac{100}{d_{adj}} - \frac{100}{d_{oa}} \times P_{bdry}$

- Value can be drawn from Figure 5.5.

- Energy input (kJ/kg dry air) = 440 kJ/kg dry air – 58 kJ/kg dry air = 382 kJ/kg dry air

- Air use (kg dry air/ kg PWE) = \frac{1000}{W_{VAP_{exhaust}} - W_{VAP_{supply}}}

- Energy use (kJ/kg PWE) = Energy input (kJ/kg dry air) * Air use (kg dry air/ kg PWE)

- The total drying energy is given by the total evaporation per t paper (kg PWE/ t dry paper) multiplied with the energy use for evaporation (MJ/kg PWE).

The amount of water evaporation in the pre-drying sections is calculated with eq.1 and the amount of water evaporation in the final-drying section is calculated with eq.2. The energy use per kg PWE can be drawn from Figure 5.5, using equations 3, 4 and 5. The results are shown in Table 5.2. The total drying energy is given by the total evaporation per t paper multiplied with the energy use for evaporation. The calculated total drying energy in the reference situation is 3.9 GJ/t paper.
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5.4.2 Decreasing water evaporation

The amount of evaporated water per kg of final product is the difference in dry matter content of the web before and after the drying sections and the amount of water that added by means of sizing, coating or gluing.

Decreasing the water evaporation in the drying section could be achieved by:

- a) increasing the dry matter content of the web before the first dryer (dm_i)
- b) increasing the dry matter content before the final drying section (dm_ifd)
- c) decreasing the dry matter content of the final product (dm_o)

(or by a combination of these options).

Option a) could be established by e.g. increasing the process water temperature to increase dewatering in the wire and press section (see below) or by increasing the performance of the press section. Over the years, many improvements have been established in the press section including the shoe press with extended nip as one of the key improvements (Meinecke, 1986; Kivimaa et al., 1998). Therefore, we will not investgate the latter option further in this study.

Option c) is a difficult option as it has a large influence on the paper quality and end product specifications; we will not take these into consideration. Here, we will focus on option b). The difference between the dry matter content of the paper web after the pre-dryer section and before the after-dryer section is caused by the addition of coating, starch or glue (in a solution of water) in a size press in between the drying sections.

**Starch**

In the case of starch, typically, size press additions involve re-wetting the pre-dried paper on flooded rollers with a starch solution to soak the starch into the paper. Once soaked, the treated paper is dried again, thereby providing paper of increased strength. In the production of paper for corrugated board from recovered paper, approximately 3.5% of the end weight of the product is starch. Currently, starch is typically added in a solution with only 8% dry matter content. This means that for every 100 t paper produced, 3.5 t starch is added in a solution of 40 t water that needs to be evaporated in the after-dryer section.

**Coating**

Coatings can constitute a large share of the total end weight of the paper (e.g. up to 30%) Coatings are added to the paper in much higher consistency than starch, typically 68% dry matter content. This means that for every 100 t paper produced, 30 t coating is added in a solution of 14 t water.


Glues

Glues are used to laminate board with a layer of paper. The amount of paper added to the board can be a large share of the total end weight of the product, but the glue is only 1.5% of the final board mass (without paper additions). Glue is typically added to the board in a solution of 30% dry matter content. This means that for every 100 t board produced, 1.5 t glue is added in a solution of 3.5 t water.

An option to decrease the amount of water evaporation (and thus energy use) in the drying section would be to apply these additives in higher consistencies. The highest potential is found in the addition of starch as water input is largest in this case. In Figure 5.6, the energy use per t paper of the after-drying section is plotted against the consistency of the additive. We assume an energy use of 2.8 GJ/t PWE in the drying section (reference situation). Figure 5.6 shows an expected reduction in energy use with increasing consistencies however, the energy saving potential decreases with higher consistencies, as the water removal is inversely proportional to the dry matter content of the starch solution. The largest energy savings are realized in the first part of the graph; for increases in dry matter content from 8% to around 30%, the energy saving in the after-drying section is 0.9 GJ/t paper (i.e. more than 50% of the energy use in the after drying section). Although the use of high consistency sizing agents is not yet commercial, research is currently being undertaken to develop economic viable high dry content sizing and glue agents (Bumaga, 2009).

![Figure 5.6 Energy use in the final drying section at different starch solution consistencies](image-url)
5.4.3 Decreasing energy use for water evaporation

In order to define the optimal drying conditions (i.e. with lowest energy use) we have used the Mollier chart for humid air to find the relation between the temperature of the exhaust air and the energy use per kg water evaporation. This relation is shown in Figure 5.7, where also different dew point temperatures, relative humidity and drying air temperatures are depicted. The supply air condition is set at 10°C and 80% relative moisture content.

As can be seen from Figure 5.7, point A indicates the conditions with the lowest energy use per kg evaporated water. However, this point is located on the pure vapor line where moisture content of the air is 100% and drying will be impossible. In order to keep the drying process at sufficient speed, the relative humidity of the air should be around 40% at maximum (PITA, 2005). It can be seen that the energy use per kg evaporated water decreases with increasing temperature. This may seem contradictory since higher temperatures demand a higher energy use. However, following thermodynamic rules the capacity of air to hold moisture increases...
exponentially with increasing temperatures, meaning that much less air is needed to evaporate a kg of water. Therefore, although the temperature increases, the amount of air that needs to be heated decreases which results in a decrease in total energy use. This is validated by our model. Hence, in theory, the optimal drying condition would be a relative moisture content of around 40% with as high temperature as possible (i.e. just above the pure vapor line). Current best available dryers have guaranteed maximum dew points of 62°C (Lindell and Stenström, 2004). While some paper mills operate on higher dew point than 62°C, many paper mills with closed hoods have dryers with operating dew points only around 55°C or even lower. A transition from a dew point of 55°C to a dew point of 70°C would decrease energy use per kg of water evaporation with more than 8%.

5.4.4 Combined energy saving potential including increased heat recovery

Not only energy use in the drying section decreases with increasing dew point temperatures, also the heat recovery potential increases. An option to further recover heat from the exhaust air is to first pre-heat the supply air of the drying section and to subsequently heat the process- and spray-water in a heat exchanger. In this section, we estimate the combined effect of the above identified optimization options to reduce energy in the drying section. Moreover, we include heat recovery for process water heating. The process conditions are depicted in Figure 5.8. We assume (see Figures 5.4 and 5.8) that the outside air conditions for both the reference
situation and the optimized situation are the same. The exhaust air of the dryer in the
optimized situation has the same relative humidity as in the reference drying process (40%)
but the exhaust temperature is 92.6°C (instead of 80°C) which results in a dew point of 70°C
as compared to 59°C. The process water temperature in the optimized situation is 55°C. The
increase in process water temperature from an average 40°C to 55°C increases the dry matter
content after the press section. Based on our assumptions, we estimate that the dry matter
content after the press section increases from 48% to 50% due to increasing process
temperature.

### Table 5.3 Total drying energy in the optimized situation: input values and calculated results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Assumption</th>
<th>Calculated input values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process water temperature</td>
<td>°C</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Evaporation heat</td>
<td>GJ/t</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Wirewidth</td>
<td>m</td>
<td>6^a</td>
<td></td>
</tr>
<tr>
<td>Spontaneous water evaporation</td>
<td>t H₂O/(h*m)</td>
<td>2^b</td>
<td></td>
</tr>
<tr>
<td>Heat loss</td>
<td>(GJ/h)</td>
<td>28</td>
<td>0.4^c</td>
</tr>
<tr>
<td>Heat loss (GJ/t dry air)</td>
<td>%</td>
<td>50^d</td>
<td></td>
</tr>
<tr>
<td>dm₁</td>
<td>%</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>dm₁adp</td>
<td>%</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>dm₁ffd</td>
<td>%</td>
<td>75.6^f</td>
<td></td>
</tr>
<tr>
<td>Pbdry</td>
<td>t paper</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>PWEpd</td>
<td>kg PWE/ t dry paper</td>
<td>750^f</td>
<td></td>
</tr>
<tr>
<td>PWEfd</td>
<td>kg PWE/ t dry paper</td>
<td>270^f</td>
<td></td>
</tr>
<tr>
<td>PWEtotal</td>
<td>kg PWE/ t dry paper</td>
<td>1020</td>
<td></td>
</tr>
<tr>
<td>hexhaust</td>
<td>kJ/kg dry air</td>
<td>772^h</td>
<td></td>
</tr>
<tr>
<td>happly</td>
<td>kJ/kg dry air</td>
<td>64^b</td>
<td></td>
</tr>
<tr>
<td>WVAPExhaust</td>
<td>kg vapor/kg dry air</td>
<td>277.5^b</td>
<td></td>
</tr>
<tr>
<td>WVAAPapply</td>
<td>kg vapor/kg dry air</td>
<td>6.1^b</td>
<td></td>
</tr>
<tr>
<td>Energy input</td>
<td>kJ/kg dry air</td>
<td>709^j</td>
<td></td>
</tr>
<tr>
<td>Air use</td>
<td>kg dry air/kg PWE</td>
<td>3.68^l</td>
<td></td>
</tr>
<tr>
<td>Energy use evaporation</td>
<td>GJ/t PWE</td>
<td>2.6^k</td>
<td></td>
</tr>
<tr>
<td>Total drying energy</td>
<td>GJ/t paper</td>
<td>2.7^l</td>
<td></td>
</tr>
</tbody>
</table>

^a The width of the paper web in the paper machine ranges from over 2 to 12 meter (Van Lieshout, 2006). We have chosen an average wire width of 6 m in this example.
^b According to Metso, the wire section exhaust for a newsprint machine with a wire width of 10 m and 1800 m/min machine speed, contains 61 g H₂O / kg dry air. 99 kg dry air/sec is released into the machine room.

---

23 Process-water from 40°C to 50°C, increase d.m. 1.5%, (steam saving 6%)  
Process-water from 50°C to 60°C, increase d.m. 1.3%, (steam saving 5.2%)
Compared to outside air (moisture content of approximately 6 g H2O/kg dry air, see Figure 5.5), the water uptake is 55 g / kg dry air. The water evaporation is then 99 * 55 = 5.5 kg / sec for 10 m wire width. This is 0.55 kg H2O / (s*m) or 2.0 t H2O/(h * m).

c Product water evaporation (PWE) = (100/50 – 100/ 95) * 20 t/h = 18.9 t PWE/h

Heat loss by spontaneous evaporation per ton PWE = 2.8*10⁻⁴ MJ/h : 18.9 t PWE /h = 1.5 GJ / ton PWE

Heat loss per kg dry air = 1.5 GJ / ton PWE: 3.68 kg dry air / kg PWE = 0.4 GJ/t dry air

d The increase in process water temperature from an average 40°C to 55°C increases the dry matter content after the press section from 48% to 50%.

e Starch comprises 3.5% of the final end weight (bone dry) so for 1000kg paper, 35kg starch is added. We assume starch is added in 30% consistency. In that case, 82 kg of water is used to add starch. The dry matter content after the size press is calculated to be 75.6%.

f PWEpd = \( \frac{100}{dm_i} - \frac{100}{dm_{apd}} \) \( \times P_{bdry} \)

g PWEfd = \( \frac{100}{dm_{fd}} - \frac{100}{dm_{o}} \) \( \times P_{bdry} \)

h Value can be drawn from Figure 9.

i Energy input (kJ/kg dry air) = 770 kJ/kg dry air – 60 kJ/kg dry air = 710 kJ/kg dry air

j Air use (kg dry air/ kg PWE) = \( \frac{1000 \text{ g}}{W_{\text{VA/Exhaust}} - W_{\text{VA/Supply}}} \)

k Energy use (kJ/kg PWE) = Energy input (kJ/kg dry air) * Air use (kg dry air/ kg PWE)

l The total drying energy is given by the total evaporation per t paper (kg PWE/ t dry paper) multiplied with the energy use for evaporation (MJ/kg PWE).

