Global CO_2 abatement potential in the pulp and paper industry up to 2030

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Summary

The aim of this research is to conduct an in-depth analysis of the Pulp and Paper industry. In essence the aim of this research is to analyze the technological options for CO2 emission reduction and their implementation potential by constructing CO2 abatement curves. Pulp and paper industry is one of the largest sectors globally and according to IEA is the fourth largest industrial consumer of energy. During 2004, 6.45 exajoules of final energy where consumed by Pulp and Paper industry, or 5.7% of the total industrial energy use.

Data will be analyzed from the major producing countries that constitute approximately 80% of the global paper and pulp production. These countries are the United States of America, China, Japan, Germany, Canada, Finland, Sweden, the Republic of Korea, Italy, France, the Russian Federation and Brazil.

Two different baseline scenarios have been examined in this research. These scenarios are the frozen efficiency scenario and the business-as-usual scenario. The main difference of these two scenarios is that in the frozen efficiency scenario the new stock efficiency is operating with similar efficiency to the base year (2005) while in the business-as-usual scenario the new stock consists of efficient state-of-the-art equipment.

In the Frozen efficiency scenario the overall energy consumption is estimated to rise at 14.1 EJ or increased by 67% compared to 2003. On the other hand, in the business-as-usual scenario the overall energy demand is 12 EJ. Compared to the frozen efficiency scenario the energy demand is reduced by 2.1 EJ or 14.8%.

The overall energy savings potential in the Frozen efficiency scenario is estimated to be 2.8 EJ, which represents 20.4% of the global energy demand of the pulp and paper industry in year 2030. These savings leads to 129.8 mtonnes CO2 emissions reduction. In the business-as-usual scenario the energy reduction potential is 745PJ or else the energy consumption is reduced by 6.2%. The CO2 abatement potential in this scenario is 35.6 mtonnes.

According to our results the greatest abatement potential, which is approximately 55%, is located in China’s pulp and paper industry due to two different reasons. Firstly the domestic industry is expected to drastically increase and become the dominant paper producer. Secondly the fact that China’s pulp and paper mills are operating highly inefficiently.

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Chapter 1

1. Introduction

1.1Background

A significant amount of total CO_2 emissions, approximately 36% (Holik, 2006), derives from manufacturing industries. The most energy intensive sectors of manufacturing industries are primary material industry, chemical, petrochemical, iron and steel, pulp and paper, cement, and other minerals and metals. This master thesis focuses on the pulp and paper industry. This industry is one of the largest sectors globally and according to IEA is the fourth largest industrial consumer of energy. During 2004, 6.45 exajoules of final energy where consumed by Pulp and Paper industry, or 5.7% of the total industrial energy use (IEA, 2008). Pulp and Paper industry has constantly increased; during the second half of the 20th century the overall paper consumption has doubled three times. From 1946 until 1987 the annual production growth rate was 4.12% since the global production has increased from 30 million tonnes to 214 million tones (IPPC, 2001). The following years the annual growth rate had decreased to 3.25% and the global production of 1997 had rise to 280 million tones.

The pulp and paper consumption is expected to growth the following years in the Asian region, where the income per-capita is rising, therefore, the share of the Europe and North America in global paper demand is expected to decline. Besides Japan paper production growth rate is estimated to rise. This increase in paper consumption is expected to be covered by countries with strongly growing economies such as the Republic of Korea, China, Brazil and the Russian Federation. Currently, these countries are highly inefficient and therefore the energy consumption and GHG emissions are expected to further rise (IEA, 2008). Recovered paper utilization was one of the main reasons for specific energy consumption reduction. On the other hand, regions where income per-capita is rising, are expected to improve recycling. The overall potential for additional energy efficiency improvement from paper recovery is limited (IEA, 2009).

Pulp and Paper industry CO_2 emissions intensity is relatively low compared to other industries, due to the bioenergy used. From an energy systems point of view however improving the overall efficiency of the sector can direct available bioenergy resources to other activities. The overall energy efficiency intensity of the Pulp and Paper sector can be significantly reduced leading to lower energy demand. According to the theoretical potential of Pulp and Paper industry, pulp and paper can be produced without emitting CO_2 if residues are used efficiently (IEA, 2008).

The most energy intensive stages of the industry are the mechanical pulping and the paper drying. The potential for adequate efficiency improvements exist in both areas (Smith, 1997). Moreover, in chemical pulping black liquor is produced and consumed for energy production with low efficiencies. Additional energy savings can be obtained from this activity, since new technologies where higher efficiency can be achieved, are available (Sixta, 2006).

Table 1 Statistical data for pulp and paper industries in thousand tonnes (2007)

		Paper and Paperboard	Pulp for Paper
1	**United States of America**	83,826	51,622
2	**China**	78,026	19,886
3	**Japan**	28,930	10,850
4	**Germany**	23,172	3,001
5	**Canada**	18,113	22,145
6	**Finland**	14,334	12,856
7	**Sweden**	11,902	12,402
8	**Korea, Republic of**	10,932	418
9	**Italy**	10,112	713
10	**France**	9,871	2,254
11	**Russian Federation**	7,559	6,830
12	**Brazil**	5,836	11,998
13	***Indonesia***	*7,223 (2,33%)*	*5,282 (3,30%)*
SUM (excluding Indonesia)		302,613	154,975
Global production		383,603	192,001
Percentage of major producers		78.89%	80.72%
Data retrieved from Food and Agriculture Organization of the United Nations database and all quantities are given in thousand tonnes (ktonnes)			

The technologies used for pulp and paper production vary among different regions. Determining and analyzing the technologies used in each region or country that produce pulp and paper; is hard to implement in this research and for that reason data will be analyzed from the major producing countries that constitute approximately 80% of the global paper and pulp production. These countries are the United States of America, China, Japan, Germany, Canada, Finland, Sweden, the Republic of Korea, Italy, France, the Russian Federation and Brazil (FAO, 2007).

1.2 Literature review

Various modeling approaches have been implemented in order to examine pulp and paper industry's energy, forestry use and emissions performance and reduction potential. Some of them are mostly focusing on the forestry sector, such as Global Forest Products Model (GFPM) (Tomberline et al, 1998) conducted by the Food and Agriculture Organization of the United Nations, the Global Forest Sector Model of the European Forest Institute (Kallio et al, 2004) and the World Forest Products Model (WFPM) (IPTS, 2006). A wide list of references in the literature is also focusing on modeling the pulp and paper industry but these works are mostly limited to specific countries or small regions, such as the NAPAP regional model which is focusing on the North American pulp and paper industry (Ince, 1998). Besides modeling Farahani et al. (Farahani et al., 2004) worked on the energy reduction potential on the USA and Sweden based on the black liquor gasification-combined cycle technology and Farla et al. (Farla et al., 1997) focused on the OECD countries by comparing their energy efficiency developments. Benchmarking studies also exist; these studies are trying to estimate the efficiency improvement potential by comparing their results to the best available technologies performance. These reports however, are typically carried out by consultants, and are mostly limited to specific countries and in most cases the outcome of their reports is confidential. The most important of this reports have been conducted from the Poyry, Paprican and IETS and these reports are focusing in Finland, Canada and the U.S.A. respectively (IEA, 2007).The International Energy Agency has also conducted a cross country indicator analysis in order to estimate the global and per country efficiency potentials (IEA, 2007). Finally, some reports were focusing on a broader field of industry, aiming on estimating the energy and emissions reduction potential. In this report other dominant energy consuming sectors were under examination as well. These reports were not in depth examining pulp and paper sector (Szabo et al., 2009, Akimoto et al., 202, Hoogwijk et al. 2010, ECN, 2007). In essence a significant amount of reports is dealing with the evolution of the pulp and paper industry and several forecasts exist. On the other hand an in-depth analysis of the technical, economic, and implementation potential in order to identify which technologies can be implemented; resulting to energy performance improvement and to the available potential below a defined cost have not been conducted.

Emerging energy technologies that can reduce energy consumption and lead to further CO_2 abatement potential have been developed. The main aim of this research is to examine and identify these technologies and their potential related to energy savings and CO_2 emissions. By constructing marginal abatement curves the CO_2 abatement potential that can be implemented cost effectively can be determined, while an insight in the relation of additional costs and further CO_2 reduction can be estimated. Cost curves for the most dominant pulp and paper producing countries have been conducted in order to examine the main characteristics of these countries and not only focus globally without high lighting the individuality and variety in each country's energy performance .

1.3 Problem definition

The aforementioned importance of the conduction of CO_2 abatement curves for the major industries is directly related to the problem definition of this case study. The Pulp and Paper industry is one of the major greenhouse gas emitters compared to the rest of the manufacturing industries. Additionally, the potential for CO_2 emissions reduction have not been examined adequately. In order to proceed to a less energy consuming Pulp and Paper industry, further investigation of the energy and greenhouse gases emissions potential is required.

The aim of this research is to conduct an in-depth analysis of the Pulp and Paper industry. In essence the aim of this research is to analyze the technological options for CO_2 emission reduction and their implementation potential by constructing CO_2 abatement curves.

1.4 Research Question

What is the global CO_2 abatement potential in the pulp and paper industry up to 2030?

Sub-Questions

-What are the energy consumption and energy intensities for the major Pulp and Paper production countries?
-What are the CO_2 emissions and CO_2 intensities for the major Pulp and Paper production countries?
-What is the business-as-usual scenario for the sector, and what are the CO_2 emissions and CO_2 intensities for this scenario?
-Which are the key processes and technologies in Pulp and Paper industry and which will be the technological options for CO_2 reduction available in the following years?
-What are the implementation potential and their CO_2 emissions avoided of these technologies?

The following chapter describes the main characteristics of the pulp and paper industry and its energy performance globally. In chapter 3 pulp and paper production processes are illustrated, the methodology used is given in chapter 4. An analysis of the various scenarios examined can be found in chapter 5. In chapter 6 an examination of the technological assumptions used in this research is given while the next chapter describes the technological measures taken into account in this research. The results of this work are depicted in chapter 8 and finally the last chapter includes the main conclusions and the discussion of the thesis.

Chapter 2

2. Pulp and Paper industry and Energy use

The Pulp and paper industry consists of a wide variety of production process and products. The differences among different counties and sometimes even among different regions are substantial. The product mix of each country affects the specific energy consumption, since energy demand for various products is not constant. Pulp is needed in order to produce each kind of paper or paperboard. Pulp used can be categorized in 6 different types. A list of the existing pulp options in global market and their shares in the global production can be found in the following table (Table 2).

Table 2 Pulp types and its share in global market

Pulp Types	Global Share (%)
Chemical Pulp	33,19%
Dissolving Pulp	0,88%
Mechanical Pulp	8,49%
Non-wood Pulp	4,94%
Semi-Chemical Pulp	2,64%
Pulp from Recovered Paper	49,86%
Total	**100%**
Data retrieved from Food and Agriculture Organization of the United Nations database and all quantities are given in thousand tonnes (ktonnes)	

The chemical pulp can be either sulphite pulp or sulphate pulp, sulphate pulp is mostly know as Kraft pulp and consists over 96% of the global chemical pulp use. The sulphite pulp is not taken into account in this report, since its' share is insignificant compared to the overall global pulp use. Furthermore, sulphite pulping is reducing its share and is replaced from other pulp types over the last years. Besides sulphite pulp, two more pulp types were not examined. These two types are dissolving pulp and non-wood pulp. Dissolving pulp is the pulp with the smallest partial in global production, while non-wood pulp is mostly used in China in relatively old mills that are replaced from modern mills over the last years. The modern mills entering China's market are not using non-wood pulp for paper production. Non-wood pulp consumption is expected to decline drastically due to environmental restrictions (Zhuang, 2006). Pulp products therefore, that were taken into account in this study are the following:

- Chemical (Kraft) pulp
- Mechanical (including chemi-mechanical)
- Pulp from recovered paper

The main products of papermaking industry are the following:

- Newsprint
- Packaging paper boards
- Uncoated printing and writing papers
- Liner and fluting
- Coated printing and writing papers
- Tissue
- Packaging papers
- Speciality papers

The aforementioned products shares on the global production vary significantly. In the European market the greatest part of paper consumption is packaging which is almost 40%, other products and their shares are newsprint with a 13% proportion, tissue with 6% share, and other graphic papers including both writing and printing with a share of 38% (IPPC, 2001). Each of these product types is produced by different manufacturing procedure, therefore the processes and the production routes for each product's manufactory has specific characteristics and properties.

From an energy point of view pulp from recovered paper is the most energy-efficient way for papermaking. Pulp market is different in various countries where some countries can be important recovered pulp importers/consumers while other countries can be great exporters/producers. This difference can significantly affect the energy profile of the countries, since countries with low energy efficiency performance may have lower energy consumption per product due to the high ratio of recovered pulp used per paper production.

The integrated production of pulp and paper is a critical feature of pulp and paper plants. Integrated plants are more energy efficient than stand alone pulp and paper mills, since transportation and drying of the pulp between mills does not occur. Integrated mills can reduce the overall energy consumption also due to the possibility of exploiting thermal use produced in a process to other processes. Limitations occur however, and the penetration of integrated mill to market cannot exceed a certain share.

Combined heat and power production can also drastically affect the energy profile of pulp and paper industry. Further penetration of combined heat and power in the pulp and paper sector will raise the energy efficiency in both thermal and electricity production, in cases where the excess electricity can be sold to electricity grid the energy and emissions benefits can be even larger.

Fuel mix used by the industry is also an important aspect related to energy consumption and emissions. Pulp and paper industry is characterized by comparatively low energy intensity due to the increased biomass ratio consumption for energy production. Once again, different product mixes occur among different countries and potential for additional emissions savings occur.

In this case study technological options that are commercially available will be taken into account; rising technological measures however, that are not commercially implemented yet are offering the potential for significant energy and emissions reduction, the most promising of these technologies are black liquor gasification, advanced drying technologies and biorefineries (IEA, 2009).

Finally, we should note that greenhouse emissions emitted from pulp and paper sector derive mostly from energy consumption. In essence emissions from various processes within the industry that are not related to energy use are insignificant compared to those deriving from energy consumption (EC, 2001). Thus in this report emissions from other sources will not be taken into account.

Chapter 3

3. Outline of process

The pulp and paper industry converts fibrous raw materials into pulp, paper and paperboard. The main steps involved in this conversion process are raw materials preparation, pulping, bleaching, chemical recovery, pulp drying and papermaking (IPPC, 2001). For the pulping process several technologies are currently used globally, these technologies are: chemical, semi-chemical, mechanical and waste paper pulping. Each of these pulping techniques has its own intermediate steps which are characterized by different properties; the pulp produced can be used for the production of various paper products. In most cases pulp is used in subsequent manufacture of paper and paperboard. Pulp can also be used for thick fibreboard production of products manufactured from dissolved cellulose. The typical raw materials preparation processes include debarking, chipping and conveying (Martin et al., 2001). The raw materials that can be used for pulp and paper production are wood logs or recycled used paper. Additional processes that can be used if necessary are de-inking and coating. The use of recycled paper as a raw material for paper production requires cleaning of contaminants before usage (IPPC, 2001). Furthermore, the recycled paper should be de-inked in some cases; the need for de-inking is based on the quality of the recycled paper and the quality requirements of the final product. A flow diagram of the main processes that take place in pulp and paper industry is depicted in Figure 1.