The optimized drying process is schematically depicted in the Mollier-chart in Figure 5.9. Since the process water is heated to 55°C in the optimized situation, we need to take into account the heat loss by spontaneous water evaporation. The amount of water evaporation in the drying sections is calculated with eq.1 and eq.2. The energy use per kg PWE can be drawn from Figure 5.9, using equations 3, 4 and 5. The heat loss and evaporation heat are calculated with equation 8 and 9. Table 5.3 shows the input values and calculated results for energy use in the optimized situation. The calculated total drying energy in the optimized situation is 2.7 GJ/t paper. The heat loss due to spontaneous water evaporation is calculated at 0.4 GJ/t. We use Figure 5.9 in order to check if the exhaust air contains enough energy to compensate for the heat loss due to spontaneous water evaporation. Figure 5.7 shows that in the exhaust air 0.4 GJ/t is available for this purpose. This means that the heat losses can be completely covered with heat from the exhaust air.

5.4.5 Summary of results

Comparing the results of the reference drying process and the optimal drying process including all proposed measures gives the results as reflected in Table 5.4.
Table 5.4. Summarized results: water evaporation and heat use in the reference and optimized situation

<table>
<thead>
<tr>
<th></th>
<th>Reference situation</th>
<th>Optimal situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat use per t PWE</td>
<td>2.8 GJ/tPWE</td>
<td>2.6 GJ/tPWE</td>
</tr>
<tr>
<td>Water evaporation pre-dryer</td>
<td>833 kg PWE/t paper.</td>
<td>750 kg PWE/t paper</td>
</tr>
<tr>
<td>Water evaporation final dryer</td>
<td>592 kg PWE/t paper.</td>
<td>270 kg PWE/t paper.</td>
</tr>
<tr>
<td>PWE total</td>
<td>1425 kg PWE/t paper</td>
<td>1020 kg PWE/t paper</td>
</tr>
<tr>
<td>Heat use per t bone dry product</td>
<td><strong>3.9 GJ/t paper</strong></td>
<td><strong>2.7 GJ/t paper</strong></td>
</tr>
</tbody>
</table>

The heat saving due to the optimization actions of the drying section is 1.3 GJ/t paper, or 32% compared to the reference situation. Part of the savings are the result of increased dew point of the dryer, that results in a lower air use and increased dryer efficiency. Most of the savings are however due to reductions in the amount of water evaporation. This is partly the result of increased consistency in starch additives (final dryer) and partly due to increased process temperatures (pre-dryer). The increased process temperature became possible due to a higher dew point temperature in the dryer hood, which increased heat recovery potential.
Moisture increase per kg dry air: \[ \Delta w_{i1} - w_{i1} = 271 \text{ g moisture/kg air} \]

Required air per kg PWE: \[ 1000 \text{ g} \Delta w / \text{kg} = 3.68 \text{ kg air/kg PWE} \]

Consumption with HRC supply air: \[ 7.23 \times (h_{i3} - h_{i2}) = 2612 \text{ kJ/kg PWE} \]

**HRC when cooling exhaust air till 60°C** \[ = 59 \% \text{ of heat consumption} \]

*Fig. 5.9 The optimised drying process in the Mollier-chart*
5.5 Discussion

This study has shown that there is large energy saving potential in multi-cylinder dryers. Only heat savings were taken into account. It is however expected that as a result of a decreased air flow in the drying section, electricity use will also decrease. We did not take into account the effect on the drying rate. The drying rate is dependent on the heat conductivity in the drying cylinders. The energy for paper drying comes from steam inside the drying cylinders, which partly condensates and releases condensation heat. One of the most important thermal resistances during heat transfer is the condensate layer on the inside of the cylinder, of which the thickness can be controlled by water removing siphons. The thermal conductivity of the water layer can be increased by e.g. the application of spoiler bars that are used to induce turbulence in the condensate layer. The main purpose of implementing these bars is to improve the uniformity and rate of heat transfer (drying rate) of the dryers. They can be used to either increase productivity or to use lower operating steam pressures while maintaining the same paper production rates. The amount of energy needed to evaporate water, however, is not dependent on the heat conductivity and this will therefore not impact our results.

Water in a moist paper web consists of different fractions: free water in between the fibers and in large pores, and bound water (micro-capillary moist). The fractions differ in their thermodynamic properties. Most of the water removed in the drying section of a paper machine is free water. Only when the paper web’s moisture ratio decreases below approximately 30%, most of the free water has been evaporated and the remaining part is bound water (Karlsson, 2000). For evaporation of bound water an extra amount of energy (which is called heat of sorption) is necessary besides the latent heat of vaporization for free water. In this study we have not taken into account the heat of sorption as it is only a small (approximately 1%) fraction of the total energy use in the dryer (Karlsson, 2000). However, it increases exponentially with decreasing moisture content of the paper web. Drying to very low moisture contents should therefore be avoided. Also fiber selection can play a role in energy efficiency improvements in a paper mill (Westenbroek and Dekker, 2005). The water retention value (WRV) of fibers indicates the ability of fibers to hold (free) water. The lower the WRV, the better the dewatering in the wire and press sections. This indirectly influences drying energy as less water needs to be removed thermally. The WRV depends mainly on the external and internal fibrillation of fibers and on the absence/presence of fines. Different fiber species (e.g. softwood/hardwood) can have different WRVs. Moreover, the WRV can be increased by refining (beating of the fibers to increase strengths properties) or decreased by the treatment with enzymes. The use of (chemical) retention agents is already widely used in the paper and board industry to increase the dewatering of the fibers in the wire and press section. The WRV of fibres impacts wire and press dewatering, and hence the dry matter content before the press section; it does not impact the drying efficiency.
As indicated, the higher the dry solid content of the paper web after the press section, the smaller the energy use in the drying section. The efficiency of press section water removal is dependent on several factors: e.g. the WRV of the fibers, the ash content of the furnish, the construction/design of the press (e.g. the residence time in the press, the applied pressure and the quality of the press felt) and the temperature of the process water. In this study, we only investigated the effect of increased process water temperature on drying section energy use. Increasing process water temperature is assumed to have a positive effect on the dry matter content after the press section (Cutshall et al., 1988; Patterson and Iwamasa, 1999), however, information and practical studies on the precise relationship are scarce. More information about the effect of increased water temperatures on the dry matter content is therefore needed. Moreover, there could be possible disadvantages of high process water temperatures like higher wastewater temperatures (energy loss), higher pipe temperatures (safety), increased contamination of press felts, extra maintenance, and air in process water. On the other hand, there could be possible advantages besides steam savings in the drying section, like lower specific energy consumption for pulping and vacuum, lower biological activity in the process water circulation loop and lower specific water consumption. It is recommended that the possible side-effects of increased process water temperatures are studied further.

The other proposed optimization measures could also have side-effects. If the air flow in the dryer is reduced, it might decrease the ability of the paper web to stay connected to the cylinder’s surface. Therefore, extra equipment to circulate the air internally might need to be installed. A positive side-effect of the increased exhaust temperature and smaller air volumes is that the heat recovery equipment can be much smaller than with larger air volumes, which reduces the investment costs of this type of equipment significantly. An overall side-effect of heat reduction is that for existing mills, the CHP plant is optimized for the mills’ specific heat demand. A decreasing heat demand could results in less optimized operation of the CHP plant and could therefore have a significant impact on the efficiency of the CHP plant.

In this study, several options for heat savings in the drying section of conventional multi-cylinder dryers in the paper industry have been identified. The influence of these measures on the operating performance and/or product quality are however uncertain. Moreover, the cost effectiveness of the different measures is unknown and will probably differ largely from case to case. The cost of a drying hood depends largely on scale, machine type, product produced and on the currently installed dryer and its technical age. The same is valid regarding heat recovery equipment. Because the options discussed are mainly retro-fit solutions, it is hardly possible to estimate the effect on costs. The high-consistency starch solutions are not commercially available yet, which makes it impossible to give cost figures also on this option. Therefore, although a large energy saving potential has been identified, further research and practical tests are required. These should make clear if the potential could be fully exploited.
5.6 Conclusion

The paper industry is, with about 6% of total worldwide industrial energy use, an energy-intensive industry. The drying section, is with about 50% the largest energy user in the papermaking process (excluding pulping). Energy use in the drying section is mainly heat use. In this study, several options to decrease heat use in the drying sections have been investigated and the combined effect of these optimization measures has been calculated.

The energy use to evaporate water can be decreased by increasing the temperature in the dryer. A transition in dew point from 55°C to 70°C decreases energy use of water evaporation with more than 8%. The relative moisture content of the exhaust air should with this measure be kept around or below 40% in order to keep the drying capacity. Increasing the temperature also increases the heat recovery potential of the exhaust air. Heat from the exhaust air can first be used to pre-heat the incoming air of the dryer and then to increase the process water temperature. An increase in process water temperature from an average 40°C to 55°C is assumed to reduce steam use with about 8% due to better dehydration on the wire. The third optimization measure aims to decrease the amount of water evaporation in the drying section by applying additives in higher consistencies. The highest potential is found in the addition of starch as water input is largest in this case. For increases in dry matter content from 8% to around 30%, the energy saving in the after-drying section is approximately 0.9 GJ/t paper (i.e. more than 50% of the energy use in this section).