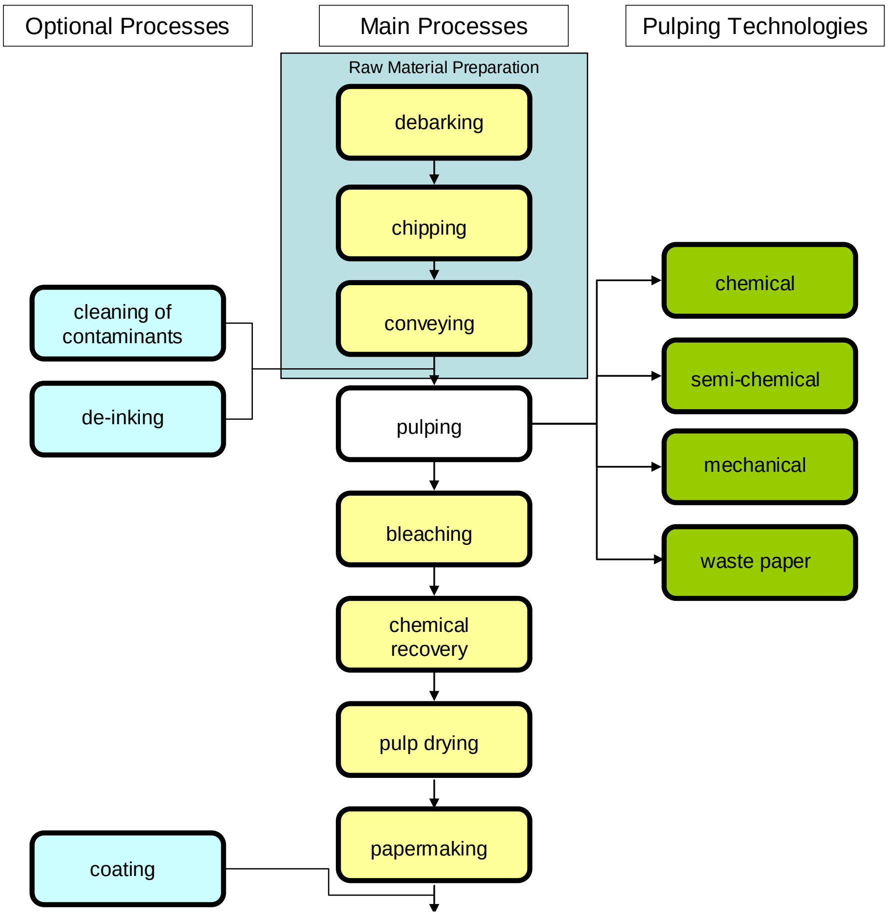


Figure 1 Flow Chart of Paper Production Process

3.1 Raw material preparation

Primary or secondary fibers are used as raw material for paper making. These fibers can originate from either wood sources or non-wood sources such as annual plants (e.g. straw). The typical raw material preparation consists of debarking, chipping, screening and conveying.

Debarking is the process where bark is removed from the logs. Debarking can be accomplished by using a rotating drum. The logs are placed on the rotating drum and are rubbed against each other while the bark is removed, this process is named drum debarking. Another option is the hydraulic debarking, which is a more energy intensive option (Holik, 2006). Another option is the dry debarking process, where the main characteristic of this process is the limited use of water resulting in a less energy intensive debarking method (EC,2001). Two main products derive from debarking process, the chips which are the main product and the bark that can be characterized as by-product. Bark can be used as a fuel or it can be sold off-site for other purposes. Bark is typically used as a fuel in burners for energy production. Other debarking methods that are being used are the following (Sixta, 2006):

- Rotary or cradle debarker

- Ring debarker
- Flail debarker
- Rosserhead debarker
- Mobile debarker

After the logs have been debarked, the chipping of the logs occurs in order to reduce logs size and produce chips; a typical option for chipping is the use of a radial chipper. The chips' quality is of high importance, since if the chips produced are not homogeneous, raw material consumption will increase. Furthermore, a homogenized chip distribution will improve the energy performance of the system (EC, 2001).

The next process is the screening of the produced chips in order to separate long size chips that are not adequately chipped; the screening process also contributes by removing sawdust. The recovered sawdust is also a by-product that can be burnt while the long size chips can be re-chipped in a crusher or re-chipper (EC, 2001). The screening process can affect the plant's performance. Optimizing the screening process can lead to the production of high-quality pulp and can improve the environmental performance of the mill by reducing pollution. In order to achieve the optimum screening performance however, raw material consumption should be increased.

Chips produced can now be transported to the next step which is pulping. Chips transportation is made using conveyors. Various types of conveyors exist, such as chain conveyor, roller conveyor, steel plate conveyor, vibrating conveyor, belt conveyor, scraper conveyor and screw conveyor (Sixta, 2006).

Storage facilities may be needed for storing materials or products in some cases; both raw material (wood) and chips produced may demand storage. Storage conditions are essential in cases where the material need to be transported.

3.2 Chemical pulping

The chemical pulp's main characteristics are the relatively better quality and the low-yield compared to other pulp products (Martin et al., 2001). Chemical pulp is mostly used for the production of high quality paper products such as office paper. Chemical pulping can be distinguished to sulphate (Kraft) pulping, sulphite pulping and semi-chemical pulping. The dominant type of chemical pulp used globally is sulphate (Kraft) pulping. From this point on when the term "chemical pulping" is mentioned it will indicate that sulphate (Kraft) pulping is considered.

The pulping process is also known as de-lignification process. In this process the incoming chips are pre-steamed in order to weaken the bounds connecting them; moreover, air captured within the chips is removed by pre-steaming the chips. After the chips have been pre-steamed and soften white liquor is added. White liquor is a highly alkaline solution that consists of sodium hydroxide (NaOH) and sodium sulfide (Na_2S) (Martin et al., 2001). The mixture subsequently enters digesters where it is cooked.

The wood components that are not fibrous are dissolved in cooking process and become separated from the pulp produced. The separation of the dissolved contaminants occurs at a blow-down low-pressure tank (Martin et al., 2001).Black liquor is produced from this process. The black liquor consists of degraded wood components and the spent black liquor that can be burned for heat production. The chemical additives used in pulping can be collected and reused in this stage. The pulp produced is washed out so it can be moved to the next step.

Pulp washing aims at obtaining pulp clean of undesired contaminants; this can be done by replacing the black liquor with fresh water. The main advantage of a modern chemical pulping process is the high recovery rates of organic compounds dissolved from chips that can be burned or further processed. An additional advantage is the increase of the chemical recovery substances' which also leads to better quality of the pulp produced. A crucial characteristic of this process is the fresh water use that should be optimized in order to improve the environmental performance of the plant.

The pulp is washed out and then, pulp screening takes place. The pulp is pressurized during this process. The screening process removes wood particles that have not been converted into pulp, such as dense sections from branches and heartwood (Sixta, 2006), remaining bark and chips that have not been adequately cooked and non-wood contaminants such as sand, stones or metal and plastic pieces (Sixta, 2006). The main benefits deriving from the screening process are the removal of undesired components that can reduce energy performance or even cause corrosion of the plant's equipment, the reduction of chemical consumption -which leads to both economic savings and optimized environmental performance-, and the improvement of pulp quality, which is crucial for paper products using chemical pulping.

3.3 Mechanical

The main difference between chemical and mechanical pulp is the yield ratio. Mechanical pulp is using 80% to 95% of the wood fiber, while chemical pulp uses approximately 45% to 55%. Mechanical pulping seems as a more favorable option from a material perspective, since the wood demand can be decreased by 50% for the same amount of paper production. The key characteristic of the mechanical pulp is that it is primarily used for the production of paper products where quality is not criteria major concern, (e.g. newsprint). Mechanical pulping is additionally the only option for processing recovered paper for pulp production. Several mechanical pulping techniques exist:

- Refiner mechanical pulping (RMP). Its key characteristics are the high yield and the fact that fibers are not too short. RMP can use chips as raw material which is processed by two grooved discs. The fibers produced with this technique are lighter than usual and thus the ratio of paper produced per wood use is increased compared to other pulping techniques.
- Stone groundwood pulping (SGW). This is the oldest pulping process. The energy demand of SGW pulping is the lowest compared to other mechanical pulping options, while its high yield is an additional advantage. The main drawbacks of this process are related to the fiber's size, and that SGW pulp need to be mixed with expensive chemicals due to their short size.
- Thermomechanical pulping (TMP). Fibers produced from TMP are the longest compared to those of other mechanical pulping techniques, thus its penetration to the market is increasing and TMP became the dominant type of mechanical pulping. Main disadvantages of this technique are the high energy consumption and the reduced brightness characteristics of the produced pulp.
- Chemi-thermomechanical pulping (CTMP). This technique is characterized by the use of chemicals in the refining process, the increased flexibility and brightness of the produced fiber which are the main advantages of this pulp type, while the major drawback is the relatively high energy demand.
- Recovered paper pulping. This process is comprehensively described in the next section due to its high importance in the industry's performance.

The main disadvantage of mechanical pulping is that it is an energy intensive process and that is the greatest energy consumer per product quantity compared to other pulping options. Some additional drawbacks are the relatively short fibers of pulp produced, the low ratio of impurities removal and the low strength and brightness characteristics of the paper products.

3.4 Recovered paper pulping

The pulp produced from recovered paper is also produced with mechanical techniques; recovered paper pulp however, offers the possibility of raw material use reduction due to recycling. Furthermore, the energy demand of this technique is considerably lower than that of all the aforementioned techniques. The environmental performance of this technique in general, is the most desirable by far. Landfilling is also reduced when recovered paper pulping occurs. Moreover, the cost of recovered paper pulping is the lowest, making pulp and paper producers keen to apply this technique. Water usage is also limited, thus increasing the environmental benefits of recovered paper pulping process.

For pulp production the recovered paper and hot water are added into a pulper. Mechanical and hydraulic pressure is required in order to dissolve the paper into fibers. Various pulper types exist and they can be divided into low consistency (LC), high consistency (HC) and drum pulpers (EC, 2001). Both continuous and batch digesters can be used in the pulping process. In the pulp production process contaminants are separated from the raw material paper, this contaminant should be removed in order to avoid equipment corrosion. Dirt taps are used for the contaminants removal, which is a continuous process, and the contaminants are rejected via conveyors (EC, 2001).

Solid wastes are produced from this technique. These wastes consist of both organic and in-organic components. In most countries the organic components are separated and are incinerated in order to reduce the solid waste amounts.

The recovered paper sorting demands human workload since it is a labor intensive technique, even though various efforts and attention have been made for the development of technological alternative measures (Sixta, 2006). Handling and storage of the recovered paper is also essential since its volume is significant and constantly growing due to the increase of recovered paper quantities.

Ink removal is a necessary process when recovered paper is used as a raw material. Various types of paper products such as newsprint, printing and writing paper and tissue demand pulp with high brightness characteristics. Besides the brightness of the produced pulp, the de-inking process also assists in reducing the stickies and improving the cleanliness of the pulp. The de-inking process takes place also in the pulper, where chemical additives are used for this purpose. For de-inking to be a successful process ink should be separated from the fibers and kept in dispersion. Flotation is then applied to the mix in order to adequately remove ink. Optional treatment of the produced pulp may be additionally needed such as ash removal and bleaching.

3.5 Bleaching

Bleaching is used for the removal of the remaining lignin quantities of the produced pulp. This removal will lead to improved pulp characteristics such as improved brightness, brightness stability, or increased cleanliness and strength of the produced pulp (EC, 2001). Lignin removal takes place also in other stages, such as cooking and oxygen delignification, but the desired lignin removal and the improvement of the pulp characteristics cannot be accomplished without further removal of the lignin and of the undesirable impurities. This further removal is accomplished within the bleaching process. Bleaching options can vary according to the desired characteristics of the paper product and to the chemical used (e.g. ozone, hydrogen peroxide, chlorine, enzymes and chlorine dioxide). This options variation leads to a variation of the energy demand for bleaching. The bleaching process consists of intermediate steps that are repeated within the towers (either up-flow or down-flow towers). These towers are also known as bleaching reactors.

Chemical additives are added to the pulp, lignin quantities are separated from the fibers, the chemical additives are taken away and the remaining pulp is washed. This pulp washing takes place in washers that can be either drum or diffuser washers (EC, 2001).The pulp needs further whitening which is accomplished through the additions of sodium hypochlorite, chlorine dioxide or hydrogen peroxide (Martin et al., 2001).

3.6 Chemical and Energy recovery

The chemical recovery process can actually be separated in three intermediate steps/sub-processes. These steps are the black liquor capture, the energy recovery and generation and the recaustization of the remaining liquor (Martin et al., 2001).

Evaporators are used for the black liquor capture in order to remove water quantities and increase the liquor ratio in the mixture. Two types of evaporators are used. Firstly, thermal energy in the form of steam is used at the Multiple Effect Evaporators, within which water is heated, converted to steam and removed from the black liquor. Direct Contact Evaporators are subsequently taking advantage of the excess thermal power contained in the boilers' exhaust gas for further water removal. The black liquor recovered from this water evaporation is then entering recovery boilers where the water removal is completed and the black liquor is burned and heat is generated. This produced heat is used for the smelting of the chemicals.

Green liquor (a mix of sodium carbonate and sodium sulfide) which is processed for white liquor production is produced from this method. Thus, white liquor recycling occurs, this liquor can be re-used in the pulping process. Lime (CaO) is another product of this process is and it can be used in the recaustization process.

The chemical recovery is an essential part of the pulp and paper production since great economical and energy savings can be achieved through it. Chemicals used within the process are recycled at high ratios and can be reused. As a consequence cost is reduced since additional chemical purchases are reduced.

Furthermore, the environmental performance of the mill is optimized. In addition the organic material of the mix is separated and its thermal value can be used in the whole process covering most of the heat demand. Modern plant facilities that maximize this energy generation can actually be self-sufficient due to the extended energy recovery. The cycle of chemical recovery process is depicted in figure 2.

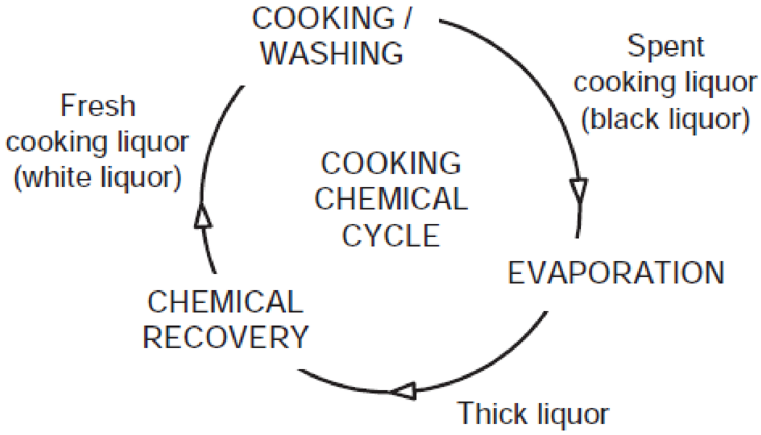


Figure 2 Chemical Recovery Cycle (Sixta, 2006)

3.7 Pulp drying

In cases where pulp mills are not close to paper plants, something that happens in most non-integrated plants, the pulp should be transported. After transportation and possible storage the humidity of the pulp is increased and pulp drying is needed before the pulp enters the papermaking stage. Additionally, the pulp should be processed in a pulper and in some cases re-pulped. This optional stage is considered as an energy intensive stage and therefore, integrated plants or co-located pulp and paper mills are much more energy efficient.

3.8 Papermaking

The papermaking process can generally vary significantly according to the desired characteristics of the paper products. Furthermore, machinery options for papermaking are not limited in the market. A general categorization of the intermediate steps that comprise paper making is the following:

1) Stock preparation: The pulp is blended, chemicals are added in order to create a homogenized uniform and continuous flow of the pulp which is called slurry

2) Sheet formation: Paper machines are used to create a web, where the pulp is placed. This web is called “paper web” since sheet formatting is the final step before paper is formed. The pulp is further dewatered in this section. Various paper machines exist in the market, some of them are suitable for thin sheet forming such as the

Fourdrinier paper machines while other types are suitable for thick or even multilayered sheets such as twin formers or cylinder board machines (Martin et al., 2001).

3) Finishing (pressing and drying): In the final step pressure is applied to the pulp, water is removed and the bonds between the fibers are getting stronger and thicker. Steam is needed to remove the remaining water after pressing section and then paper is formed.

The main parts of the paper machines are the following (EC, 2001):

- Head box (the fibers are suspended to the wire)
- Wire section (the paper web is drained in order to reach approximately 12-20% of solids)
- Press section (the solids content is increased to 50%)
- Drying section (the web is heated and paper web is formed)
- Reeler section (the paper is rolled)

Additional processes are needed in some cases according to the desired characteristics of the paper products. These additional processes may be sizing, coating or dyeing.

The specific energy consumption of each process varies significantly among different countries and some times even within the same country (e.g. new and old mills in China). Determining average energy consumption per process is thus, a challenging task and the given values are most likely not totally accurate. However, a table providing some typical energy consumption values can be useful, since an overview of each country's energy performance could be presented.

Table 3 Typical energy consumption per process for stand alone mills (EC, 2001)

	(kwh/t)	(GJ/t)
Processes	**electricity**	**steam**
Raw material Preparation	50	0
Bleaching	100-200	3.5-5
Ch. Recovery	50-150	6-10 *
Pulp Drying	10-50	4-5
Paper Making	500-1500	5-10
Pulping		
Chemical	300-600	3-6
Mechanical	1500-2500	0.5-2
Recovered	350-450	0.5-1

The chemical recovery can be an energy producing process but in this table only the energy requirements for the operation of the process are included.

Chapter 4

4. Methodology

Marginal abatement cost (MAC) curves will be used for the analysis of the available potential of energy savings and CO_2 emissions reductions. In order to optimize the environmental performance of an industry its management should be completely aware of the available beneficial technologies, their characteristics and their costs. This can occur by using MAC curves. By applying this management plan, the industry can have additional benefits besides the attainment of the emissions reduction target, since both the quality and the efficiency of the industry will be improved (Beaumant et al., 2004).

MAC curves are an essential tool that can be used for analyzing the technical, economic and implementation potential of a case study, this case study can range from a specific industry to higher levels such as the potential of a group of countries (Blok, 2007). When the environmental performance in the terms of emissions is the item of the case study (such as CO_2 emissions) MAC can be used for determining an analyzing the relation between a firm/sector/country emissions level and the cost or benefits of additional unit of emission reduction (McKitrick, 1999). This can be done by determining the exact cost effects of the technologies. In a policy level MAC curve can be used in order to assist a firm negotiates more efficiently with governments and regulators. This can be done by providing energy performance information to the firms to improve their environmental awareness (Beaumant et al., 2004).

Furthermore, MAC curves can be used to influence policy makers regarding large-scale energy-policy scenarios (Izquierdo et al., 2008). MAC curves have been used for the determination of the abatement costs and the reduction potential for various impact categories. MAC curves are used in order to identify which technologies can be applied and how much is the available potential below a defined cost. For constructing such curves all available and applicable technologies that can reduce CO_2 emissions in a specific case study should be ordered. Afterwards, an estimation of each technology's specific cost is made and then plotting the total cumulative emissions reduction in a diagram is needed. On the horizontal axis the cumulative emission abatement is given, while on the vertical axis the specific cost of each technology is given (Blok, 2007).

In order to construct marginal abatement cost curves the technological options are listed according to their cost of conserved energy values (CCE). CCE is determined by the change in annualized cost/benefits caused by implementing a measure, divided by the annual energy savings.

The formula used for the calculation of CCE is the following:

$$CCE = \frac{An.Inv + An.O\&M}{An.En.Sav.} - Ben._{(FUEL)} - Ben._{(EL)}$$

Where Annualized Investment cost (An.Inv.) is calculated as follows:

$$An.Inv = Inv.Cost * \frac{d}{(1-(1+d)^{-n})}$$

Where:

CCE: Cost of Conserved Energy (USD/GJ)
An.O&M: Annualized operation and maintenance cost (USD)
$Ben._{(FUEL)}$: Cost reduction from fuel use reduction (USD)
$Ben._{(EL)}$: Cost reduction from electricity use reduction (USD)
An.En.Sav.: Annual energy savings (concerning primary energy savings) (GJ)
Inv.Cost: Total investment cost (USD)
d: discount rate
n: lifetime of the technological option used (years)

The benefits deriving from implementing a measure is calculated from the following formula and can be applied to both electricity and fuel use:

$$Ben._{(x)} = \frac{Fuel\_use * Fuel\_price * Fuel\_Savings}{\mathrm{Pr}imary\_Energy\_Savings}$$

Fuel price: Price of the examined fuel in each country (USD/GJ)
Fuel savings: Energy savings derived from implementing a technological option (GJ)
Fuel use: Amount of each fuel type used per overall annual energy consumed (% as share of the total fuel consumption)
Energy consumption in pulp and paper industry is divided to fuel use and electricity use. When this formula is used for calculating the benefits from electricity savings Fuel use is equal to 1 (100%).

CCE prices could be either negative or positive. Negative values can occur when the benefits from fuel and/or electricity consumption reduction are greater than the annualized costs. The mean that measures with negative CCE values are cost-beneficial and can be implemented.

A discount rate selection is essential and can significantly affect the outcome of the equation. In this project 30% discount rate is taken into account in order to express the capital restraints and the measures limitation with short payback periods and high internal rates of return that are more desirable in the pulp and paper industry (Martin et al., 2001).

MAC curves can be used in essence for determining the cheapest solution for achieving an emissions reduction target and for implementing this via the most efficient route (Beaumant et al., 2004). MAC curves can assist by showing the abatement potential that can be achieved cost beneficially and, furthermore, by calculating the additional abatement potential that can be achieved within a defined cost/price (Worrell et al., 2004).Additional advantages of MAC curves are the fact that they can be applied in a broad field of cases and that they are rather straightforward to plot (Van Huuren, 1970).

MAC curves are not constant for each country, the differences between countries could be accrued to either the electricity and fuel prices or to differences in the electricity supply sectors. The same emissions reduction can result in lower costs in countries where electricity and fuel prices are relatively low. Electricity supply grids that are based on an emissions intensive fuel mix, such as coal and lignite, may achieve higher emissions reductions with reduced costs. The fuel mix within the industry can also affect the MAC curves, since different energy mixes are used in different regions (Criqui et al., 1999).

Chapter 5

5. System boundaries and data limitations

5.1 Timeframe

Defining the future potential of a sector requires the tracking and analysis of all the technological improvements. However, the appearance of new technological developments is most likely to occur in the following years since new technologies are expected to become commercially available and penetrate the market. A valid timeframe therefore should be stated in order to define what technologies can be taken into account. A time span of 20 years will constitute the timeframe of this research. Consequently, the target of this thesis is to determine the CO_2 abatement potential of the Pulp and Paper industry up to 2030.

5.2 Emissions

Greenhouse emissions emitted from the pulp and paper sector are stemming mostly from energy consumption. The missions from various processes within the industry that are not related to energy use are in essence insignificant compared to those deriving from energy consumption (EC, 2001). Emissions from other sources (e.g. emissions deriving from lime production in chemical pulping) therefore, will not be taken into account in this report.

The emissions under examination are strictly energy consumption derived and can be divided into two categories: emissions that occur on-site by fuel consumption and emissions due to consumption of electricity generated from the national grid. Primary emissions are taken into account and thus, second order values for the energy requirement for energy for different fuels is used (Table 4).

Table 4 Energy requirement for energy

Fuel type	Energy requirement for energy (MJ primary per MJ delivered)
Coal	1.07
Oil products	1.12
Natural Gas	1.03
Values taken from Introduction to Energy Analysis book (Block, 2007)	

Additionally, the electricity mix of each country is examined and primary emission factors have been calculated. Data for each country's energy grid related to the fuel mix have been used (Graus, 2008, OEE, 2010). For the electricity purchased from the grid the following emissions factors have been estimated.

Table 5 CO2 emissions factor for national electricity grids

Electricity emission factor (Kg/CJ)	
U.S.A.	60,73
Canada	21,25
Russia	33,00
China	76,74
Brazil	7,19
Japan	45,37
Korea	49,33
Finland	36,49
Sweden	2,15
Germany	53,54
France	6,08
Italy	55,99

5.3 Geographical

The technologies used for pulp and paper production vary among different regions. Determining and analyzing the technologies used in each region or country that produces pulp and paper is hard to implement in this research and for that reason data will be analyzed from the major producing countries that constitute approximately 80% of the global paper and pulp production. These countries are the United States of America, China, Japan, Germany, Canada, Finland, Sweden, the Republic of Korea, Italy, France, the Russian Federation and Brazil (FAO, 2007). The Indonesian pulp and paper industry is also one relatively of the most dominant producers and, according to the research proposal of this thesis was included in the countries examined. However, obtaining data for the Indonesian pulp and paper industry was an extremely hard task, since neither coherent energy data nor adequate information on the energy performance (e.g. specific energy consumption) were available. The Indonesian pulp and paper industry has been therefore excluded from the countries examined. This decision is not expected to significantly affect the results of this report since the remaining countries represent approximately 80% of the global pulp and paper production. Table 6 presents the production of the countries examined including Indonesia and their share related to global production.

Table 6 Statistical data for Pulp and Paper Industries in thousand tonnes (2007)

		Paper and Paperboard	Pulp for Paper
1	**United States of America**	83,826	51,622
2	**China**	78,026	19,886
3	**Japan**	28,930	10,850
4	**Germany**	23,172	3,001
5	**Canada**	18,113	22,145
6	**Finland**	14,334	12,856
7	**Sweden**	11,902	12,402
8	**Korea, Republic of**	10,932	418
9	**Italy**	10,112	713
10	**France**	9,871	2,254
11	**Russian Federation**	7,559	6,830
12	**Brazil**	5,836	11,998
13	***Indonesia***	*7,223 (2,33%)*	*5,282 (3,30%)*
SUM (excluding Indonesia)		302,613	154,975
Global production		383,603	192,001
Percentage of major producers		78.89%	80.72%
Data retrieved from Food and Agriculture Organization of the United Nations database and all quantities are given in thousand tonnes (ktonnes)			

5.4 Process Included

This research will focus on the industrial technologies and no additional steps will be analyzed. As a result the cultivation and production of wood will not be taken into account. The intermediate processes that take place within the pulp and paper industry have already been described in Chapter 3. For the calculations of this report a distinction of the most essential processes which are also the most energy intensive processes has been made. These processes are the following

- Raw Material Preparation
- Bleaching
- Pulping
- Chemical Recovery
- Pulp Drying
- Papermaking

Of those processes special attention is given to the Pulping and Papermaking processes. Specific energy consumption values for the various paper products fluctuate significantly considering the papermaking process. The Pulping process product is pulp for papermaking but the pulping process can be characterized by significantly different energy performance based on the fiber used for pulp making. Thus three types of pulping are taken into account:

- Chemical Pulping
- Mechanical Pulping
- Recovered Paper Pulping

Finally, the papermaking process can produce a multitude of different paper and paperboard grades and once again the energy performance of each paper type is different from the rest. The paper types taken into account are the following:

- Paper Board
- Kraft Paper
- Special Paper Products
- Packaging
- Printing and Writing
- Tissue and Sanitary
- Newsprint
- Other Paper Types

5.5 *Information on Data used and limitations*

5.5.1 Pulp and Paper Production

Pulp and paper data are taken from the Food and Agriculture Association (FAO) of the United Nations Statistical Database. The FAO Statistical database is available on-line at http://faostat.fao.org/, the statistical information on the database cover over 200 countries and territories. There is a list of subcategories, one of which is the Forestry domain (ForeSTAT) where the production, imports and exports of various wood, pulp and paper products are listed. All the aforementioned data are available for 244 different countries and regions.

The FAO Statistical Database is one of the most reliable sources for wood, pulp and paper production and trade information. The global capacity is adequately covered, since world total values are estimated including estimations for countries where comprehensive directories do not exist. Statistics are taken from members of the United Nations and are cohesive since the retrieved information is based on standardized questionnaires.

Data for two years retrieved for this report. Statistical information for year 2007 was the latest updated and available, and thus has been used in order to determine the market share and future estimations for 2030. Furthermore, 2003 data have been retrieved for calculating the specific energy consumption of each examined country. The year 2003 was selected due to the fact that the latest available data for the energy consumption in the pulp and paper industry are those of year 2003.

5.5.2 Energy consumption and balances

The energy profiles of the examined countries have been analyzed based on the IEA database Beyond 20/20. For each country in essence, the overall energy consumed from the pulp and paper industries have been used, these information were available for the year 2003. The energy consumed was divided in six different categories based on the fuel type used.