The combined heat saving potential due to the optimization actions in the drying section is 1.3GJ/t paper (or 32%) as compared to the reference situation. This is a saving of about 15% of the total primary energy use in the paper mill. These savings are considerable and could not only contribute to the mills’ competitiveness, as energy costs have become one of the key cost components of the pulp and paper sector, they also contribute to the energy efficiency targets of the national and European governments. The main uncertainties in this study are the influence of the optimization options on the operating performance and/or product quality and the effect of increased process water temperature on water removal in the press section. Moreover, the cost effectiveness of the different measures is unknown and will probably differ largely from case to case. Furthermore, the use of high consistency starch additives is not commercial yet, but R&D in this field is currently ongoing. Research and implementation by trials is recommended to investigate the side-effects of the proposed measures and to identify if the heat saving potential could be fully exploited.
References


Optimizing the energy efficiency of conventional multi-cylinder dryers in the paper industry


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Westenbroek APH Dekker JC. Energy reduction by control of recycled fibre selection and processing, PTS Pulp Technology Symposium, Dresden, Germany, 24-26 October 2005.
6. Summary and conclusions

6.1 Introduction

The energy intensive manufacturing industry is a significant contributor to the global economy. Historic developments of the manufacturing industries have been dependent on the large scale use of raw materials and fossil energy. The increasing scarcity of fossil resources and a number of raw materials as well as a growing world population, make a transition to more sustainable supply and a more efficient use of energy and raw materials imperative. The pulp and paper sector is a very interesting sector in this respect: the global pulp and paper industry is the fourth largest industrial energy user worldwide. Despite its significant energy use, greenhouse gas emissions in the pulp and paper industry are relatively low due to the large scale use of renewable energy; the industry's main raw material (wood) is renewable, while recycling contributes to over 50% of its current feedstock use. Because the pulp and paper industry is such a large scale biomass user and pulp and paper factories are increasingly considered for bioenergy production and other bio based products, the sector is well positioned to contribute to the development of a future bio-based economy, where biomass resources are used for a multitude of energy carriers, chemicals and renewable materials. At the same time, the economic performance of the sector is also very sensitive to energy, material and CO$_2$ prices and large investments in new technologies and capacities are therefore risky. Furthermore, growing biomass use for energy can lead to increasing pressure on biomass resources. All these factors make it critical that the sector becomes more energy and resource efficient and innovative in general. Such a strategy involves improvements on all levels (i.e. process, mill, country and sector). The central research question for this thesis is:

What is the improvement potential, at different levels, to reduce the life cycle impact in terms of energy use and GHG emissions of paper and board?

Considering the opportunities, constraints and research needs identified, the specific research aims of this thesis are to:

- Assess and evaluate the availability of high quality industrial data and, based on such data, explore the energy efficiency improvement potential of the paper industry, taking into account the diversity of the sector that is reflected in a variety of product and feedstock mixes.
- Assess the potential of technological improvement options to reduce energy consumption and CO$_2$ emissions in the paper industry, taking into account local circumstances and capital intensity of the sector.
Develop and apply analysis methods that allow for assessment of the influence of recycling on the life cycle impact of different paper and board grades.

6.2 Summary of results

6.2.1 Opportunities at sector level

Since the EU made a commitment to reduce greenhouse gas emissions, companies in the pulp and paper sector have been worried about unfair competition in the raw material market for both virgin and recycled fibres that could arise as a result of competition distorting support mechanisms, e.g. subsidies for bio-energy generation. Increased demand for biomass increases pressure on the availability of this resource, generating tensions on the feedstock markets and posing a risk to the supply of raw materials. This could be overcome by increasing biomass supply or by improving the efficiency with which we use biomass for energy and materials. Recycling of paper could be a key part of such a strategy. The paper industry is already a leader in recycling, especially in Europe, where almost 70% of the consumed paper is currently recovered. In Chapter 2, the impact of recycling on CO$_2$ emissions, energy use and land use over the total life-cycle of paper is assessed. The effect of increasing pressure on biomass availability is explored. The chosen system boundary was found to have a large impact on the results. Especially regarding the in- or exclusion of surplus biomass that becomes available via increased recycling. Assuming no constraints on resource availability, the paper production life cycle from chemical pulping has the lowest CO$_2$ emission intensity (300 kg CO$_2$/t) but the highest energy intensity (44 GJ/t). This is explained by the high feedstock use for energy generation. Assuming limitations on biomass availability, recycling of paper has the lowest energy intensity (22 GJ/t) and CO$_2$ footprint (-1100kg CO$_2$/t). In a system where the virgin and recycling chains are so dependent, however, one should be careful selecting system boundaries, as an input of virgin fibres in the paper cycle will always be needed to ensure continuation of the recycling loop.

One of the unique elements of this study is the distinction between different paper grades. In our individual paper grade analysis in the analysis, we chose to directly transfer the benefits of recyclability to the life-cycle of that grade. This method gives the paper grade not only credits for the recovered fibre input, but also for the recovered fibres that can be extracted after their use. Therefore, this approach also allocates recycling benefits to the virgin paper grades that are crucial in continuing the recycling loop. Large differences exist between paper grades in e.g. electricity and heat use during production, fibre furnish, filler content and recyclability. Although recycling was found to have a positive impact on life-cycle energy use of all grades, the size of the impact differs from grade to grade. Reduced heat consumption in papermaking, decreased filler percentage, increased recycled fibre input and increased recycling were all found to reduce life-cycle energy intensity of printing and writing paper.
production. The calculated energy reduction potentials were found in different parts of the life-cycle (resource use, production process, end-of-life phase) and together amount to savings of 15 GJ/ton. The average life-cycle energy use of the paper mix produced in The Netherlands, where the recycling rate amounts approximately 75%, is about 14 GJ/t. Paper recycling in The Netherlands has led to CO₂ savings of about 1 t CO₂/ t paper, compared to a situation where no recycled fibres would be used. For paper production in the Netherlands, this equals about 3 Mt avoided CO₂ emissions per year, equivalent to approximately 9% of the total Dutch industrial CO₂ emissions in 2007.

Our results show that increasing recycling rates as well as increasing recyclability of individual grades offer good improvement potentials for the pulp and paper sector.

6.2.2 Opportunities at country level

With rising energy prices, controlling energy costs has become increasingly important for the pulp and paper industry. The increase in energy prices is a global phenomenon, but even for paper mills with similar energy efficiencies, large differences in energy costs of paper production occur between paper mills in different European countries. In chapter 3 we analyse which energy conversion strategies can reduce energy costs, primary energy use and CO₂ emissions for paper mills within different European countries. Three case study countries were selected (the Netherlands, Poland and Sweden), all countries having a thriving paper industry and individually having a large variation in available natural resources. Our results show that differences in history and availability of resources have led to clearly different energy conversion strategies in the three European countries.

The Dutch paper industry mainly uses recovered fibres (>80%) as feedstock, as (domestic) biomass is hardly available. With The Netherlands being the second largest producer of natural gas in the EU, the energy use of the Dutch paper industry is almost exclusively (for approximately 97%) covered by this fuel. Approximately 75% of the Dutch paper mills have a (natural gas fired) CHP installation installed. Energy costs for Dutch mills are high compared to the other studied countries. The Dutch paper industry was found to have a low primary energy use due to the high share of gas-fuelled CHP installations, but relatively high CO₂ emissions due to the minimal share of bio-energy compared to other countries. A switch from natural gas to biomass in the Dutch paper industry would reduce CO₂ emissions by approximately 500 kg CO₂/ t paper. However, due to the lack of domestically available biomass, most of the biomass based alternatives do not seem to be promising alternatives in the near future, unless prices for imported biomass decrease. Our results show that, with current biomass prices, a carbon price of more than 60 €/ton CO₂ would be needed to provoke a switch to biomass fuels in The Netherlands. At such high carbon prices, however, Dutch
mills would be outcompeted by the Swedish and Polish bio-based mills that benefit from increasing carbon prices and lower costs of indigenous biomass supplies. Provided with few alternatives, the most effective strategy in The Netherlands would be an increase in energy efficiency.

Biomass resources are widely available in Sweden and the Swedish paper industry is therefore mainly virgin fibre-based. Only 17% of the fibre raw material input is recovered paper. About half of the electricity generated in Sweden is currently produced from nuclear energy, the other half from renewables as hydropower and biomass. The limited use of fossil fuels has caused the CO$_2$ emissions related to Swedish electricity production to be very low (+/- 0.4 kg CO$_2$/kWh). Due to a long history of low electricity prices, CHP has not been so common in Sweden. Most Swedish paper mills produce only heat and therefore have a relatively high primary energy demand. However, due to the large abundance of wood, many Swedish mills use biomass as an energy source. Because of this and due to low CO$_2$ emissions of national electricity production, the CO$_2$ emission profile of the Swedish paper industry is very low.

Our results imply that the most promising future conversion routes for the Swedish paper and board industry are again wood based. Depending on future electricity prices, these would either be heat only options, or biomass (gasification) based CHP solutions.

Poland has the largest coal reserves of Europe. The Polish paper and board industry has relatively low energy costs, due to the availability of both coal (25%) and biomass (69%) at low prices. These fuels are mostly used in heat only boilers, which results in relatively high primary energy demand for Polish mills. A switch from coal to biomass would reduce CO$_2$ emissions in the Polish pulp and paper industry with 800 kgCO$_2$/t paper on average (approximately 0.6 Mton/year). A carbon price of 20-25 €/ton would, according to our results, be enough to provoke this switch in Poland. Since the electricity mix in Poland is also dominated by coal, the on-site production of electricity (CHP) from biomass would, in the case of high CO$_2$ prices, be a beneficial strategy.

In the past, European policies have focused mainly on CO$_2$ emission reduction and sustainable energy production and less on energy efficiency. Our results show that there are, in many cases, trade-offs between the three. We found that increasing the share of biofuels and CHP (Poland and Sweden) as well as increasing energy efficiency (all countries but especially The Netherlands) offer good improvement potentials for the pulp and paper industry at the national level.
6.2.3 Opportunities at mill level

Manufacturing of paper consists of a series of unit processes, often linked and interdependent. Although there are large differences between different paper mills, using different types of feedstock and producing different paper grades, the typical processes involved in paper production can be divided into a number of main categories (e.g. stock preparation, forming and press section, drying) that apply to all mill types. In Chapter 4, we benchmark the specific energy consumption of similar processes within different paper mills to identify energy improvement potentials. We define improvement potentials as measures that could be taken at mill/process level under assumed fixed inputs and outputs. We were able to use detailed industrial data on process level and we conducted energy benchmarking comparisons, based on energy and material balances per process, in 23 Dutch paper mills.

We found a large energy efficiency improvement potential in the forming and press section, indicated by a large range in SEC (0.5-3.0 GJ/t paper) between mills in this section and supported by the fact that the average SEC was found to be comparable between grades. We further found that water removal in the drying section is rather grade specific, while differences in energy consumption for evaporation indicated significant improvement potentials in the drying section (up to 2.6 GJ/t water removed). Differences in energy efficiency could also be found in stock preparation, de-inking and dispersion, but energy use in these processes is largely related to quality issues. The energy efficiency improvement potential, in the combined de-inking and dispersion processes was found to be 0.7 GJ/t pulp for the least efficient tissue mill. In stock preparation, the improvement potential was found to be low for board mills (0.3 GJ/t stock) and tissue (0.6 GJ/t stock). The highest range in SEC was found in graphical paper grades (1.5-3.0 GJ/t paper), although this range is not an indication for an improvement opportunity per se, given the large contribution of refining to energy use in this section and the fact that refining energy largely influences product specifications. Moreover, refining affects the water retention of fibres, increasing energy use in upstream processes (dewatering and drying). The latter emphasizes that even a benchmark on detailed process level does not necessarily lead to clear estimates of energy improvement potentials without accounting for structural effects and without having a decent understanding of the process.