5.5.3 Specific energy consumption per process (SEC)

Aggregate values for the specific energy consumption per country have been determined by using the energy consumption of the pulp and paper industry aggregate values have been taken from the IEA database, combined with the production data taken from the FAO statistics database. This overall energy consumption has then been disaggregated to the various processes. Values for the energy intensity of the intermediate processes have been used for this disaggregation. The energy intensity values for each process are also mentioned in the literature as specific energy consumption per process (SEC per process) and is expressed as the energy consumption per ton of paper product. However, the SEC values for each process may vary significantly among different countries since additional parameters can affect the energy performance (e.g. use of integrated mills, pulp type, CHP use, type of paper products). A literature survey has been conducted therefore for each country, in order to investigate the regional characteristics of the various countries and estimate the intermediate SEC values. For four countries SEC values per process have been reported, these values have been cross checked with the SEC country values and insignificant differences were detected. These four countries are the U.S.A, Canada, Brazil and China. For the rest of the countries SEC per process values have been estimated based on the SEC per country values and the average energy details for various processes reported at the European Commission's report "Reference Document on Best Available Techniques in the Pulp and Paper Industry" (EC, 2001). The energy use of each process is divided to fuel energy consumption and electricity consumption, these two energy consumption types consist the SEC per process

5.5.4 Electricity production and fuel mix of the industry

The fuel mix varies among different countries leading to different CO_2 emissions per ton product. Additionally, power generation in different countries have different fuel mix shares. Therefore, the specific CO_2 emission factors per country are not the same. Furthermore, the energy used within the industry is divided to fuel use and electricity use. Therefore, two different emission factors are estimated for each country, one related to emissions deriving from electricity production and allocated to the national grid and one concerning the average fuel mix of each country. For estimating these emission factors information for the energy grids have been used, these information have been retrieved from Natural Resources Canada organization, Office of Energy Efficiency (www.nrcan.gc.ca) and from a report conducted by Ecofys, entitled 'International comparison of fossil power efficiency and CO_2 intensity' (Graus, 2008). Fuel information taken from Beyond 20/20 database is distinguished to six different types. Four of those are used in boilers for energy production (coal and coal products, petroleum products, natural gas and combustible renewable and waste). In Appendix I the fuel type used are given.

Biomass use as fuel for heat or electricity generation within pulp and paper industries is a critical aspect of the industry. Some byproducts of the various processes may be used for energy generation such as bark residues and liquor. In this report a biomass emission factor equal to zero is used since biomass is considered to be a renewable energy source.

An average fuel mix per case is used in the calculations of this project. Some of the measures considered in this report may be applied to a certain process in order to reduce the energy consumption of the process but additional energy savings can be achieved in other processes as well. Treating these energy savings separately in order to allocate the energy savings per process is expected to be difficult if not impossible.

5.5.5 Prices

Fuel and electricity prices for the pulp and paper industry are different from the commercially available prices in some countries. This happens due to policy regulations in order to promote and assist pulp and paper production. In countries where prices for the pulp and paper industry were available are taken into account, while for the remaining countries fuel and electricity prices are taken from the International Energy Agency Key World Energy Statistics (Poyry, 2009, China Energy Database, 2008, IEA, 2007).

Table 7 Electricity and fuel prices

	Electricity	Natural Gas	Oil Products	Coal
U.S.A	***13,70***	***8,36***	7,36	0,86
Canada	13,61	6,09	7,56	3,67
Russian Federation	11,61	2,33	3,10	9,31
China	***18,65***	***8,36***	6,77	0,80
Brazil	21,39	10,34	4,49	9,18
Japan	29,07	10,46	10,62	1,84
Republic of Korea	18,94	12,03	12,28	1,37
Finland	***16,55***	***11,37***	9,35	2,08
Sweden	***15,22***	***17,81***	21,85	2,38
Germany	***23,02***	***10,28***	7,62	2,38
France	***20,93***	***11,78***	7,60	1,87
Italy	***34,25***	***11,51***	8,85	1,11

Values are given in $/GJ. U.S.A. dollars 2005 are taken into account.
Values that are specified for Pulp and Paper industries are given in Bold Italic

5.6 Stock turnover and retrofit measures

This research is taking into account the affect of stock turnover. Stock turnover is used to describe the replacement of old capital stock that is retired with new stock. Stock used over the years wears out, get damaged and finally is getting inefficient. The time period during which equipment can technically operate before it must be replaced is called technical lifetime. Technical lifetime is an important aspect when the abatement potential is examined since, when stock is replaced by new stock is common to have significant changes in operational characteristics such as costs, productivity, efficiency and energy consumption. Finally stock turnover and the implementation of retrofit measures are the methods used for improving energy efficiency in industry and a distinction between these two methods should be done. The technical lifetime of pulp and paper industries equipment is assumed to be 30years (Worrell et al., 2005).

Chapter 6

6. Baseline scenarios

The main driving force for estimating the trends in the paper demand for different countries is related to the income per capita; and it is mentioned in the literature as the 'intensity of use' hypothesis (van Ruijven et al., 2008). This hypothesis can be applied in long term models (IPTS, 2006), since the per capita income and the demand for materials is not expressed by a single elasticity but their relation changes over the time.

The material intensity performance is strictly related to two phenomena. Firstly, is related to the demand side where consumers and their behavioral are prevailing in changing the share and composition of the materials demand in the market (Mannaerts, 2000). This phenomenon occurs due to the income consumption of the final user, in a wide variety of commodities and products. The main characteristics of the consumers behavior is the income level, the products prices and the individuals' preferences (Mannaerts, 2000). Secondly, producers' side is affecting material intensity performance. This occurs due to their selection of commercial products, their change consumption can modify the trends in the material intensity. The main characteristics of the producers side is the technological development and the raw material prices (Mannaerts, 2000). These two phenomena constitute the domestic use of materials and products and affect the material demand in the market. Historical data related to the Intensity of use hypothesis (expressed as material use per income per capita) depict the intensity of material use as an inverted U curve. This curve appears when the time period corresponds to tens of years. In figure 3 (Mannaerts, 2000) the material use per income for the U.S.A. market depicted is revealing the inverted U curve of material use over the years.

By examining the trends in figure 3 three intermediate phases differentiate. Firstly, due to the innovation and the rapid economic growth the material use is rising; since new applications of materials are penetrating the market, while their prices are relatively declining. The second phase is characterized by consumers' saturation which leads to the stabilization of the demand. Finally, the material intensity declines due to both substitution of the materials and to the use of new innovative materials with improved characteristics and material efficiency.

Critics of this phenomenon consist of three main arguments, the important role of economy's transition, the re-allocation of the materials production and the substitution of materials. Economy's transition in essence, is related to the national development characteristic. Initially, a country is characterized by low income and the domestic activity is agriculture, thus material demand is relatively low. The next phase of development is based on heavy infrastructure which is a material intensive phase. Secondly, the low material intensive service sector is developed while infrastructure needs have been stabilized or reduced. Re-allocation of materials argument is based on the increased imports of materials from industrialized countries. However, this argument seems to be false when data related to material use are examined (Mannaerts, 2000). Finally, uncertainties occur to the role of substitution among different products, in this report -where the paper products are the case study- the arguments are related to the impacts of the digital technology, the regulation of packaging materials, the efficiency of material use, and the waste policies which may lead to substitution of paper products from other kind of materials.

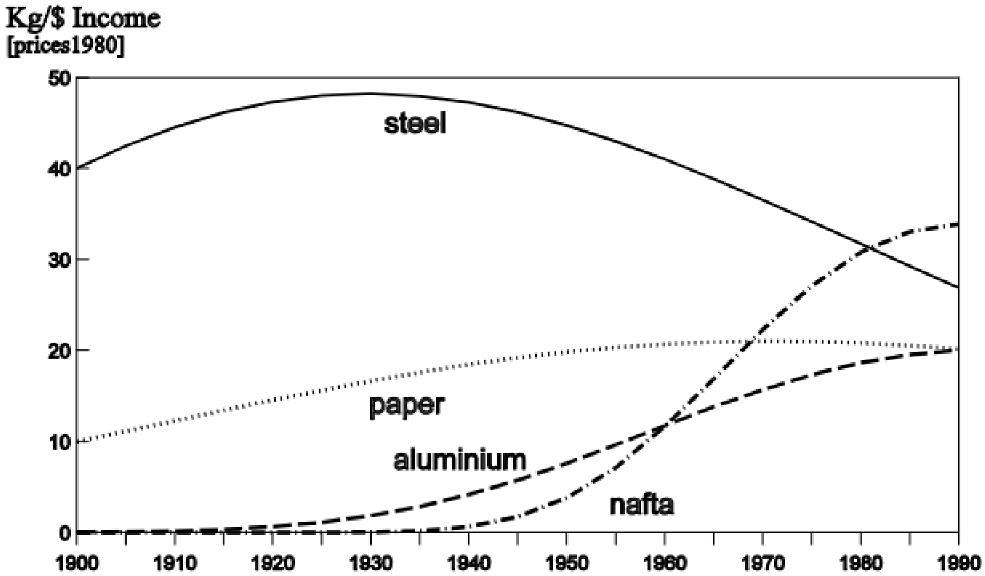


Figure 3 Material Intensity in the U.S.A.(Mannaerts, 2000)

From the twelve countries examined in this report, Japan and Sweden seem to approach the saturation limits and their material intensity performance is expected to remain moderate or even decline. The remaining countries are either developing and their material intensity is expected to rise, or are developed but have not approached the saturation limits yet.

A simplified generic model has been constructed to forecast the pulp and paper industry's basic characteristics for the year 2030. Certain factors have been used in order to build up this model. These factors are the main driving forces of the pulp and paper market operation and are essential for forecasting the future structure of the industry. First of all, per capita income has been used in order to express the commodity intensity for the selected countries, in terms of GDP growth rate and population growth rate. A dematerialization factor has also been used to express the reduction of paper consumption per GDP; this factor is estimated according to literature and is extensively described in the following sections. Next, the product factor is introduced in order to distinguish the differences in the demand between various paper product types; since different trends for various types are expected the following years. Finally, a producer country factor have been estimated and used in this forecast. The producer country factor has been used to express the substitution among different countries in the pulp and paper production based on literature. The primary outcome of this model is the overall pulp and paper production for the year 2030. Using these primary results, the emission and energy performance for 2030 is estimated for different scenarios.

The base year for this forecast is year 2007 since the last available data for pulp and paper production were for year 2007.

The intermediate factors and their abbreviations are the following:

- GDP g.r. (GDP)
- Population g.r. (Pop)
- Dematerialization factor (Dem)
- Product factor (Prod)
- Producer country factor (Cou)

6.1 GDP growth rate (GDP)

Growth rate values have been retrieved from the United Nations online databases (available at http://data.un.org/), in order to determine the intensity of pulp and paper demand population. The population growth rate of the countries are given for 5-year time spans, and thus an overall growth equivalent for the period 2007 – 2030 has been estimated. These figures have been combined with the average estimated GDP growth rate values which have been retrieved from the JRC report 'Development of a Model of the World Pulp and Paper Industry' (IPTS, 2006). GDP growth rate is not available per country but for certain regions, therefore a classification of the dominant pulp and paper producing countries in these given regions has been made.

In this report the first two factors used are the GDP growth rate and the population growth rate. These two factors are used to determine the demand in 2030 without considering the dematerialization phenomenon. The dematerialization phenomenon is entering the model with the introduction of the dematerialization factor.

6.2 Dematerialization factor (Dem)

The dematerialization phenomenon based on the saturation of consumers demand mentioned previously, is expressed by the dematerialization factor. This factor is taken from the JRC report and is calculated based on the paper demand per GDP projections for year 2030 for a list of regions. This factor in essence is used to describe the fact that after a certain level of GDP per capita growth, the material demand per income growth rate is declining. Values for this factor have been retrieved from the JRC report 'Development of a Model of the World Pulp and Paper Industry' (IPTS, 2006).

6.3 Product factor (Prod)

The product mix of pulp and paper industry consists of a wide variety of wood and raw materials, which are used for pulping. Different types of pulp are used for papermaking, where different kinds of paper products are produced. These changes on product types' demand are not expected to develop uniformly, since each type of material or product is affected by its characteristics.

The raw materials used for pulping are strictly related to the availability of sources and the price evolution (CEPI, 2008). While the demand for paper products is rising the demand for raw materials will also rise. Therefore the share of different types of raw material in global market will change. The raw materials in surplus are expected to dominate the market. On the other hand, raw materials with limited sources are expected to have a significant increase in their price, as a result their share in the global pulp market will decline. These changes are expected to modify the shares of countries in pulp and paper production, (this change will be explained in the following section). The changes in raw material use have not been examined in this report. Concerning the changes in product shares, this reported is limited to paper products and recycling characteristics, since the pulp and paper use is much more important than the wood type used as a raw material.

Similar differences will be observed in the pulp market. The main driving force of this change is the availability of recovered paper and its price. Furthermore changes in wood price are also expected to affect the pulp market. The effect of recovered paper but will be further analyzed later on with the implementation of different scenarios regarding the practical limits of paper recovery and the existing trends.

Paper products shares in the market are also expected to differentiate. The main driving forces for these upcoming changes are the following:

- The significant reduction in newsprint demand due to the high penetration of the digital technology in both the developed and the developing countries.
- The digital technology is expected to reduce printing and writing paper demand, but not as dramatically compared to the newsprint products.
- The use of paper in the packaging products and the coated papers is expected to decline due to the regulation of packaging materials, the efficiency of material use, and waste policies.
- Moderate changes in market share are most likely to occur to paper products where the paper quality is of high importance, such us sanitary tissue and speciality paper products.

The product factor used in this report is aiming on approaching these changes in the market shares of the various paper products. This is essential for forecasting the energy performance of the pulp and paper industry since the energy demand per paper product varies significantly. The various paper products are

6.4 Production Country factor (Cou)

Another factor that is expected to affect the shares of global share among different countries is international trade. Demand and supply in each country is expected to evolve; based on the future price differences between imported and domestic paper products, raw material and pulp types will occur. The pulp and paper sector in not homogenized and the trade between countries is widely interconnected. Eventually, some countries are expected to be more competitive and play a dominant role the following years, while other regions may reduce their productivity and their shares are expected to decline. Furthermore, the availability in resources and the domestic demand of products are expected to change the global map of the pulp and paper industry. Some countries will manage to operate more productively in pulp production, while other countries would limit their industry in paper production by importing raw materials (IEA, 2009).

According to estimations from the IEA and Poyry, the regions where pulp and paper industries are expected to growth rapidly the following years are Eastern Europe, most Asian countries except Japan and Latin America (IEA, 2009). On the other hand, countries and regions where the pulp and paper industry is already widely expanded, such as the European Union and Japan, are expected to moderate increase their consumption. These develop regions will manage to be competitive the following year, due to their decent energy performance (pulp and paper industries within these countries are the pioneers related to low energy intensive techniques), Thus their decent energy performance will assist them on remaining competitive the following years, since fuel prices are expected to rise. Finally, the pulp and paper industries on North America are not expected to be competitive enough the following years, since they are not performing efficiently and their production costs are expected to be significantly higher than those of industries located in developing countries. Therefore, some estimation about future performance of North Americas pulp and paper sectors, are forecasting that their share in the global market is expected to decline (IEA, 2009). As a conclusion, the expected trends show that a portion of paper consumption will be re-allocated form North America to Asian and Latin America countries (excluding Japan) while European share of global paper production is expected to fluctuate at the present level.

Therefore, the production capacity factor is introduced in order to implement these changes in paper products shares between the examined countries.