Our results show that there are significant opportunities for energy efficiency improvement at mill level, especially in the wire and press section as well as in the drying section. The total energy improvement potential based on identified best practices in these sections was estimated at 5.4 PJ (or 15% of the total primary energy use in the selected mills).
6.2.4 Opportunities at process level

By far the largest share of energy use (>50%) in a non-integrated paper mill is in the drying sections. Thermal drying is often responsible for more than 80% of the total steam use. The paper machine drying section and its operating principal have remained almost unchanged since their initial development and the share of conventional multi-cylinder dryers in paper production is still 95%. Attempts to develop new drying techniques in the paper industry are known (e.g. impulse, impingement, through-air and condensing belt drying), but most of these technologies are not commercially available yet. Rapid implementation of novel dryers on substantial scale is unlikely, given the capital-intensive nature of the industry and the long economic and technical lifetime of drying equipment (20-40 years).

Since energy efficiency is crucial, also on the short-term, Chapter 5 studied the improvement options in conventional multi-cylinder dryers in the paper industry. The obtained results show that energy use for evaporating water can be decreased by increasing the temperature in the dryer. A transition in dew point from 55°C to 70°C decreases energy use of water evaporation with more than 8%. The relative moisture content of the exhaust air should with this measure be kept around or below 40% in order to keep the drying capacity. Increasing the temperature also increases the heat recovery potential of the exhaust air. Heat from the exhaust air can first be used to pre-heat the incoming air of the dryer and then to increase the process water temperature. An increase in process water temperature from an average 40°C to 55°C is assumed to reduce steam use with about 8% due to better dehydration on the wire. A third optimization measure involves a decrease in the amount of water evaporation in the drying section by applying additives in higher consistencies. The highest potential is found in the addition of starch as water input is largest in this case. For increases in dry matter content from 8% to around 30%, the energy saving in the after-drying section is approximately 0.9 GJ/t paper (i.e. more than 50% of the energy use in this section).

All measures identified in Chapter 5 could be achieved by retrofitting and/or choosing different processing conditions in existing mills. At process level, the results identify a combined heat saving potential of 1.3GJ/t paper (or 32%). This equals savings of about 15% of the total primary energy use in the paper mill.

6.3 Conclusions and recommendations

To conclude this thesis, it would be interesting to identify an overall improvement potential for the paper sector based on the results throughout this thesis. However, the results of the analyses and the discussions in the different chapters of this thesis have made clear that one should be cautious to draw general conclusions for a sector as complex and diverse as the
paper industry. The work throughout this thesis deals with different aspects of the paper life cycle, various paper grades and processes, as well as different regions in Europe. All presented research, however, deals (at least for some part) with the Dutch paper and board industry. Therefore, in order to synthesize results and identify overall improvement potentials, focus lays on the Dutch context. More generic conclusions for the sector or for other countries will be drawn when applicable and possible. In the final section also the methodological findings of the combined work will be synthesized.

In Chapter 4, energy efficiency improvement potentials have been identified based on a detailed energy benchmark of different process units within the Dutch paper industry. The results of the benchmark identified improvement potentials in different areas of paper production for different paper grades. Despite the detailed data we were able to use in this study, it is difficult to draw precise conclusions on the available energy efficiency potential in the Dutch paper and board industry. Energy efficiency improvement potentials could be found in stock preparation, de-inking and dispersion, but energy use in these processes was found to be too dependent on quality requirements and product specifications to quantify this potential. On a more generic level, significant opportunities for energy efficiency improvement were identified in the wire and press section as well as in the drying section. The total energy improvement potential in those sections was estimated at 15% of the total primary energy use of the Dutch paper industry. This energy efficiency improvement potential is based on the implementation of readily available technology in the Dutch paper industry, as the figures represent existing best practice examples among the 23 paper mills investigated. The interaction effect between implementing various measures has not been investigated in the presented work (in other words, reduction in energy consumption in a certain process unit may affect the efficiency improvement potential in another process unit), but we consider this effect to be relatively small. Moreover, energy efficiency measures in other sections (e.g. stock preparation, finishing) have not been taken into account and the figure could therefore be seen as a conservative estimation of the energy efficiency improvement potential from implementing best practices in the Dutch paper industry.

In Chapter 5, energy efficiency improvement potentials in the drying section were further explored, by means of a thermodynamic optimisation exercise. Based on the results of this study, an improvement potential of 32% in heat use per ton (bone dry) paper was calculated for the drying section. Energy use in the drying section represents approximately half of the total energy use of a Dutch paper mill. Therefore, the energy efficiency improvement at mill level, by implementing the identified measures in the drying section, was found to be approximately 15%. The improvement potential calculated in Chapter 5 was based on the implementation of retrofit measures in existing dryers. Part of these measures are already implemented by some paper mills (e.g. a dew point of 60 °C instead of 55°C is common in
most Dutch paper mills today and several mills already heat up their process water with waste heat. Many of the other measures described, however, are currently not implemented in the paper industry. They could therefore be seen as ‘next practice’ measures. It should be noted though, that the improvement potential is based on model calculations only and the implementation potential may be lower. We estimate conservatively, that about half of the identified energy efficiency improvement potential (as described in Chapter 5) (7%) can be considered as additional potential to the efficiency improvements represented by the adoption of best practices (e.g. reduction of vacuum capacity, correct dimensioning of pumps and compressors, hood closure and heat recovery) in Chapter 4 (15%). Combined, this results in an energy efficiency improvement potential of approximately 22% (in terms of primary energy use per ton of per produced) for the Dutch paper machines as compared to the base year 2005.

In Chapter 3, we explored the improvement opportunities, in terms of energy efficiency, CO\(_2\) emissions and energy costs, related to energy generation at paper mills. Due to the already high penetration levels of CHP in the Dutch paper industry, the sector already achieves a high energy efficiency in its energy conversion facilities. Based on the results of this chapter, we found that further improvement options for the Dutch paper sector are limited. The limited availability of low cost, sustainable biomass or other renewable energy sources hampers the potential to reduce CO\(_2\) emissions in the sectors energy supply. For the Dutch paper industry, improving energy efficiency is the most feasible route for improving its energetic performance. At present, despite its’ high energy efficiency, the use of CHP facilities is under pressure for economic reasons. Due to increased capacity on the grid, electricity prices have decreased in recent years. At the same time, the prices for natural gas kept rising, thereby reducing the spark spread and consequently the margins for industrial CHP. The decision to close down a CHP facility for economic reasons can have a major negative impact on energy use and CO\(_2\) emissions, as paper mills will start buying electricity from the grid (which is expectedly increasingly coal-based) while generating steam in a stand-alone gas fired heat boiler. In general, it can therefore be concluded that maintaining the high implementation level of CHP in the Dutch paper industry is essential to avoid negative impacts on energy use and CO\(_2\) emissions. More or less the same conclusion can be drawn with respect to recycling. The Netherlands already have a very high recycling rate (75%) for paper and board. The results in Chapter 2 have shown that this recycling rate has led to a CO\(_2\) reduction of about 1 t CO\(_2\)/ t paper, compared to a situation where no recycled fibres would be used. For the total paper production in the Netherlands, this difference equals about 3 Mt avoided CO\(_2\) emissions per year. A further increase in recycling in The Netherlands is hardly expected, as the country is already reaching the limit of what is economically and technically feasible; the share of non-collectable and non-recyclable paper is, for technical reasons, estimated to be 19% of the total paper and board consumption, such as libraries, archives, sanitary paper, etc.
Consequently the theoretical maximum collection rate would be 81% instead of 100%. The more one approaches this threshold, additional improvement that can be achieved declines e.g. due to longer transportation distances and a lack of economies of scale.

Considering these results for other countries, it is clear that energy efficiency is always important. Based on our findings in the Dutch paper industry, and taking into account that the Dutch paper industry belongs to the most energy-efficient paper industries in the world (based on results from the Benchmarking Covenant (2000-2010), an energy efficiency improvement potential of at least 20-25% could be considered a conservative figure for the paper industry in general. CHP could in many countries be an interesting improvement opportunity as the technology fits well in the paper industry. We found that the least efficient energy conversion routes in the European paper industry have a 2-3 times higher primary energy demand than available CHP solutions. Economic feasibility of CHP, however, varies from country to country (depending on the spread between prices of available fuel sources and electricity). Biomass energy conversion technologies should be implemented when possible and feasible, as they are effective in reducing CO\textsubscript{2} emissions (provided the biomass is sustainably produced) especially in cases where the current energy generation is based on carbon-intensive fuels. We found that a switch from coal to biomass is able to reduce CO\textsubscript{2} emissions with 800 kgCO\textsubscript{2}/t paper on average, as is the case in Poland. Also at sector level, the paper industry has improvement opportunities. A further increase in material efficiency, by increasing the overall recycling rate with, for example, 10%, could contribute not only to a reduction in final energy consumption of approximately 2 GJ/ton of paper, but also to a reduction in CO\textsubscript{2} emission intensity of about 130 kg CO\textsubscript{2}/ton. Only a few European countries have reached their limit in paper recycling, whereas in most European countries there is still potential for growth. The combined effect of the different technologies and measures across the sector and lifecycle of paper production and use could result in a significant CO\textsubscript{2} emission reductions and energy savings; the implementation of energy-efficiency measures could lead to 20-25% primary energy reduction in most paper mills; a transition to CHP could reduce primary energy demand up to 50% while a switch to biomass fuel could reduce CO\textsubscript{2} emissions by more than 90% (in both cases depending on the reference situation). Moreover, a 10% increase in recycling could bring savings of approximately 10% in primary energy and CO\textsubscript{2} emissions over the total life cycle of paper.

The variety of research methods introduced and applied throughout this thesis, which takes into account the complexity of the sector in terms of variability of feedstock and product ranges, have contributed to a more detailed and nuanced analysis of energy efficiency improvement and CO\textsubscript{2} reduction potentials compared to earlier studies of the sector. The analyses in Chapter 2 and 3 have shown that using a single indicator (e.g. CO\textsubscript{2} emissions or energy use) is often not sufficient to determine the sustainability or improvement potential of
paper production chains, especially when comparing different chains (e.g. recycling or virgin) or different countries. The results from Chapter 3 make it clear that there are often trade-offs between energy efficiency, CO₂ emissions and energy costs of a certain conversion route. Moreover, the possible improvement potential is highly dependent on local circumstances. Also in policy making, trade-offs between various sustainability indicators are often not well reflected. European policies have, until recently, mainly focused on CO₂ emission reduction and renewable energy production while less on energy-efficiency. The results from Chapter 3 show that a focus on energy efficiency is (at least) equally important. In some cases (e.g. countries without sufficient availability of low cost renewable energy sources), energy efficiency is in fact the only viable improvement opportunity. In the Netherlands, for example, a large primary energy reduction has been achieved over the years by the contribution of (natural gas fuelled) CHP plants. While policy makers are nowadays mainly focused on renewable energy targets, the deteriorating economic position of CHP is leading to several closures of CHP facilities, resulting in a consequent increases in primary energy demand. The methodologies applied in this thesis enable to account for these types of effects.