6.5 Limitations

Additional factors that are expected to affect the pulp and paper industry development exist but unfortunately could not be implemented in this model. The prices of the paper products and the intermediate material used for paper production are crucial for understanding the market's trends. Raw material availability, such us different type of woods or recovered fiber, can affect their prices and in addition can modify the shares between the raw material producing countries. Furthermore, the prices of the paper products are affecting their demand and their penetration in the global market. The price evolution and its importance in forecasting the performance of pulp and paper industry is not taken into account in this forecast.

Concerning the forecast of emissions, fuel mix should also been considered. Oil and gas prices are expected to increase while coal and coal product prices rise is expected to be moderate. Therefore, coal share in industrial use may rise substituting less emission-intensive fuels. On the other hand, policy regulations may limit the coal use in favor of less emission-intensive fuels or even to neutral-emissions fuels. The fuel share parameter is also not taken into account in this forecast.

The twelve countries that where under examination for determining the energy performance of the pulp and paper industry, are also taken into account for forecasting the industry's structure at year 2030. As mentioned above, the different characteristics among different regions lead to changes in development of the domestic industries. Thus, the pulp and paper market cannot be treated as a homogenized industry and different 'production country factors' are used for each country. Developing countries such India which is expected to act dominantly in the pulp and paper global market, should also be taken into account; however the geographical limitations used for the base year are also used for forecasting, since the deriving outcomes are homogenized and comparable between the selected time periods.

6.6 Recycling

Another aspect that demands special attention is the use of recovered paper as raw material for pulping. Once again, the recovery rates vary among countries and limitations on recovery occur. Every time fiber is recovered and reprocessed its strength and quality is further reduced. As a result, a maximum limit of recycling at 5 or 6 cycles of recovery occurs (CEPI, 2006).

On the other hand, when pulp form recovered paper is used the cost is reduced (comparing to the virgin pulp). Additional benefits of recycling are the improved environmental performance of the mill and the low energy demand. Therefore recovered fiber is raising its share in the market, since more and more firms are moving towards recovered paper use and as a result recovered paper prices are also expected to rise. This increase in recovered paper demand is also affected from the increased demand of paper production.

Paper recovery schemes and its statistics also vary between countries. Developed regions are pioneers in paper recovery, Europe is recycling over the half of the paper consumed and some countries in Europe are reaching the practical limits of paper recycling. On the other hand, paper recovery schemes in other regions are not that developed (Jokinen, 2005).

Therefore, the paper recovery in this work is treated by applying two different scenarios. Firstly, the pulp from recovered paper use in the paper making is assumed to growth similar to the paper production. This assumption is based on the fact that paper recovery schemes effectiveness remains constant and the amount of recovered paper is strictly related to paper productions. Therefore, paper recovery rates for 2030 are those of year 2007.

Next scenario assumes that paper recovery rates growth is similar to GDP growth, since countries where income is rising rapidly are countries with not that strict recycling policies but are expected to develop their paper recovery systems in the following years. On the other hand, developed countries have already adequate recovered paper policies and further growth will be moderate.

All twelve countries are examined separately since practical limits on paper recovery occur. According to Poyry the practical limits of paper recovery approximately 65% of the total paper consumption (CEPI, 2007). Countries which have already recovery rates close to the practical limits are assumed to continue operate at that level. Recovered paper growth rate for the rest of the countries is assumed to growth similar to its nation estimate GDP growth rates until year 2030. Countries that will reach the practical limit of 65% will be stabilized at that rate.

6.7 Paper production in 2030

The following figures and results are estimated for the twelve dominant paper producing countries. Paper production in year 2003 which is the base year was 266 million tones, until 2007 the global production was 303 million tones and based on the calculation of this study, the paper production for 2030 is estimated to be 383 million tones. Concerning the dominant producers China is expected to significantly enlarge their capacity while the U.S.A. and Canada industries are expected to reduce in size.

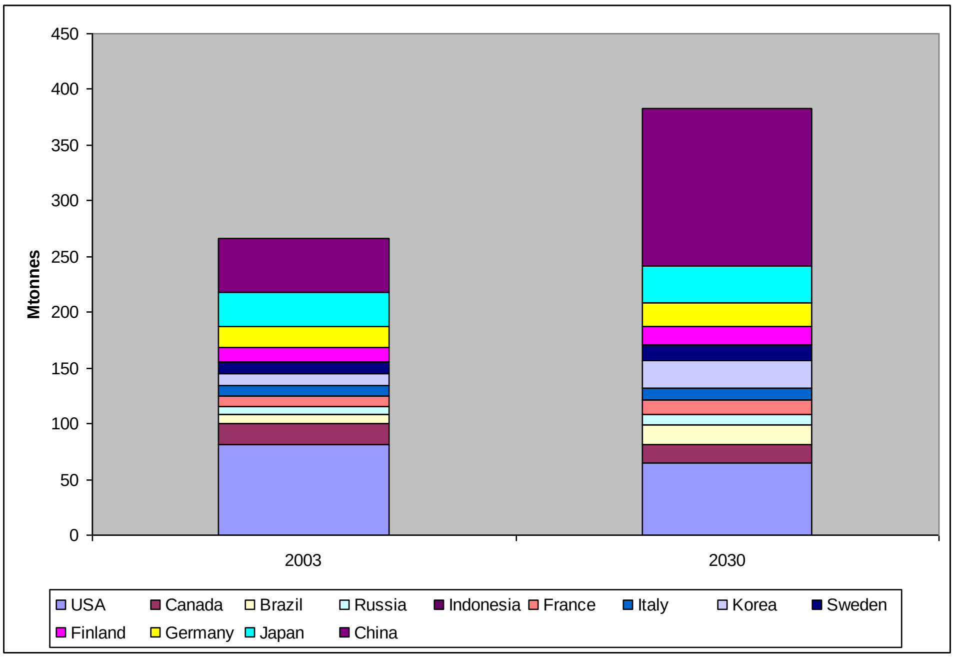


Figure 4 Paper production per country for 2003 and 2030

Figure 4 depicts the share of various product types for year 2003 and our forecast for year 2030. While next figure represents the difference in market pulp on 2030 based on the two scenarios used about recycling.

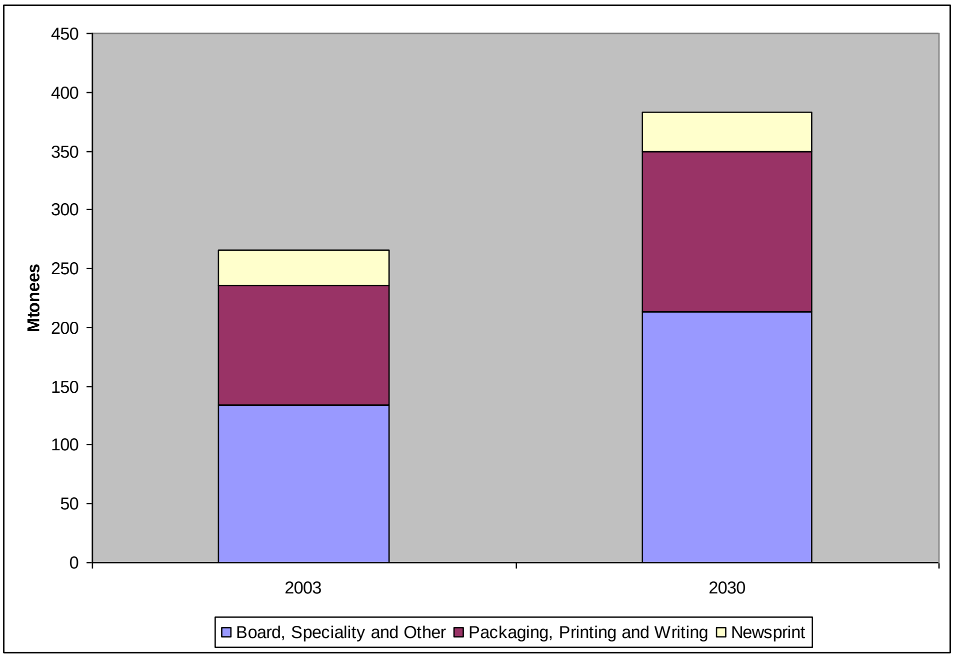


Figure 5 Paper production per paper product for 2003 and 2030

Calculating the share of the various paper products in the market a change in the categorization of the paper products have been made. Gathering information related the future share of the seven categories distinguished initially in this research. Therefore a separation on three grater categories has been made in order to limit the uncertainties.

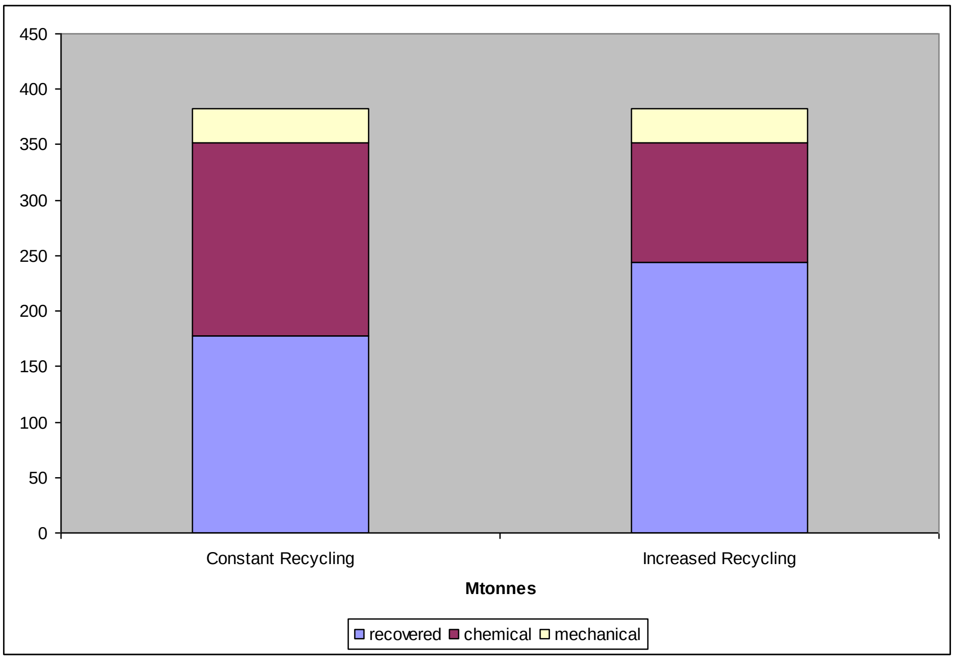


Figure 6 Pulp demand per pulp type for 2030

6.8 Baseline energy scenarios

Two different scenarios have been chosen for examining the global CO_2 abatement potential. The first scenario used is the frozen efficiency scenario. The main assumption made in this assumption is that all the new stock in pulp and paper industry will perform with similar energy efficiency to the existing stock. The new stock is divided to expansion stock that is used to cover the increasing demand in pulp and paper products, and the stock turnover which is used to replace retired stock. As mentioned above this new stock is assumed to perform with the same characteristics compared to existing stock, therefore in each examined country the average specific energy consumption values will remain constant and equal to 2003 SEC values.

Next scenario is the business-as-usual scenario. The main assumption made in this assumption is that all the new stock in pulp and paper industry will be based on modernized equipment. In essence, the new stock state-of-the –art-technologies will be implemented. These technologies will be economically competitive and will consume less energy compared to retired technologies. Therefore it is assumed that the new stock includes all the retrofit measures examined that are proven economically feasible.

Chapter 7

7. Technological measures

7.1 Mechanical Pulping

7.1.1 Refiner improvements

Modifications that can improve the performance of the refiner in a mechanical pulp mill occur. This improvement in performance is related to the electricity reduction potential of various measures. Some of these measures are the following. A refiner control strategy to minimize variations in the freeness of ultra-high-yield sulfite pulps which can reduce the electricity consumption due to reduced motor load (Tessier et al., 1997). The usage of conical refiners instead of the common used disk refiners is an additional promising modification that can be implemented on a refiner, the main benefit of the conical refiners is that electricity demand can be reduced by decreasing the consistency of the pulp produced (Alami, 1997). However the reduction of pulps consistency may cause an increase in energy consumption in the papermaking process. Moreover by applying conical refiners, fibers can be developed to the desired quality (IPST, 2006). As described above the implementation of this measures results to electricity savings which are estimated at 0.81GJ/t and a capital cost of 7.7$/t pulp while the annual operating cost change is estimated at 2.6$/t (Martin et al., 2001).

7.1.2 Heat recovery in TMP

In thermomechanical pulping another important technological option can reduce the energy consumption of the process; heat that is used for this process can be recovered and re-used. This technological measure can be applied especially to older mills where pressurized refining occurs but heat recovery is lacking, since nowadays most modernized thermomechanical pulp mills already include heat recovery equipment. However, this technological option is hard to be implemented on mechanical mills that are not performing efficient, thus in order to consider heat recovery energy efficient equipment should be already installed (FOE, 2005). The potential for heat recovery derives from the significant amount of steam that is produced as by-product when mechanical pulping is produced. This steam produced even though is contaminated and low-pressure can be re-used in some other process. The contaminated low-pressure steam can be captured and via direct contact heat exchangers can produce refining energy in the form of high-pressure clean steam and/or hot water (FOE, 2005). This refining energy produced can be used in the papermaking process via hot water used on the paper machines and on the steam plant by heating make up air in the boilers. Additional options that can be implemented in integrated mills include the recompression of steam used in the mechanical pulping process which can be used in paper drying at the paper machine dryer section (Kramer, 2009). Finally equipment such as thermo vapor recompression and cyclotherm plus heat pump systems can also be used for capturing and turn to account the by-product steam (Kramer, 2009). This technological measure benefits, is the additional steam produced which can be translated in heat consumption reduction, the estimated fuel savings are 6.05 GJ/t. The electricity demand of the process is estimated to be slightly increased by implementing this measures, this difference is estimated at 0.54GJe additional consumption per ton product. The overall additional cost in form of installation, operations and maintenance costs varies at the literature, for this report the capital cost is estimated at 21$/t while the annual operating cost change is estimated at 18$/t (Martin et al., 2001).

7.2 Chemical Pulping

7.2.1 Continuous digesters including modifications

Technological options that can reduce the energy requirements and improve the operation process exist also for chemical pulp mills. The technological options that taken under consideration in this report are related to the digesters that are used for cooking the chips to produce fibers. This process is one of the most intensive steam consuming parts of the paper industry. Two types of digesters are operating in pulp making, batch and continuous digesters. In essence continuous digesters are more desirable in an environmental point of view and from an energy reduction perspective. The main benefits related to the use of continuous digesters are the following:

- heat recovery possibility due to continuous flow of materials and thus improved energy performance
- more space efficient
- computer control can be applied in order to monitor performance
- labor requirements are less intensive
- optimized operating conditions that reduce the digester corrosion
- pulp produced is of higher strength resulting in increasing paper quality and quantity

However some drawbacks also take place such as the increased number of pumps and fans needed, the lower capital cost and the lack of flexibility. As a result there are some cases, such as mills with low capacity, where the applicability of continuous digesters is not feasible. In this report the digesters' technological measure includes the replacement of batch digesters when applicable and the modifications of existing continuous digesters. The modifications of batch digesters are not taken into account.

Possible modifications that can be applied on continuous digesters are the implementation of control systems in order to improve the process operation by modifying various parameters. Some of these parameters are the liquor to wood ratio that can be minimized and the waste heat recycling that can be improved. Furthermore, additional adjustments can take place such as the application of heat exchangers for heat recovery purposes, optimizing the steam recovery process and improving the insulation in order to reduce the energy losses (Martin et al., 2001). The overall energy improvement occurs due to reduced demand for steam and thus for fuel in the chemical pulping process. This difference is estimated at 7.27GJ/t. Continuous digesters require 0.27GJe/t additional electricity to operate. Finally, a capital cost of 197.3$/t pulp is estimated, while the annual operating cost change is estimated at 0.2$/t (Martin et al., 2001).

7.3 Chemical recovery

7.3.1 Lime kiln modifications

Technological improvements can take place also in the chemical recovery process of the pulp making. In this report the most well-known technology which is the lime kiln modifications is considered. The lime kiln process is the process where quicklime (CaO) is produced. Several modifications can be applied for achieving energy reduction such as the appliance of high efficiency filters in order to reduce the moisture in the incoming materials which will reduce the energy demand for evaporation. Another technological modification that can be implemented is the upgrading of heat transfer in the kiln by installing chains or high efficiency refractory bricks. Heat contained in the exhaust gases can be captured and reused for preheating the inputs such as lime and combustion air. The implementation of these measures results to further benefits since the recovery rate of lime from green liquor can be improved. The savings achieved by implementing these measures are related to fuel consumption and are estimated at 0.46GJ/t, the electricity performance of the kiln is not expected to change. The capital cost is estimated at 2.5$/t pulp (Martin et al., 2001). Additional modifications that are not considered in this report due to lack of data but are estimated to further improve the energy performance of the process are the usage of pressure filters for solids separation from liquors (Francis et al., 2009) and the oxygen enrichment of the incoming air stream (FOE, 2005).

7.4 Papermaking

7.4.1 Extended nip press (shoe press)

Part of the papermaking process is the drying procedure where after paper is formed water is removed. Initially water is removed mechanically by applying pressure to the formed paper and when no further amounts of water can pressed out water is removed thermally. The mechanical water removal if significantly less energy intensive then the thermal-drying process, therefore a decrease in water concentration of the formed paper can result to overall reduction of energy consumption (Kramer et al., 2005). The mechanical dewatering process can be improved by applying extended nip press; the well known technology that is broadly used is the application of pressure by using two felt liners pressed between two rotating cylinders. The extended nip press technique increases the area of pressure, reduces the dwell time during the pressing procedure and thus increases the water removed quantities by approximately 5%. Extended nip press consists of a large concave shoe that is replacing one of the two cylinders. Additional advantage of this technology is that the capacity of the paper plant can be increased since the maximized fiber concentration results to relatively reduced load on the drying section. This change in the dryer load can increase the capacity by 25% on cases where the paper production is limited by the drying section. Further advantages of this process are the better sheet properties and productivity, enhanced strength and sheet consistency that can result to lightweighting and fiber replacement, therefore extended nip press is mostly used in mills which are more interested in product characteristics and less in energy reduction (FOE, 2005). The overall energy improved occurs due to reduced demand for steam and thus for fuel in the paper making. This difference is estimated at 1.6GJ/t. while the overall electricity performance of the paper plant remains constant. Finally, the capital cost is estimated at 38$/t pulp while the annual operating cost change is estimated at 2.24$/t (Martin et al., 2001).

7.4.2 Reduced air requirements

A considerable difference in the energy performance of various paper machines exists, paper machine where the hoods are enclosed and are not additional parts (canopy hoods) are much more preferable from an energy consumption perspective since steam demand per water ratio can be declined to approximately 50% (Kramer, 2009). As a result, the fuel-heat consumption is significantly reduced since less air needs to be heated. Additional energy savings can be achieved by implementing this measure since the electricity consumption is also reduced. These technological adjustments are applicable to all paper product grades including board and tissue products (FOE, 2005). The savings achieved by implementing these measures are related to fuel and electricity consumption, the overall fuel energy savings achievable by applying this measure are estimated at 0.76GJ/t, some additional savings can be achieved by reducing the electricity consumption if an optimized ventilation system and a closed hood system installed, these electricity savings are estimated at 0.02GJe/t. Differences also occur at the costs due to the measure implementation, the additional capital cost are approximately 9.5$/t while the additional operational and savings costs are 0.07$/t (Martin et al., 2001).

7.4.3 Waste heat recovery

There is a significant amount of energy contained in the exhaust air of the hood which is not adequately turned into account, some modifications that include proper maintenance of the equipment and extensions of the existing papermaking system can increase the percentage of the hood exhaust which can be reused at the papermaking process. Once again heat recovery technology can be applied to reclaim this amount of excess energy. Various alternatives of heat recovery systems can be applied, such as air to air, air to water and air to glycol systems (FOE, 2005). These aforementioned systems can be combined and applied together, either in a single system or separately in order to maximize the heat recovery potential (FOE, 2005).Various techniques can be implemented in the papermaking process in order to recover waste heat and steam heat and reuse their thermal energy. One option can be considered the replacements of common dryers used on the paper machine with stationary siphons; this technique helps the drying procedure to perform more efficient. Another option also applied in the drying section applies mechanical vapor recompression in order to reuse superheated steam. Heat pumps can also be implemented in the drying section for capturing and reusing excess steam. The main drawback of this technique is the additional operational and maintenance cost since all this system demand cleaning of the equipment on a periodic basis. Additional thermal savings can be found on the ventilation air of the drying system, this amount of heat can be reused beneficially in other facilities of the plant such as heating when applicable. Heat recovery potential can be located on direct-fired air dryer hoods, the exhaust air of these hoods has a thermal amount that can be captured and re used in order to rise the temperature of the air entering the combustion chamber. By applying this system the fuel demand of the burners can be declined, this kind of hoods is mostly used on tissue and toweling machines. Finally, additional energy savings can be obtained from this hoods by implementing an economizer in order to reclaim heat from exhaust air and use it to the for high pressure showers section of the paper machine by heating the incoming fresh water. There are no electricity savings by implementing this measure but the heat consumption can be limited by 0.5Gj/t. As mentioned above the operational and maintenance cost will be higher in this case, this difference is estimated at 1.6$/t while the installation cost are estimated to be 17.6$/t of paper.

7.4.4 Energy efficient vacuum systems for dewatering

Vacuum pumps and vacuum systems is an essential part of the paper machines, such systems that do not operate efficient enough can increase the energy losses related to water removal within paper manufacturing sector. High inefficiencies often occur due to adjustments and changes that took place since the vacuum system was new. In essence this kind of adjustments could be changes in furnish, chemistry, headbox consistency, retention, and forming and press fabrics (Kramer, 2009). Vacuum system optimization can be achieved following system modifications, operational changes, and even removal of some vacuum pumps (Kramer, 2009). This modification can be implemented with no capital cost and negligible operational and maintenance cost while the energy benefits of this measure are related to the reduced electricity consumption of 0.2GJe/t.

7.5 General Measures

7.5.1 Efficient motor systems

Motor systems are the most energy consuming sector of an average pulp and paper mill. A system approach should be used in order to perform an analysis of both the energy supply and energy demand, in order to examine their relation for optimizing motor performance. This will result not only to energy savings but to further beneficial changes related to productivity and system uptime. The intermediate steps of a proper system approach are the following:

-Location and identification of mills motors

-Recording of motors characteristics and forming an inventory

-Determination of whether the motors are properly sized and if are suitable to meet the system demands

-Determination of potential upgrades and repairs (including cost and energy requirements)

-Implementation of the beneficial upgrades

-Monitoring of the motor systems' performance

The measures that can be applied as part of the system approach mentioned above are the following:

By determining a proper motor management plan the energy performance of the motor systems can be optimized. This can be achieved by selecting of suitable motors according to various performance characteristics such as motor speed, horsepower, enclosure type, temperature rating, efficiency level, lifecycle cost, and quality of power supply. This selection of more efficient motors will decrease energy demand through improved design, better materials, tighter tolerances, and improved manufacturing techniques (Martin et al., 2001).

Proper maintenance of the motors can assist to prevent unexpected downtime of motors, include electrical consideration, voltage imbalance minimization, load consideration, and motor ventilation, alignment, and lubrication. Furthermore, proper maintenance can operate as a predictive measure by monitoring ongoing motor temperature, vibration and other operating characteristics in order to be determined when a replacement or overhaul of a motor is essential prior a failure took place.

Motors size is essential for reducing the electricity consumption on pulp and paper mills. Where peak loads on driven equipment can be reduced, motor size can also be reduced. For motor selection software packages exist and can further assist in proper size selection.

By implementing adjustable speed drives the speed operation of motors can be adjusted to load demands in order to maximize the energy consumption of motors.

Low power factors can increase the power consumption of a plant; therefore by correcting the power factor energy savings can be achieved. This correction can occur by minimizing idling of motors since motors on idle state result to ineffective energy consumption. In essence by replacing motors with premium-efficient motors, adding capacitors in the AC circuit, selection of large horsepower motors the power factor can be optimized.

Finally voltage unbalances can be optimized for further energy savings. Voltage unbalance leads to current unbalances that can cause torque pulsations, increased vibration and mechanical stress, increased losses, and motor overheating (EC 2001). The electricity savings that can be obtained by optimizing motors performance is estimated at 0.62GJe/t, the installation costs of those measures are approximately 6$/t paper produced (Martin et al., 2001).

7.5.2 Pinch analysis

Pinch analysis can be characterized as process integration tools, pinch analysis can be used to identify the energy savings potential according to minimum theoretical limitations of the system. However, the usage of such a tool should be treated cautiously since certain limitations occur. Some of the outcomes derived from the pinch analysis may seem reasonable but due to high capital costs cannot be implemented. Furthermore, some of the pinch analysis suggested techniques may be beneficial when implemented with the aforementioned expensive measures (Francis et al., 2009). Even though there are some drawbacks the pinch analysis offers the possibility for estimating energy savings plans without applying trial-errors techniques. Additionally, the determination of the theoretical minimum energy potential can act as an influential motivation for reducing energy performance (Francis et al., 2009).

Pinch analysis is based on the correlation of heating and cooling potential which is represented by the development of “composite curves” which are used to signify to the thermal profile of the system and alternative profile for the process of the mill (Kramer, 2009). In essence the composite curves when are drawn on a temperature-enthalpy graph the optimum point with the closest temperature approach can be determined. At that point the maximum theoretical savings for heating and cooling occur. After identifying these energy targets the heat exchangers network can be re-designed to achieve the heating-cooling optimum performance. Finally, the final outcome is selected according the equilibrium of capital costs and energy benefits for achieving the desired return of investment. The measures applied based on pinch analysis results are not limited to conventional well-known techniques (heat recovery from exhaust gas, insulation and steam trap techniques). Additional advantages of the pinch analysis measure is that water usage is also optimized leading to minimizing wastewater, plants effluent can be reduced, and finally this measure can be applied to both new paper plants and to existing plants as retrofit measure. Electricity savings do not occur when pinch analysis is implemented but fuel demand is assumed to be reduced by 1.8GJ/t. The capital cost is estimated at 8$/t paper while the operational and maintenance cost are not affected (Martin et al., 2001).

7.6 Efficient steam production and distribution

7.6.1. Boiler improvements

Boiler improvements measure is an aggregate of intermediate measures that can be applied on boiler sector of a pulp and paper mill. In the following paragraphs the techniques that are used in this report are briefly described while at the end an amount of additional measures that are referred in literature but not taken into account in this work are listed.

1-Improved process control

Boiler performance can be improved by monitoring flue gas, monitoring process can assist in locating both leaks in the boilers and insufficiencies in fuel burning. The boiler leaks can be traced when oxygen amounts are recorded in the outcoming flue gas. Oxygen on flue gas can is a result of either excess air usage or possible leaks, in most cases both leakages and excess air occurs. The usage of excess air can be purposely introduced for safety reasons or for emission reduction purposes. The leakages however, are undesirable and can be eliminated by installing intake airflow and an oxygen monitoring system. Furthermore, monitoring systems can be used to locate CO emissions or smoke in the flue gas which means that air quantities are less than needed to perform optimum fuel burning. Therefore a proper monitoring system can improve the fuel to air ratio resulting to desirable flame temperature. The optimum flame temperature will not only reduce energy losses but will reduce pollutant emissions such as CO. The capital cost of this measure is hard to be returned when monitoring is implemented in relatively small boilers ant thus improved process control is suitable for large boilers.

2-Boiler maintenance

Periodic and appropriate maintenance can significantly reduced boiler losses and sustain high efficiencies on boilers for longer periods. The wear out of boilers and the lack of boilers' adjustment that can be accelerated when maintenance is inadequate, can reduce the boilers efficiency by 30% of initial performance within a period of two or three years (Kramer, 2009). Adequate proper maintenance can achieve energy savings of approximately 10%. Undesirable emissions in exhaust gas can also be declined.

3-Flue gas heat recovery

Steam systems such as boilers are a good opportunity for heat recovery. Captured heat can be used for preheating boiler's incoming water. Heat recovery is directly related to the wall temperature since when high temperature is not achieved acids of the flue gas can be dewed. This can be optimized by preheating the feed up boiler's water due to the high heat transfer coefficient of water. This technique is much more beneficial from an energy point of view than the common technique of maintaining flue gases at significantly high temperatures (over the acid dew point). Limitations exist also in this measure since in clean fuel boilers corrosion risk is higher.

4-Blowdown steam recovery

Common procedure in boilers operation is the boiler's blow down. In order to keep steam system water properties at desired levels boiler blow down is essential. A significant thermal potential is located in steam that often is not used when blow down occurs. Even though blow down steam is low grade, its thermal value can be used in other sectors of the plant such as space heating and boiler water preheating. Thermal potential exists and be captured and reused on the liquid blow down that is rejected (Kramer, 2009).Additional advantages of this measure is that corrosion in steam piping system can be reduced.

Several additional techniques for energy reduction on boilers exist but are not taken into account in this report. These measures are reduction of flue gas quantities, reduction of excess air, improved insulation, condensate return, minimizing boiler blow down and burner replacement

For this report an aggregate fuel reduction for the techniques described above is assumed at 2.28GJ/t while the capital costs are estimated at 1.54$/t and the operation and maintenance cost at 0.28GJ/t (Martin et al., 2001).