We found that the choice of the system boundary has large impacts on the results. Especially regarding the in- or exclusion of surplus biomass that becomes available via increased recycling. The research further provides new insights with respect to recycling of different paper grades and the impact of recycling of a mix of paper grades. The focus on and distinction between different paper grades and individual processes have been a structural point of attention throughout this thesis. So far, in most scientific and applied studies, energy efficiency improvement potentials are assessed at country or industry level. A specification into feedstock use and product quality is seldom made. The results from Chapter 4 as well as results from the other chapters highlight that taking into different processes, feedstock and produced paper grades is key to arrive at realistic energy and material efficiency improvement potentials. The work presented in this thesis stresses the importance of using non-aggregated data, especially when benchmarks are to be used in industrial target setting. Paper grades that, on a high level of aggregation may be categorized in a single product group (e.g. paper), often require considerably different amounts of energy (e.g. 7.5 GJ/t (board) and 14.7 GJ/t (tissue)) for their production. Moreover, even within different paper grades, there are variations in e.g. processes applied and qualities produced; knowledge of and insight in the specific production processes is found to be essential in order to identify realistic improvement potentials for paper mills.

This thesis provides insights in the energy use of the paper industry and improvement potentials for the paper sector at different levels that could be valuable to the sector itself, to policy makers as well as to the research community. The paper sector is affected by many challenges, especially related to increased competition for raw materials and energy.
Challenges, however, also provide opportunities to innovate and improve performance. In this thesis several opportunities have been identified that enable the sector to reduce its’ demand of and dependency on (fossil) energy, in lowering its energy costs and in reducing its carbon footprint. The largest improvement potential in terms of specific energy reduction for the sector is in the drying process. The paper sector should start by implementing the best practice measures that are already available (e.g. hood closure, dew point increases up to 64°C, heat recovery), while it should encourage R&D activities in the development of next practices in drying technology. Suppliers of machinery should be encouraged by the paper industry to develop dryer hoods that are able to reach even higher dew points while insights into the effects of increased process water temperature on water removal in the press section need further research. Further R&D activities are also needed in the field of high consistency additives in the paper industry. Application of high-consistency sizing agents have, until now, not been identified in the paper industry while, in theory, they could lead to large energy efficiency improvements.

With respect to energy conversion technologies, research in this thesis has explored conventional routes as well as some novel routes mainly for (solid) biomass conversion. Several improvement opportunities for the paper sector have been identified mostly concerning the combined generation of heat and power and/or a switch to biomass energy resources. However, research in this thesis clearly showed that differences in the local availability of resources (and prices) as well as national and European policy decisions strongly impact the viability of these opportunities. Policies targeting the sector should recognize and stimulate the energy efficiency potential from CHP in addition to the current support of energy (mainly electricity) generation from renewable energy sources. The support for CHP and energy efficiency in general is especially important in countries with limited access to renewable energy sources. In recent years, several alternative energy conversion routes for the pulp and paper industry have emerged, some of them offering really promising alternatives (e.g. geothermal heat, biogas and residual waste streams). Further research in these type of alternative energy sources for the paper industry is therefore recommended.

Concerning raw material supplies, research in this thesis has focused on virgin and recovered wood fibres. We quantified the effects of recycling in terms of energy use and CO₂ emissions, and identified opportunities for the paper sector by enhancing its recycling rate in countries that have not reached their techno-economical limits for recycling. Moreover, there is an increasing interest in the use of alternative fibres for paper production, for example the use of agricultural residues. The paper industry is already exploring possibilities by cooperating with other industrial sectors such as the agricultural industry and the chemical industry that is targeting production of biochemical and bioplastics. Analysing the technical and operational possibilities for using alternative fibres as well as analysing the impact of the use of
alternative fibres on the life cycle impact of paper production could be a next step in future research. With increasing efforts in developing a bio-based economy, opportunities for the paper sector also emerge in terms of supplying bio-based building blocks to other industries. It is recommended to further investigate the opportunities that arise from valorisation of paper industries’ waste streams e.g. the extraction of valuable components from waste water and the use of paper industry residues for generating building blocks for bio-chemicals.
7. Samenvatting en conclusies

7.1 Introductie

De energie-intensieve maakindustrie is een belangrijke motor van de wereld economie. De ontwikkeling van de maakindustrie is, over de jaren, erg afhankelijk geweest van het grootschalige gebruik van grondstoffen en fossiele energie. Echter, toenemende schaarse aan fossiele energiebronnen, in combinatie met een groeiende wereldbevolking, maken een transitie naar een meer duurzaam en efficiënt gebruik van energie en grondstoffen noodzakelijk. De papierindustrie is in dit opzicht een interessante sector: de pulp- en papierindustrie is de op drie na grootste industriële energiegebruiker ter wereld, maar ondanks haar aanzienlijke energieverbruik is de uitstoot van broeikasgassen door de sector relatief laag, als gevolg van de grootschalige inzet van hernieuwbare energie. Daarnaast is de belangrijkste grondstof van de pulp- en papierindustrie (hout) hernieuwbaar en voorziet recycling in ruim 50% van de totale grondstofbehoeften in de industrie. Vanwege haar toegang tot, en grootschalige inzet van biomassa wordt de pulp- en papierindustrie in toenemende mate gezien als belangrijke producent van bio-energie en andere bio-based producten. De sector lijkt daarmee in een goede positie om bij te dragen aan de ontwikkeling van een toekomstige bio-based economy, waar biomassa wordt gebruikt voor de productie van een verscheidenheid aan energiedragers, chemicaliën en duurzame materialen. Tegelijkertijd zijn de economische prestaties van de papierindustrie zeer gevoelig voor energie-, materiaal- en CO₂-prijzen, wat capaciteitsuitbreidingen en investeringen in nieuwe technologieën riskant maakt. Bovendien kan een toename in bio-energie productie leiden tot een toenemende druk op de bestaande grondstoffen voor de papierindustrie. Al deze factoren maken het essentieel dat de sector innoveert en haar energie- en materiaal efficiëntie verhoogt. Voor een dergelijke strategie zijn verbeteringen op alle niveaus in de papiersector noodzakelijk (d.w.z. op proces-, fabrieks-, nationaal en brancheniveau). De centrale onderzoeksvraag van dit proefschrift luidt:

Wat is het verbeterpotentieel, op verschillende niveaus, om de impact in termen van energiegebruik en uitstoot van broeikasgassen in de papier en kartonindustrie te reduceren?

Rekening houdend met kansen en belemmeringen voor de sector en met eerder gedefinieerde onderzoeksbehoeften zijn de volgende doelstellingen voor dit proefschrift opgesteld:

- Het evalueren van beschikbare, kwalitatief hoogwaardige, industriële data en het, op basis van deze gegevens, verkennen van het energie-efficiëntie verbeterpotentieel van de papierindustrie, rekening houdend met de diversiteit van de sector welke tot uiting komt in haar verscheidenheid aan producten en grondstoffenmixen.
- Het beoordelen van het technologisch verbeterpotentieel om het energieverbruik en de CO₂-uitstoot in de papierindustrie te verlagen, rekening houdend met regionale omstandigheden en de kapitaalintensiteit van de sector.
- Het ontwikkelen en toepassen van analysemethoden die het mogelijk maken om de invloed van recycling op de levenscyclus van verschillende papier- en kartonsoorten te beoordelen.

7.2 Samenvatting van resultaten

7.2.1 Mogelijkheden op brancheniveau

Sinds de EU zich heeft gecommitteerd aan een reductie in de uitstoot van broeikasgassen, is de papiersector bezorgd over mogelijk oneerlijke concurrentie op de grondstoffenmarkt, die zou kunnen ontstaan ten gevolge van ondermeer subsidies voor bio-energie. Toenemende druk op biomassa kan leiden tot spanningen op de grondstoffenmarkt en risico’s met betrekking tot de beschikbaarheid van grondstoffen. Vergroting van het biomassa aanbod en/of een efficiëntere inzet van biomassa in energie en producten zou een dergelijk scenario kunnen voorkomen. Recycling zou hierin een belangrijke rol kunnen spelen. De papierindustrie is op dit moment al koploper op het gebied van recycling; vooral in Europa, waar bijna 70% van het gebruikte papier momenteel wordt teruggewonnen. In hoofdstuk 2 is de impact van recycling op CO₂-uitstoot, energie- en landgebruik over de totale levenscyclus van papier onderzocht. Het effect van een toenemende druk op de beschikbaarheid van biomassa is hierin meegenomen. Uit het onderzoek blijkt dat de gekozen systeemgrens van grote invloed is op het resultaat. Dit geldt vooral voor de wijze waarop vermeden biomassagebruik, wat beschikbaar komt door toenemende recycling, wordt meegenomen in de berekeningen. Uitgaande van een systeem met ongelimiteerd beschikbare biomassa, waarbij het grondstofgebruik per pulpsoort varieert, heeft papierproductie uit chemische pulp de laagste CO₂-intensiteit (300 kg CO₂/t) maar de hoogste energie-intensiteit (44 GJ/t). Dit kan worden verklaard door een hoog biomassagebruik dat deels wordt aangewend voor de opwekking van energie. Uitgaande van een gelimiteerde (vaste hoeveelheid) beschikbare biomassa, heeft papier productie uit oud papier zowel de laagste energie- (22 GJ/t) als CO₂-intensiteit (-1100kg CO₂/t). Dit kan verklaard worden door het biomassa surplus dat ontstaat door recycling. In een systeem waar ketens van verse en gerecyclede vezels zo afhankelijk zijn van elkaar, moet men echter voorzichtig zijn met het opstellen van systeemgrenzen; niet alle papiersoorten kunnen uit oud papier worden vervaardigd en daarnaast zal de inbreng van verse vezels altijd nodig zijn om de recyclingloop in stand te houden.

Het onderscheiden van verschillende papiersoorten is één van de bijzondere aandachtspunten in het uitgevoerde onderzoek. In de uitgevoerde analyse is ervoor gekozen om de voordelen
van recycleerbaarheid van een papiersoort ook toe te kennen aan die specifieke soort. Deze methode geeft een bepaalde kwaliteit papier dus niet alleen krediet voor de inzet van oud papier als grondstof, maar ook voor het aandeel vezels dat na gebruik teruggewonnen wordt. Deze aanpak rekent daardoor ook voordelen van recycling toe aan papiersoorten die worden geproduceerd uit verse vezels en die cruciaal zijn voor het in stand houden van de recyclingloop. Er bestaan grote verschillen tussen papiersoorten voor wat betreft elektriciteit- en stoomgebruik, grondstof- en vulstofgebruik en recycleerbaarheid. Hoewel recycling bij alle producten een positief effect heeft op het bruto energieverbruik gedurende de levenscyclus, verschilt de hoogte hiervan per papiersoort. Stoombesparingen, verlaagde vulstofpercentages, verhoogde inzet van oud papiervezels en een toename in recycling hebben allen een gunstig effect op de energie-intensiteit. De besparingseffecten treden op in verschillende fasen van de levenscyclus (grondstofgebruik, productieproces, end-of-life) en bedragen in totaal circa 15 GJ/ton voor print- en schrijfpapier. De Nederlandse papiermix, met een recycling percentage van circa 75%, heeft een gemiddeld energieverbruik gedurende de levenscyclus van ongeveer 14 GJ/t. Door papierrecycling in Nederland een CO\textsubscript{2}-besparing van ongeveer 1 tCO\textsubscript{2}/t papier bereikt, ten opzichte van een referentiesituatie zonder recycling. Dit is ca. 3 Mt vermeden CO\textsubscript{2}-uitstoot per jaar en komt overeen met circa 9% van de totale Nederlandse industriële CO\textsubscript{2}-uitstoot in 2007.

Onze resultaten tonen hiermee aan dat het verhogen van zowel recycling als recycleerbaarheid van individuele papiersoorten nog een aanzienlijk reductiepotentieel van het energiegebruik en CO\textsubscript{2} emissies van de pulp- en papiersector vertegenwoordigen.

7.2.2 Mogelijkheden op nationaal niveau

Stijgende energieprijzen vergroten het belang van beheersing van de energiekosten van de pulp- en papierindustrie. Hoewel de stijging van energieprijzen een wereldwijd fenomeen is, bestaan er grote regionale verschillen in energiekosten tussen papierfabrieken in verschillende Europese landen, zelfs bij een vergelijkbaar energiegebruik. In hoofdstuk 3 analyseren we welke energieconversie strategieën in verschillende Europese landen energiekosten, primair energieverbruik en CO\textsubscript{2}-uitstoot in de papierindustrie kunnen verminderen. Hiervoor zijn drie landen geselecteerd (Nederland, Polen en Zweden) met allen een florerende papierindustrie en met onderling een groot verschil in productiestructuur en beschikbare energiebronnen. Onze resultaten tonen aan dat historische verschillen in beschikbaarheid van grondstoffen en energiebronnen tot duidelijk verschillende energieconversie strategieën van de papierindustrie in de drie onderzochte Europese landen hebben geleid.

De Nederlandse papierindustrie gebruikt hoofdzakelijk oud papier (> 80%) als grondstof; lokale biomassa is nauwelijks beschikbaar. Nederland is de op één na grootste producent van
aardgas in de EU, en de Nederlandse papierindustrie gebruikt dan ook vrijwel uitsluitend aardgas (circa 97%) als energiebron. Ongeveer 75% van de Nederlandse papierfabrieken heeft een WKK-installatie. In vergelijking met de andere onderzochte landen, zijn kosten van energie voor de Nederlandse papierindustrie hoog. De Nederlandse papierindustrie heeft een laag primair energiegebruik als gevolg van het hoge aandeel gasgestookte WKK-installaties, maar een relatief hoge CO₂-uitstoot door de minimale inzet van bio-energie in vergelijking met papierindustrieën in andere landen. Een overgang van aardgas naar biomassa zou de CO₂-uitstoot in de Nederlandse papierindustrie met ongeveer 500 kgCO₂/t papier reduceren. Vanwege het gebrek aan lokaal beschikbare biomassa zijn de onderzochte alternatieven op basis van bio-energie in de nabije toekomst echter niet rendabel, tenzij de prijzen voor geïmporteerde biomassa dalen. Uit onze resultaten blijkt, dat met de huidige biomassa prijzen, een CO₂ prijs van meer dan 60 €/t nodig zou zijn om in Nederland de overstap naar biomassa te overwegen. Met zulke hoge CO₂ prijzen zou de Nederlandse papier- en kartonindustrie echter niet meer kunnen concurreren met bijvoorbeeld Zweedse en Poolse fabrieken die meer profiteren van stijgende CO₂ prijzen door lagere biomassaprijzen uit regionale bronnen. Gezien de beperkte alternatieven, lijkt een toename in energie-efficiëntie de meest effectieve strategie voor de Nederlandse papierindustrie.

Zweden beschikt over grote biomassahoogteveelheden en de Zweedse papierproductie is dan ook voornamelijk op verse vezels gebaseerd. Slechts 17% van de grondstoffinzet is oud papier. Elektriciteit wordt in Zweden geproduceerd uit kernenergie (50%) en uit hernieuwbare energiebronnen (50%) zoals waterkracht en biomassa. Door het lage aandeel aan fossiele brandstoffen is de CO₂-intensiteit van Zweedse elektriciteitsproductie erg laag (+/- 0,4 kg CO₂/kWh). Als gevolg van een lange historie van lage elektriciteitsprijzen is WKK in Zweden niet zo gebruikelijk. De meeste Zweedse papierfabrieken wekken alleen warmte op en hebben daarom een relatief hoog primair energieverbruik. Ze gebruiken voornamelijk biomassa als energiebron, vanwege de ruime beschikbaarheid. Hierdoor, en vanwege de lage CO₂-intensiteit van elektriciteit, is de CO₂-intensiteit van de Zweedse papierindustrie zeer laag. Uit de resultaten blijkt dat de meest veelbelovende toekomstige conversieroutes voor de Zweedse papier- en kartonindustrie wederom op basis van biomassa (vergassing) ofwel biomassa boilers.

Polen beschikt over de grootste steenkoolvoorraden van Europa. Door de inzet van relatief goedkope kolen (25%) en biomassa (69%), profiteert de Poolse papier- en kartonindustrie van relatief lage energiekosten. Brandstoffen worden meestal ingezet in stoomboilers waarbij elektriciteit van het net wordt ingekocht. Dit verklaart het relatief hoge primaire energieverbruik van Poolse papierfabrieken. Een overgang van kolen naar biomassa zou de CO₂-uitstoot in de Poolse pulp- en papierindustrie met gemiddeld 800 kg CO₂/t papier
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verminderen (ongeveer 0,6 Mton/jaar). Een CO₂ prijs van 20-25 €/t CO₂ zou, volgens onze resultaten, voldoende zijn om dit te bewerkstelligen. Omdat de elektriciteitsmix in Polen ook wordt gedomineerd door steenkool, zijn warmtekrachtcentrales gestookt met biomassa, bij hogere CO₂-prijzen, een aantrekkelijke conversieroute.

In het verleden heeft het Europese beleid zich vooral gericht op zowel CO₂-emissiereductie als duurzame energieproductie en in veel minder mate op energie-efficiëntie. Onze resultaten laten zien dat er in veel gevallen trade-offs zijn tussen deze drie mogelijkheden. Het verhogen van het aandeel biomassa en WKK (Polen en Zweden) evenals het verhogen van de energie-efficiëntie (alle landen, maar vooral in Nederland) bieden in deze landen aanmerkelijke mogelijkheden energie-efficiency te verhogen en CO₂ emissies van de papierindustrie te verlagen.

7.2.3 Mogelijkheden op fabrieksniveau

Papierproductie bestaat uit een serie processen die vaak gekoppeld en onderling afhankelijk van elkaar zijn. Hoewel er grote verschillen bestaan tussen papierfabrieken die verschillende soorten produceren en verschillende grondstoffen inzetten, kunnen een aantal typische activiteiten worden onderscheiden (e.g. stofvoorbereiding, zeef- en perspartij, droogpartij) die voor alle fabrieken min of meer vergelijkbaar zijn. In hoofdstuk 4 vergelijken we het specifieke energieverbruik van vergelijkbare processstappen tussen verschillende fabrieken. Het doel van de benchmark is om energiebesparingspotentiëlen te identificeren. We definiëren besparingspotentiëlen als maatregelen die kunnen worden genomen op fabrieks- of procesniveau uitgaande van vastgelegde in- en outputs (grondstofmix en papierproduct(en)). We gebruiken hierbij gedetailleerde industriële gegevens, gebaseerd op energie- en materiaalbalansen op procesniveau, van 23 Nederlandse papierfabrieken.

Uit onze resultaten blijkt een aanzienlijk energiebesparingspotentieel in de zeef- en perspartij. Dit is gebaseerd op de grote variatie in specifiek energiegebruik (0.5 tot 3.0 GI/t papier) tussen de fabrieken, terwijl het gemiddeld specifiek energiegebruik in de zeef- en perspartij tussen diverse soorten vergelijkbaar is. Verder blijkt dat de hoeveelheid waterverdamping in de droogpartij erg afhankelijk is van de papiersoort, terwijl verschillen in energie-efficiënte van waterverdamping duiden op een groot verbeterpotentieel in de droogpartij (tot 2,6 GI/t water verdamping). Ook is een grote variatie in het energiegebruik van de stofvoorbereiding-, ontinkting- en dispersieprocessen tussen de verschillende fabrieken gevonden. Het verschil in energieverbruik in deze processen is echter grotendeels gerelateerd aan kwaliteitsaspecten van het geproduceerde papier. De potentiële energie-efficiëntieverbetering in ontinkting en dispersie is 0,7 GI/t pulp voor de minst efficiënte tissuefabriek. De potentiële energie-efficiëntieverbetering in de stofvoorbereiding is relatief laag voor kartonfabrieken (0,3 GI/t
pulp) en tissue (0,6 GJ/t pulp). Het grootste verschil in energieverbruik voor stofvoorbereiding werd gevonden tussen grafische papiersoorten (1,5-3,0 GJ/t papier). Dit duidt echter niet automatisch op een verbeterpotentieel, omdat maalenergie hieraan een grote bijdrage levert en dit grote invloed heeft op de productkwaliteit. Daarnaast heeft maling ook invloed op de waterretentie van vezels welke het energieverbruik in upstream processen (ontwatering en droging) verhoogt. Dit laatste benadrukt dat zelfs een benchmark op het gedetailleerde procesniveau niet noodzakelijkerwijs tot goede inschattingen van verbeterpotentiëlen leidt, zonder structurele effecten mee te nemen en zonder behoorlijke kennis van het productieproces.

Onze resultaten laten zien dat er aanzienlijke mogelijkheden zijn voor energie-efficiëntieverbetering op fabrieksniveau, voornamelijk in de droogpartij en in de zeef- en perspartij. Het totale energie-efficiënte verbeterpotentieel, op basis van implementatie van bekende technieken, is geschat op 5,4 PJ (ofwel 15% van het totale primair energieverbruik in onderzochte fabrieken).