7.6.2 Steam trap optimization

Steam trap can be optimized with various techniques such as proper maintenance, monitoring and by improvement of the current equipment use. Steam trap improvement can reduce energy consumption and losses by implementing modern thermostatic element steam traps. Additional benefits of these traps are the improvement of systems reliability, system discharge when temperature rises to saturated steam levels, purge of non-condensable gases with each opening and reduction of steam warm up time period. The compatibility of these traps with a wide variety of steam pressures is a supplementary advantage. Steam trap maintenance can further increase energy savings since annual failure rates can be around 10% (Martin et al., 2001). Finally monitoring systems can be applied to steam trap sector can optimize the energy performance of the system. The fuel savings of this measure are estimated to be 2.68GJ/t, with a capital cost of 2.47$/t, the operation and maintenance cost will also rise by 0.22$/t (Kramer, 2009).

7.6.3 Install and Use Real Time Energy Monitoring Systems

Substantial energy savings can be achieved when accurate real time monitoring takes place. Monitoring has been already mentioned in some aforementioned techniques since energy monitoring is critical part of a plants performance. Monitoring effects can be optimized when energy performance of a facility is treated as process that can constantly improve, as soon as an amount of measures and adjustments are applied, it is crucial to start re-planning the oncoming energy performance program. A complete monitoring system consists from equipment, software and most important form management practices. Monitoring can be part of most sectors within a plant and various characteristics should be monitored such as (FOE, 2005):

- Steam flows
- Electricity consumption
- Fuel consumption
- Water consumption/use
- Temperature
- Condensate return

Several aspects of a mill should be into consideration and not only the energy performance, e.g. quality, productivity, maintenance and safety since focusing strictly to energy performance may lead to possible drawbacks on other domains. Frequently monitoring, even in hour basis and regular reporting of the measurements, followed by determination of certain reduction targets and repeatedly review from managers and operators can maximize the gains of monitoring (Francis et al., 2009). The main gains expected from this measure is the reduction of time needed for complex tasks (Kramer, 2009) and optimization of processes. Monitoring systems can be implemented to all process but is not suggested in domains where the energy consumption is not intensive such us wood yard since payback period is expected to be undesirable. However, in intensive energy consuming process such as evaporators and paper machines this measure is expected to be cost-effective (FOE, 2005). Energy savings of this measure are assumed at approximately 2.64 GJ/t while the capital, operational and maintenance cost is estimated at roughly 3.1$/t (FOE, 2005).

In countries where energy performance is significantly un-efficient the energy savings of these technologies may be relatively bigger. In literature there are information on characteristics related to the aforementioned technologies that are given in difference percentage compared to the initial state e.g energy consumption is reduced by certain percentage. On the other hand most of the information used in this research is taken from sources where the energy reduction given in exact physical units (GJ/t product). When these technologies are applied to different industries where the specific energy consumption varies significantly the given energy savings in terms of GJ/t are not equal to those defined by a reduction percentage. However the specific energy consumption of most countries does not fluctuate significantly, except from Russian Federation and China where energy consumption is considerably greater. For those two countries the additional alternative scenarios have been examined where the energy reduction of the measures has been adjusted.

In table 8 the energy savings and the cost of conserved energy. Since differences in fuel and electricity prices occur among countries the overall CCE values is different for each country. In the following table the values given for CCE do not include benefits from fuel and/or electricity savings. The calculated CCE prices for each country are depicted in Appendix II and III where domestic and global MAC curves are given.

These technological measures are applied to each country. The rate of implementation chosen is not the same for all countries. These technologies are commercially available and are already implemented, countries that are performing efficiently are assumed to have limited implementation potential since new modernized mills are assumed to apply these measures.

Table 8 Technological measures for energy reduction

Technological Measures	Fuel savings (GJ/t)	Electricity savings (GJ/t)	Cost of conserved energy (USD/GJ)
Pulping: Mechanical			
Refiner Improvements	0	0,81	3,05
Pulping: Thermomechanical (TMP)			
Heat Recovery in TMP	6,05	-0,54	3,27
Pulping: Chemical			
Continuous Digesters (with Modifications)	7,27	-0,27	7,41
Chemical Recovery			
Lime Kiln Modifications	0,46	0	1,63
Papermaking			
Extended Nip Press (shoe press)	1,6	0	5,96
Reduced Air Requirements	0,76	0,02	2,61
Waste Heat Recovery	0,5	0	9,77
General Measures			
Efficient Motor Systems	0	0,62	1,55
Pinch Analysis	1,79	0	0,95
Steam Production and Distribution			
Boiler Improvements	2,28	0	1,19
Steam Trap Maintenance	2,68	0	1,29
Energy Efficient Vacuum Systems	0	0,2	0
Real Time Energy Monitoring Systems	2,64	0	1,59

Chapter 8

8. Results

In this chapter the results of this research are presented. These results are calculated for the dominant pulp and paper producing countries that represent approximately 80% of the global pulp and paper production globally. The energy and CO_2 emissions reduction potential are given for the examined scenarios. Related to the future energy performance of the pulp and paper industry two different scenarios have been examined. Firstly, the global energy consumption for the year 2030 is calculated according to the frozen efficiency scenario and then, the business-as-usual scenario results are presented. Furthermore an additional scenario is introduced, where the global energy consumption is calculated based on the increased recovery rate assumption. The first two scenarios are introduced in order to describe the impact of changes in the energy efficiency. In the increased recovery rate scenario the energy performance of the mills is similar to business-as-usual scenario but differences exist in the pulp demand. The influence of combined heat and power production is not examined in this research and thus is not included in the results.

8.1 Energy consumption in the various scenarios

In the Frozen efficiency scenario the overall energy consumption is estimated to rise to 14.1 EJ or increased by 67% compared to 2003. This increase occurs due to the capacity expansion since the specific energy consumption of the industry is assumed to remain constant. In the business-as-usual scenario the product mix and the demand for paper is the same with the frozen efficiency scenario. However, the stock replaced due to retirement of the equipment and the new plants penetrating the market in order to cover the additional demand perform more efficiently according to the assumptions made for the business-as-usual scenario. Thus, the overall energy demand in 2030 is 12 EJ. Compared to the frozen efficiency scenario the energy demand is reduced by 2 EJ or 14.8%. Finally in figure 7 an additional option is depicted. In this last option, which is the least energy intensive, the specific energy consumption of the mills and the pulp and paper demand are equal to those of the business-as-usual scenario, however the pulp share is different. Due to a possible increase in recovered paper use for pulp production the share of energy intensive pulp is declined. The energy demand in this scenario is estimated at 10.6 EJ for year 2030. The difference between the business-as-usual scenario and the increased recovery rate scenario is 1.4 EJ. The energy reduction in these scenarios do not include savings from implementing retrofit measures.

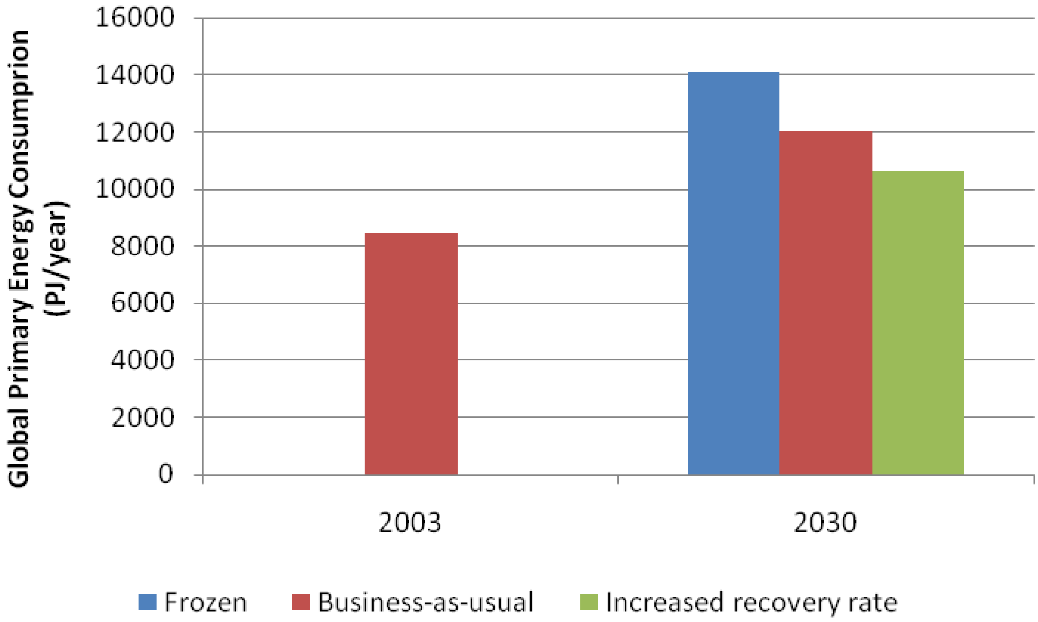


Figure 7 Global energy consumption for frozen efficiency, business-as-usual and increased recovery rate scenarios

8.2 Savings potential

The global savings potential in terms of both energy and CO_2 reduction are presented in this section.

8.2.1 Saving potential relative to the frozen efficiency scenario

Firstly, in Figure 9 the energy savings potential of the examined retrofit measures for the frozen efficiency scenario are presented. The overall energy savings potental is estimated to be 2.8 EJ, which represents 20.4% of the global energy demand of the pulp and paper industry in year 2030.

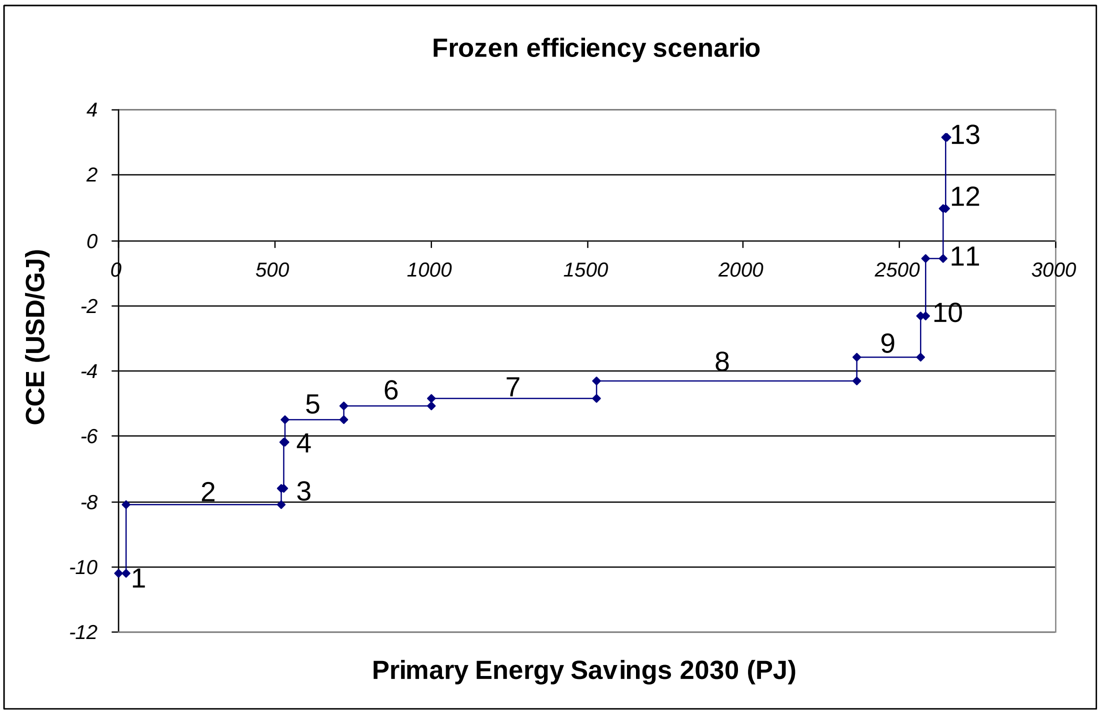


Figure 8 Energy savings potential for the Frozen Efficiency scenario

In Table 9 the saving potential of each examined measure is given. In axis X the cummulative energy savings are given while in axis Y the average CCE value for each measure is given. The average CCE prices have been selected since the values for each measure are not the same in each country. Measures presented with positive values in Figure 8 are in most countries expensive and not beneficial. However in limitated cases this measures have a lower CCE value and thus they can be implemented cost-effectively. Furhter information for each measure can be found in Appendix II where the saving potential is presented in more details since the energy savings are given for each country.

Table 9 Energy savings potential for the Frozen Efficiency scenario

	Type of Measure	PJ
1	Energy Efficient Vacuum Systems for Dewatering	22.4
2	Efficient Motor Systems	499.4
3	Lime Kiln Modifications	5.3
4	Refiner Improvements	4.7
5	Pinch Analysis	190.5
6	Boiler Improvements	279.9
7	Steam Trap Maintenance	526.7
8	Install and Use Real Time Energy Monitoring Systems	834.2
9	Reduced Air Requirements	202.6
10	Heat Recovery in TMP	19.4
11	Extended Nip Press (shoe press)	56.1
12	Continuous Digesters Including Modifications	7.6
13	Waste Heat Recovery	0.8

Most of the measures (1 to 8) have negative CCE prices in all cases, therefore these measures can be applied in all countries. CCE values of the heat recovery in

TMP, the extended nip press and the continuous digesters are different in each country. In countries with low electricity and fuel prices these measures are beneficial and can be applied while in countries with higher prices not. Finally, waste heat recovery is by far the most expensive measure and can be applied only in one case (Sweden) where the prices are relatively high. Similar trends occur also in the business-as-usual scenario.

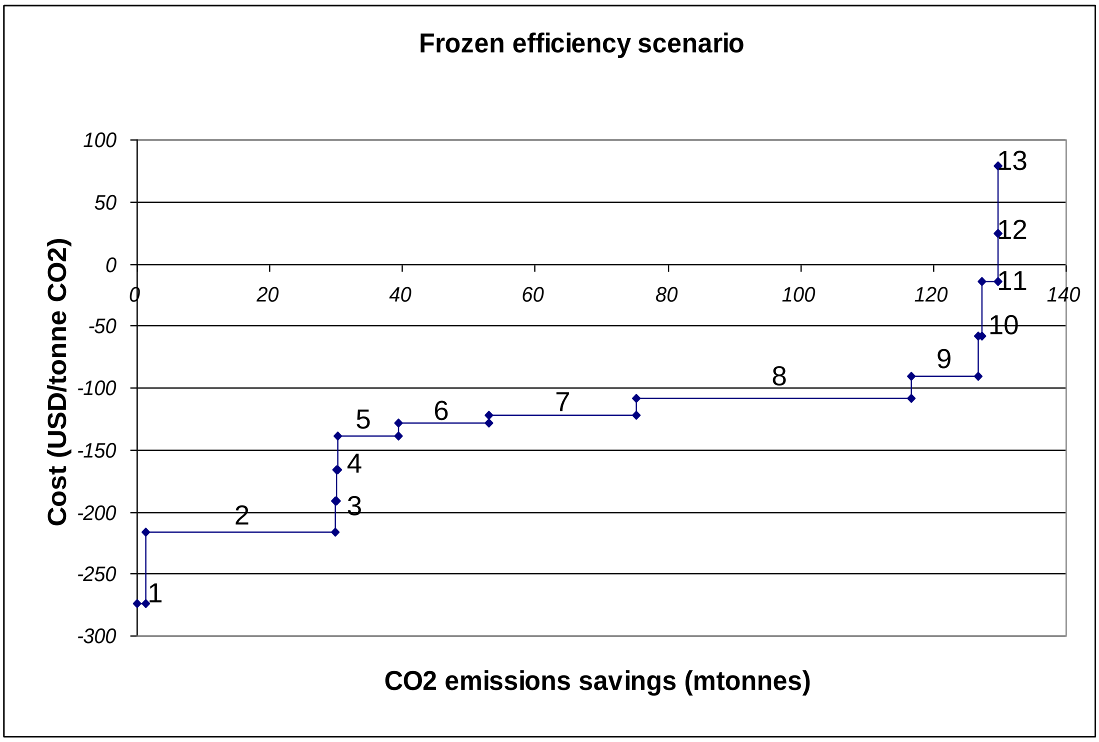


Figure 9 Energy savings potential for the Frozen Efficiency scenario

In Figure 9 the CO_2 reduction potential of the retrofit mesures is depicted. The CO_2 reduction potentials of the various measures are similar to the energy reduction potential as expected. In Table 10 details for each measure's CO_2 emissions savigs potential is given.