7.2.4 Mogelijkheden op procesniveau

Verreweg de grootste hoeveelheid energie (> 50%) in een niet-geïntegreerde papierfabriek wordt gebruikt in de droogpartij. Thermische droging is vaak verantwoordelijk voor meer dan 80% van het totale stoomgebruik. De droogsectie en haar operationele werking zijn, sinds de initiële ontwikkeling hiervan, vrijwel onveranderd gebleven en het aandeel conventionele multi-cilinder drogers in de papierproductie bedraagt nog altijd 95%. Er zijn meerdere ontwikkelingen op het gebied van nieuwe droogtechnologie in de papierindustrie bekend (bijv. impuls, impingement, through-air en condensatie), maar de meeste van deze technologieën zijn (nog) niet commercieel beschikbaar. Vlotte implementatie van nieuwe drogers op substantiële schaal is, gezien het kapitaalintensieve karakter van de industrie en de lange economische en technische levensduur van droogapparatuur (20-40 jaar), dan ook onwaarschijnlijk.

Omdat energie-efficiëntie ook op de korte termijn van cruciaal belang is, zijn in hoofdstuk 5 verbetermogelijkheden voor conventionele multi-cilinder drogers onderzocht. De resultaten tonen aan dat de energie-efficiëntie kan worden verhoogd door de uitlaatlucht temperatuur van drogers te verhogen. Een verhoging in daupunt van 55 °C naar 70 °C verlaagt het energieverbruik van waterverdamping met meer dan 8%. Het relatieve vochtgehalte van de afvoerlucht moet hierbij op maximaal 40% worden gehouden om voldoende droogcapaciteit te behouden. Met een verhoging van de droogluchttemperatuur, neemt ook het potentieel voor warmteterugwinning uit de afvoerlucht toe. Warmte uit de afvoerlucht kan worden gebruikt voor o.a. het voorverwarmen van drooglucht en voor het opwarmen van proceswater. Een
verhoging van de proceswatertemperatuur van gemiddeld 40 °C naar 55 °C leidt naar verwachting tot een reductie van het stoomgebruik met ongeveer 8%, door betere ontwatering in de zeef- en perspartij. Een derde optimalisatiemogelijkheid betreft het verminderen van waterdampdaling door het verhogen van de consistentie waarmee additieven worden toegevoegd; met name in het geval van zetmeel, omdat hier de wateraddities het grootst zijn. Een verhoging van het droge stofgehalte van zetmeel slurry van 8% naar 30%, leidt tot een energiebesparing van ongeveer 0,9 GJ / t papier (ofwel meer dan 50% van het energiegebruik in de nadroogpartij).

Alle maatregelen uit hoofdstuk 5 kunnen worden bereikt door retrofits en/of procesaanpassingen van bestaande apparatuur. De berekende resultaten wijzen op een gecombineerd besparingspotentieel van 1,3GJ/t papier (ofwel 32% van de droogenergie). Dit komt overeen met een besparing van ongeveer 15% van het totale primaire energieverbruik in een papierfabriek.

7.3 Conclusies en aanbevelingen

Tot slot is het interessant om, op basis van de resultaten uit dit proefschrift, het totale potentieel voor energiebesparing en CO₂ emissiereductie voor de papiersector te evalueren. De resultaten en discussies in de verschillende hoofdstukken van dit proefschrift, maken echter duidelijk dat men voorzichtig moet zijn om generieke conclusies te trekken voor een sector die zo complex en divers is als de papierindustrie. In dit proefschrift zijn verschillende papiersoorten en processen, verschillende regio's in Europa en verschillende aspecten over de levenscyclus van papier, behandeld. Omdat ieder onderzoek in dit proefschrift (althans deels) betrekking heeft op de Nederlandse papier- en kartonindustrie wordt, om resultaten te synthetiseren en algemene verbeterpotentiaal te identificeren, op de Nederlandse situatie gefocust. Indien van toepassing worden vervolgens meer generieke conclusies voor de sector getrokken. Tot slot worden ook de methodologische bevindingen van het gecombineerde werk besproken.

In hoofdstuk 4, zijn mogelijkheden voor energiebesparing geïdentificeerd op basis van een gedetailleerde energie-benchmark in de Nederlandse papier- en kartonindustrie. In het onderzoek zijn voor verschillende papiersoorten binnen diverse stappen van het productieproces verbeterpotentiëlen geïdentificeerd. Ondanks het detailniveau van de beschikbare gegevens, blijft het moeilijk om harde conclusies te trekken ten aanzien van het energiebesparingspotentieel. Het energieverbruik in de stofvoorbereiding-, ontinkting- en dispersieprocessen is te afhankelijk van kwaliteitseisen en productspecificaties om hiervoor potentiëlen te kwantificeren. In het algemeen zijn er wel aanzienlijke mogelijkheden voor
energiebesparing in zowel de zeef- en perspartij als in de droogsectie. Het totale reductiepotentieel in deze processen is geschat op 15% van het totale primaire energieverbruik in de Nederlandse papier Industrie. Dit cijfer is gebaseerd op implementatie van bestaande technieken in 23 Nederlandse papierfabrieken. Het effect van interactie tussen verschillende maatregelen is niet onderzocht (met andere woorden, verlaging van het energieverbruik in één proces kan de efficiëntie in een ander proces beïnvloeden); we beoordelen dit effect echter als relatief klein. Bovendien hebben we potentiële energie-efficiëntie maatregelen in andere secties (e.g. stofvoorbereiding en verwerking) niet meegenomen. Daarom kan het resultaat worden gezien als een conservatieve schatting van het energie-efficiëntie verbeterpotentieel door implementatie van bestaande technieken (‘best practice’) in de Nederlandse papierindustrie.

In hoofdstuk 5 is reductie van het energiegebruik in de droogpartij verder onderzocht door middel van een thermodynamische optimalisatie. Op basis van de resultaten is een verbeterpotentieel van 32% in stoomgebruik per ton (absoluut droog) papier vastgesteld. Stoomverbruik in de droogpartij is verantwoordelijk voor ongeveer de helft van het totale energieverbruik in de Nederlandse papierindustrie. Implementatie van de geïdentificeerde maatregelen in de droogpartij leidt dus tot een totale primaire energiebesparing van ongeveer 15%. Het berekende verbeterpotentieel is gebaseerd op de uitvoering van maatregelen in bestaande drogers. Een deel van deze maatregelen wordt al toegepast door de Nederlandse papierfabrieken (een dauwpunt van 60°C (in plaats van 55°C) is gebruikelijk en verschillende Nederlandse papierfabrieken warmen het proceswater al op met restwarmte). Een groot deel van de beschreven maatregelen wordt echter momenteel nog niet toegepast in de papierindustrie en kan worden beschouwd als ‘next practice’ maatregelen. Hierbij moet worden opgemerkt dat het verbeterpotentieel is gebaseerd op modelberekeningen en in werkelijkheid lager kan liggen. We schatten, conservatief, dat ongeveer de helft van het energie-efficiëntie verbeterpotentieel, zoals beschreven in hoofdstuk 5 (d.w.z. 7%), kan worden beschouwd als additioneel ten opzichte van verbeteringen door implementatie van beste praktijken in hoofdstuk 4 (15%) (e.g. verminderen van vacuümcapaciteit, juist dimensioneren van pompen en compressoren, afdichten van droogkap en warmteterugwinning). Dit resulteert in een totaal energie-efficiëntie verbeterpotentieel van ongeveer 22% (in termen van primair energieverbruik per ton geproduceerd papier) voor de Nederlandse papiermachines ten opzichte van het basisjaar 2005.

In hoofdstuk 3 zijn optimalisatiemogelijkheden voor energieopwekking, in termen van energie-efficiëntie, CO₂-uitstoot en energiekosten, voor de papiersector onderzocht. Door de hoge penetratiegraad van WKK, behaalt in de Nederlandse papierindustrie een hoge energie-efficiëntie. Verdere optimalisatie hierin, lijkt op basis van de resultaten uit hoofdstuk 3, slechts beperkt mogelijk. De in Nederland beperkte beschikbaarheid van goedkope en
duurzame biomassa, evenals andere hernieuwbare energiebronnen, belemmert het potentieel om de CO$_2$-uitstoot verder te verminderen. Voor de Nederlandse papierindustrie is een verbetering in energie-efficiëntie daarom de meest haalbare route om de energieprestatie te verbeteren. Momenteel staat de inzet van WKK, ondanks haar hoge efficiëntie, echter om economische redenen onder druk. Elektriciteitsprijzen zijn de laatste jaren, door toenemende capaciteit op het elektriciteitsnet, afgenomen. Tegelijkertijd is de aardgasprijs gestegen waardoor de spark spread, en dus de marge voor industriële WKK, daalt. Het besluit om WKK-installaties om economische redenen te sluiten, kan een grote negatieve invloed hebben op energieverbruik en CO$_2$-uitstoot. Papierfabrieken zullen in dat geval stoom opwekken met seperate gasketels en elektriciteit inkopen van het net (wat naar verwachting in toenemende mate uit steenkool wordt opgewekt). In het algemeen kan daarom worden geconcludeerd, dat handhaving van de hoge implementatiegraad van WKK in de Nederlandse papierindustrie van essentieel belang is om negatieve effecten op het energiegebruik en CO$_2$-emissies te vermijden. Min of meer dezelfde conclusie kan worden getrokken ten aanzien van recycling. Nederland kent een zeer hoog recyclingpercentage (75%) voor papier en karton. De resultaten in hoofdstuk 2 tonen aan dat dit recyclingpercentage resulteert in een CO$_2$ reductie van ongeveer 1 tCO$_2$/t papier, ten opzichte van een situatie zonder recycling. Voor de totale papierproductie in Nederland staat dit gelijk aan ongeveer 3 Mt vermeden CO$_2$-uitstoot per jaar. Een verdere toename van papierrecycling in Nederland is nauwelijks te verwachten, omdat de grens van wat economisch en technisch haalbaar is bijna is bereikt. Het aandeel niet-recyclebaar papier (e.g. toiletpapier, papier in bibliotheken en archieven) is ongeveer 19% van de totale papier en karton consumptie; daarom is de theoretisch maximale recyclinggraad 81% en niet 100%. Hoe dichter men deze drempel nadert, hoe lager het verbeterpotentieel wordt, door e.g. langere transportafstanden en een gebrek aan schaalgrootte.

Wanneer we de Nederlandse resultaten vertalen naar andere landen, staat voorop dat energie-efficiëntie altijd belangrijk is. Op basis van onze bevindingen in de Nederlandse papierindustrie, en gezien het feit dat de Nederlandse papierindustrie tot de meest energie-efficiënte papierindustrieën in de wereld behoort (gebaseerd op resultaten uit het Convenant Benchmarking 2000-2010), kan een energie-efficiëntie verbetering van minimaal 20-25% worden beschouwd als een conservatief cijfer voor de totale papierindustrie. In veel landen kan implementatie van WKK worden gezien als een interessante optie voor verbetering, ook omdat de technologie goed past bij de papierindustrie. Uit onze resultaten blijkt een 2 tot 3 maal hoger primair energieverbruik voor de minst efficiënte energieconversie route ten opzichte van huidig beschikbare WKK-oplossingen. De economische haalbaarheid van WKK varieert echter van land tot land (afhankelijk van het verschil tussen de prijzen van beschikbare brandstoffen en elektriciteit). Biomassaconversie technologieën moeten worden ingezet wanneer mogelijk en haalbaar, omdat ze effectief zijn in het verminderen van de CO$_2$-
uitsstoot (mits de biomassa duurzaam is geproduceerd), in het bijzonder wanneer de referentiesituatie is gebaseerd op koolstof intensieve brandstoffen. Een omschakeling van kolen naar biomassa kan de CO$_2$-uitsstoot met 800 kgCO$_2$/t papier verminderen, zoals bleek in de Poolse case. Ook op sectoraal niveau heeft de papierindustrie verbetermogelijkheden; een verdere stijging in materiaalefficiëntie, door verhoging van het recyclingpercentage met 10%, draagt bij aan een reductie in energieverbruik van ongeveer 2 GJ/ton papier en een vermindering in CO$_2$-uitsstoot van ongeveer 130 kg CO$_2$/ton. Slechts enkele Europese landen hebben de grens van papierrecycling bereikt, en in de meeste Europese landen is er daarom nog steeds ruimte voor groei. Door een combinatie van verschillende technologieën en maatregelen in de sector kan een aanzienlijke CO$_2$-emissiereductie en energiebesparing worden bereikt. In de meeste papierfabrieken kan door implementatie van bestaande en nieuwe technieken nog minimaal 20-25% aan energie worden bespaard. Inzet van WKK kan het primaire energieverbruik tot 50% verminderen, terwijl een overgang naar biomassa als primaire energiebron de CO$_2$-uitsstoot met meer dan 90% kan tegengaan (in beide gevallen afhankelijk van de referentiesituatie). Bovendien leidt een 10% toename in recycling tot ongeveer 10% besparing in zowel primair energieverbruik als CO$_2$-uitsstoot over de totale levenscyclus van papier.

De verscheidenheid aan onderzoeksmethoden die in dit proefschrift zijn toegepast, houden rekening met de complexiteit van de sector (e.g. ten gevolge van een diversiteit aan grondstoffen en eindproducten) en hebben daarmee bijgedragen aan een gedetailleerdere en genuanceerdere analyse van energie-efficiëntie en CO$_2$-reductie potentiëlen in vergelijking tot eerdere studies van de sector. De analyses in hoofdstuk 2 en 3 hebben aangetoond dat het gebruik van een enkele indicator (bijv. CO$_2$-uitsstoot of energieverbruik) vaak niet voldoende is om de duurzaamheid of het verbeterpotentieel van papierproductieketen te bepalen. Dit geldt in het bijzonder bij het vergelijken van verschillende ketens (e.g. recycling of verse vezels) of verschillende landen. De resultaten uit hoofdstuk 3 maken duidelijk dat er vaak trade-offs optreden tussen energie-efficiëntie, CO$_2$-uitsstoot en kosten van bepaalde conversie routes. Bovendien is het verbeterpotentieel ook sterk afhankelijk van lokale omstandigheden. Ook in beleidsvorming komen trade-offs tussen verschillende duurzaamheidsindicatoren vaak niet goed tot uiting. Het Europees beleid heeft zich tot voor kort vooral gericht op CO$_2$-emissiereductie en hernieuwbare energieopwekking en veel minder op energie-efficiëntie. De resultaten uit hoofdstuk 3 laten zien dat een focus op energie-efficiëntie (op zijn minst) even belangrijk is. In sommige gevallen (bv. in landen waar goedkope hernieuwbare energiebronnen slechts beperkt beschikbaar zijn), is energie-efficiëntie de meest haalbare verbeteroptie. In Nederland, bijvoorbeeld, zijn door de jaren heen grote energiebesparingen bereikt door de inzet van (aardgasgestookte) WKK-installaties. Terwijl beleidsmakers zich vandaag de dag vooral richten op streefcijfers voor duurzame energie, leidt de verslechterende economische positie van WKK tot sluitingen van WKK installaties wat direct resulteert in een
toename in primair energieverbruik. De onderzoeksmethoden uit dit proefschrift kunnen worden gebruikt om dit soort effecten beter af te wegen.

De selectie van systeemgrenzen heeft een grote invloed op de resultaten. Dit geldt vooral voor de wijze waarop vermeden biomassagebruik, welke beschikbaar komt door toenemende recycling, wordt meegenomen in de berekeningen. De toegepaste onderzoeksmethodiek biedt daarnaast ook nieuwe inzichten met betrekking tot recycling van verschillende papiersoorten en de impact van recycling op een mix van papiersoorten. De focus op, en het onderscheid tussen, verschillende papiersoorten en productieprocessen zijn een structureel punt van aandacht in dit proefschrift. Tot nu toe zijn energie-efficiëntie potentiëlen in de meeste wetenschappelijke en toegepaste studies berekend op landen- of brancheniveau, waarbij er zelden een onderverdeling wordt gemaakt in grondstofgebruik en productkwaliteit. De resultaten uit hoofdstuk 4, evenals de resultaten uit de andere hoofdstukken, laten zien dat een onderscheid in processen, grondstoffen en papiersoorten uiterst belangrijk is om realistische schattingen van de potenties voor energie- en materiaalbesparing te verkrijgen. Het in dit proefschrift gepresenteerde werk wijst op het belang van het gebruik van niet-geaggregeerde gegevens, vooral wanneer benchmarks worden gebruikt voor het vaststellen van industriële doelstellingen. Soorten die op een hoog aggregatieniveau vaak worden geclasseerd als één productgroep (e.g. papier), kennen vaak grote verschillen in energiegebruik (bijvoorbeeld 7,5 GJ/ton voor karton en 14,7 GJ/ton voor tissue). Bovendien zijn er, zelfs binnen dezelfde papiersoort, verschillen in processen en geproduceerde kwaliteiten. Kennis van en inzicht in de specifieke processen is daarom essentieel om realistische verbeterpotentiëlen voor de papierindustrie te kunnen identificeren.

Dit proefschrift geeft inzicht in het energiegebruik van de papierindustrie en de verbetermogelijkheden op verschillende niveaus wat nuttig is voor de sector zelf, alsmede voor beleidmakers en de onderzoeksgemeenschap. De papierindustrie kent diverse uitdagingen, in het bijzonder door toenemende concurrentie voor grondstoffen en kosten van energie. Uitdagingen bieden echter ook kansen om te innoveren en te verbeteren. In dit proefschrift worden verschillende mogelijkheden geschat waarmee de sector zijn vraag naar en afhankelijkheid van (fossiele) energie kan verlagen, energiekosten kan reduceren en zijn CO₂ footprint kan verkleinen. Het grootste verbeterpotentieel voor de sector, in termen van specifieke energiereductie, is in het droogproces. De papierindustrie zou moeten beginnen met het implementeren van al beschikbare ‘best practice’ maatregelen (bijvoorbeeld afdichting van de droogkop, dawpunt verhoging tot 64 °C, warmteterugwinning), terwijl het activiteiten met betrekking tot de ontwikkeling van nieuwe droogtechnologie zou moeten stimuleren. Machineleveranciers moeten door de papierindustrie worden aangezet tot het ontwikkelen van droogkappen die geschikt zijn voor hogere dauwpunten. Daarnaast is verder onderzoek nodig naar de effecten van een verhoogde proceswatertemperatuur op waterverlies in de perspartij.
R&D activiteiten zijn ook nodig op het gebied van hoog consistente additieven. Toepassingen van hoog consistente sterkemiddelen zijn nog niet bekend in de papierindustrie, terwijl ze, in theorie, kunnen leiden tot grote energie-efficiëntieverbeteringen.

Met betrekking tot energieopwekking zijn in dit proefschrift een aantal conventionele en een aantal alternatieve technologieën (hoofdzakelijk voor biomassaconversie) onderzocht. Er zijn diverse verbetermogelijkheden geïdentificeerd, voornamelijk ten aanzien van de gecombineerde opwekking van warmte en elektriciteit en / of de overstap naar biomassa. Het onderzoek in dit proefschrift heeft echter ook aangetoond dat regionale verschillen in beschikbaarheid (en prijzen) van primaire energiedragers evenals nationale en Europese beleidsmaatregelen, de (economische) levensvatbaarheid van deze mogelijkheden sterk beïnvloeden. Beleid gericht op de sector zou, in aanvulling op de huidige ondersteuning van hernieuwbare energie (welke vooral is gericht op elektriciteit), ook de energie-efficiëntie potentie van WKK moeten erkennen en stimuleren. De steun voor WKK en energie-efficiëntiemaatregelen in het algemeen, is vooral belangrijk in landen met een beperkte toegang tot hernieuwbare energiebronnen. In de afgelopen jaren zijn diverse alternatieve energieconversie technologieën verder ontwikkeld, waarvan er een aantal veelbelovend zijn voor de papierindustrie (bijvoorbeeld aardwarmte, biogas en reststromen). Verder onderzoek naar het gebruik dit soort alternatieve energiebronnen voor de papierindustrie wordt daarom aanbevolen.

Ten aanzien van grondstoffen, heeft het onderzoek in dit proefschrift zich gericht op verse en gerecyclede houtvezels. De effecten van recycling in termen van energieverbruik en CO₂-uitstoot zijn gekwantificeerd, en er zijn kansen geschetst door toename van papierrecycling in landen die hun technisch-economische grenzen daarin nog niet hebben bereikt. Daarnaast is er ook toenemende belangstelling voor het gebruik van alternatieve vezels voor papierproductie, bijvoorbeeld het gebruik van agrarische residuen. De papierindustrie onderzoekt reeds de mogelijkheden van samenwerking met andere industriële sectoren, zoals de agrarische en de chemische industrie die zich richt op de productie van bio-chemicaliën en bio-plastics. Analyse van de technische en operationele mogelijkheden voor het gebruik van alternatieve vezels, evenals analyse van de impact van het gebruik van alternatieve vezels op de levenscyclus van papierproductie, zou een volgende stap kunnen zijn in toekomstig onderzoek. Gezien de lopende ontwikkelingen in de bio-based economy, ontstaan er ook kansen voor de papiersector ten aanzien van de levering van bio-based bouwstenen voor andere industrieën. Verder onderzoek naar de mogelijkheden die voortvloeien uit de valorisatie van reststromen uit de papierindustrie wordt aanbevolen, bijvoorbeeld de extractie van waardevolle componenten uit afvalwater en het gebruik van papierresiduen voor het genereren van bouwstenen voor bio-chemicaliën.
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Na 7,5 jaar is het dan eindelijk zover en is mijn proefschrift een feit! Al vanaf de start van mijn promotie in 2006, heb ik dit traject gecombineerd met een fulltime baan in de papierindustrie. Een combinatie die enerzijds ontzettend waardevol is geweest door unieke inzichten, toegang tot data, praktijkervaringen en realiteitszin die ik aan dit promotietraject heb kunnen toevoegen. Anderzijds heeft het combineren van een drukke baan met het schrijven van een proefschrift veel discipline en opofferingen gevergd, waarbij ik me enorm gesterkte heb gevoeld door de mensen om mij heen. Via deze weg wil ik deze mensen hiervoor bedanken:

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