Table 10 CO_2 emissions saving potential for the Frozen Efficiency scenario

	Type of measure	CO2 emissions savings (mtonnes)
1	Energy Efficient Vacuum Systems for Dewatering	1.3
2	Efficient Motor Systems	28.6
3	Lime Kiln Modifications	0.2
4	Refiner Improvements	0.2
5	Pinch Analysis	9.0
6	Boiler Improvements	13.6
7	Steam Trap Maintenance	22.4
8	Install and Use Real Time Energy Monitoring Systems	41.4
9	Reduced Air Requirements	10.1
10	Heat Recovery in TMP	0.5
11	Extended Nip Press (shoe press)	2.3
12	Continuous Digesters Including Modifications	0.1
13	Waste Heat Recovery	0.0

8.2.2 Saving potential relative to the business-as-usual scenario

In Figure 10 the estimated global energy consumption and the further energy reduction potential for the business-as-usual scenarios is depicted. The blue bar corresponds to the business-as-usual energy consumption in year 2030, the overall energy is estimated at 12 EJ as mentioned before. The energy reduction deriving from the application of the various retrofit measures is depicted with the red bar and estimated at 11.2 EJ. The additional energy reduction is 0.8 EJ or else the energy consumption is reduced by 6.2%. Finally, the total savings potential that can be achieved when best available techiniques are taken into account is 3.9 EJ since the overall energy consumption for the countries examined is estimated at 7.4 EJ. For estimating the total savings potential all the examined retrofit measures have been taken into account, including those that are not cost effective.

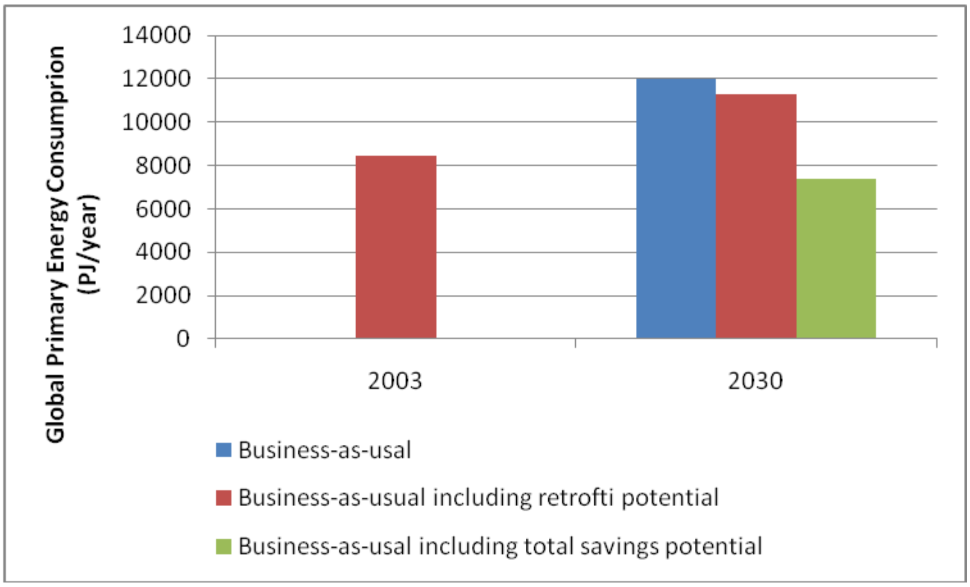


Figure 10 Global energy consumption for business-as-usual including retrofit and total savings potential

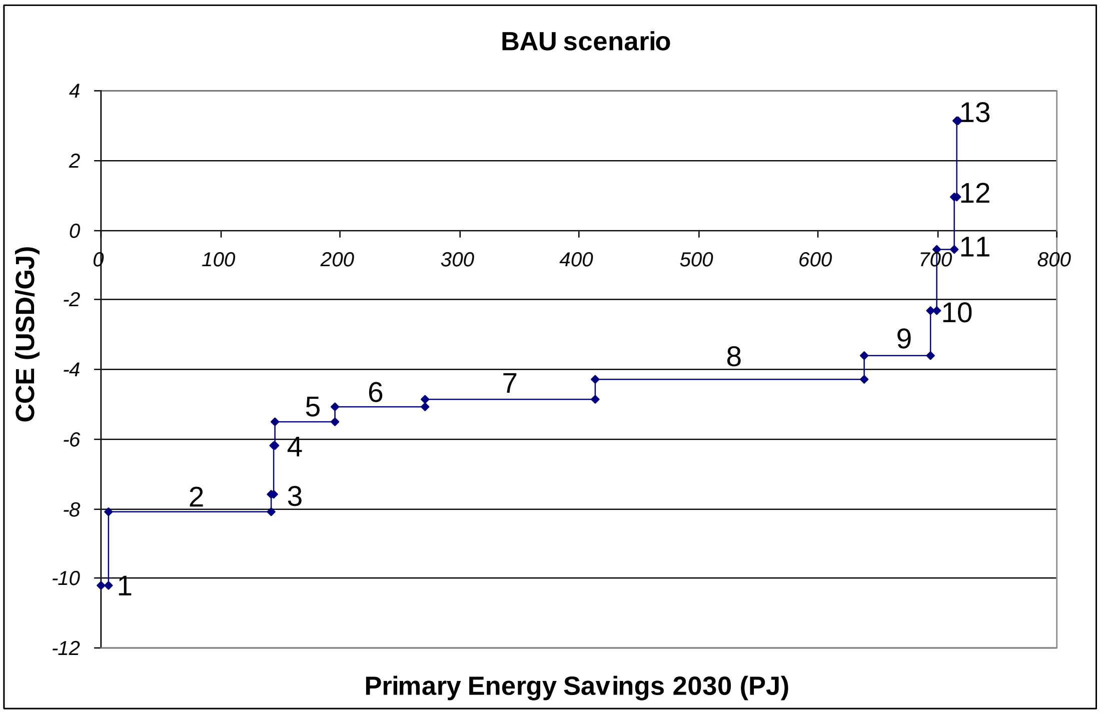


Figure 11 Energy savings potential for the Business-as-usual scenario

In Figure 11 the MAC curve for the business-as-usual scenario is given while in Table 11 further details for each measure's potential is given. Once again for the continuous digester and the waste heat recovery measures the positive CCE values indicate that the measures in most countries are not beneficial. However, in some cases their CCE values are below zero and can be applied, therefore energy savings can be obtained from all the examined measures.

Table 11 Energy savings potential for the Business-as-usual scenario

	Type of Measure	PJ
1	Energy Efficient Vacuum Systems for Dewatering	6.0
2	Efficient Motor Systems	136.6
3	Lime Kiln Modifications	1.4
4	Refiner Improvements	1.2
5	Pinch Analysis	50.9
6	Boiler Improvements	75.4
7	Steam Trap Maintenance	142.6
8	Install and Use Real Time Energy Monitoring Systems	224.9
9	Reduced Air Requirements	55.1
10	Heat Recovery in TMP	5.2
11	Extended Nip Press (shoe press)	15.2
12	Continuous Digesters Including Modifications	2.2
13	Waste Heat Recovery	0.2

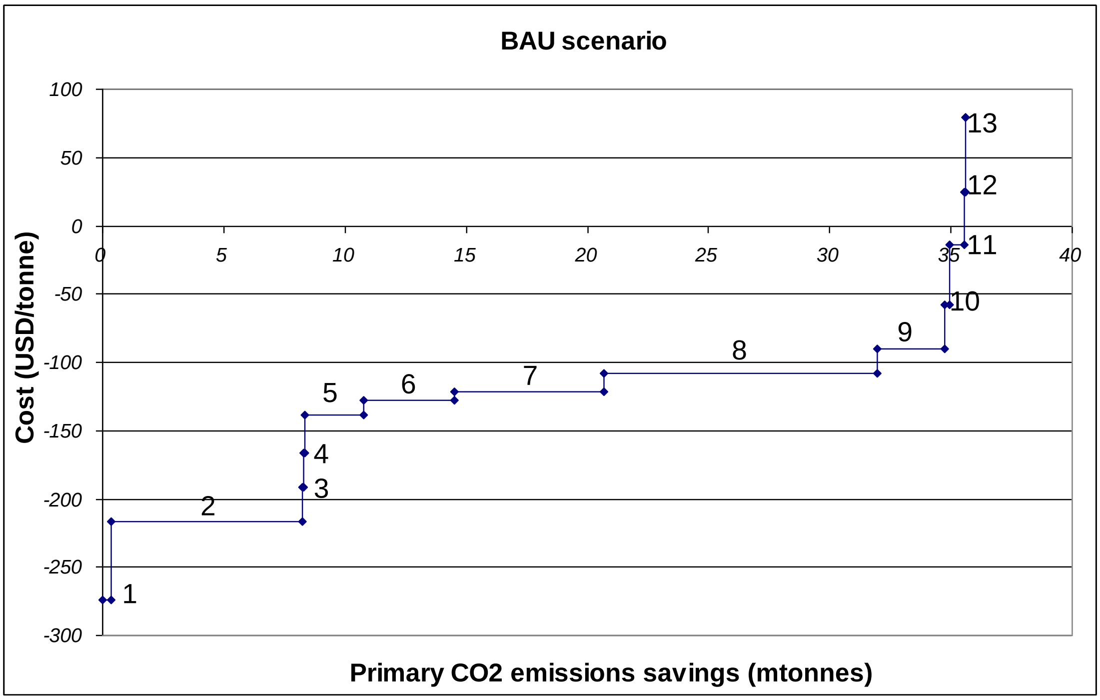


Figure 12 CO_2 emissions saving potential for the Business-as-usual scenario

Finally, CO_2 emissions reduction potential is given in Figure 12, while in Table 12 additional information for each measure can be found. Further details for the energy saving potential can be found in Appendix II.

Table 12 CO_2 emissions saving potential for the Business-as-usual scenario

	Type of measure	CO2 emissions savings (ktonnes)
1	Energy Efficient Vacuum Systems for Dewatering	358
2	Efficient Motor Systems	7,895
3	Lime Kiln Modifications	48
4	Refiner Improvements	46
5	Pinch Analysis	2,447
6	Boiler Improvements	3,718
7	Steam Trap Maintenance	6,187
8	Install and Use Real Time Energy Monitoring Systems	11,280
9	Reduced Air Requirements	2,783
10	Heat Recovery in TMP	158
11	Extended Nip Press (shoe press)	635
12	Continuous Digesters Including Modifications	32
13	Waste Heat Recovery	2

8.2.3 Saving potential of the dominant pulp and paper producing countries

In this section the energy reduction potential in each examined scenario is presented. Table 13 shows the energy reduction for the dominant pulp and paper producing countries.

Table 13 Energy savings potential per country

	Energy Savings from Retrofit measures at Frozen Efficiency scenario (PJ)		Energy Savings from Increased recovery rate scenario (PJ)		Energy Savings from Retrofit measures at Business-as-usual scenario (PJ)	
USA	440	15.58%	220	15.87%	113	15.14%
Canada	108	3.81%	29	2.08%	28	3.70%
Brazil	99	3.50%	45	3.25%	26	3.55%
Russia	99	3.50%	48	3.43%	27	3.56%
France	84	2.98%	35	2.50%	22	2.89%
Italy	71	2.51%	58	4.17%	18	2.44%
Korea	79	2.81%	0	0.00%	21	2.85%
Sweden	51	1.82%	20	1.44%	13	1.77%
Finland	64	2.26%	43	3.13%	16	2.20%
Germany	80	2.82%	0	0.00%	20	2.74%
Japan	106	3.75%	1	0.10%	27	3.65%
China	1,545	54.66%	888	64.02%	414	55.51%
Total	**2,826**	**100%**	**1,387**	**100%**	**745**	**100%**

The gratest potential in each scenario is located in China's industry in all the scenarios. China's pulp and paper industry is expected to grow drastically and become the dominant producer the following years. Furhtermore, China's industry is one of the least efficient, therefore the savings potential is the bigest compared to the rest countries. This potential could be even greater if the coal prices increase the following years. In this study current electricity and ful prices have been used. Therefore in countries with very low prices suchs as China (low coal price) and Russia (low natural gas price) some measures are not cost beneficial. If these low prices rise the following years more measures are expected to have negative CCE values and as a result the energy and CO_2 emissions reduction potential will rise.

Considering the icreased paper recovery rate scenario the share of China in energy savings is increasing while most developed countries' share is reduced. In developed countries the recovery systems are allready developed and therefore furhter improvements are limited. On the other hand proper recycling systems in developing countries can further reduce the energy consumption of the industry.

An increase in the paper recovery will lead to reduction of the chemical pulp, therefore the energy savings from the retrofit measures applied to chemical pulping will be reduced. In the increased recovery rate scenario we have not included the additional savings potential deriving from the implementation of the retrofit measures. This have been made in order to avoid possible double-counting in the overall savings potential.

8.3 Energy intensity per country in the baseline scenarios

In this section the differences among countries energy efficiency is described. For describing these differences the specific energy consumption values (SEC) are used. Unfortunately the SEC values are not exactly describing how efficient a countries industry is. Other parameters are also affecting the SEC values such as the product mix, pulp type used, fuel mix, percentage of integrated mills, combined heat and power use and average mills capacity. Therefore, in some cases countries that are using energy efficient equipment have higher SEC values compared to countries where greater opportunities for further efficiency improvement exist.

In Figure 13 and 14 SEC values for the twelve dominant pulp and paper producers are given. For each country five different SEC values are given. The SEC values given are the Frozen efficiency scenario which is equal to SEC for the base year, the SEC where all possible savings are considered, the SEC including retrofit measures, the increased recovery rate scenario and the business as usual scenario.

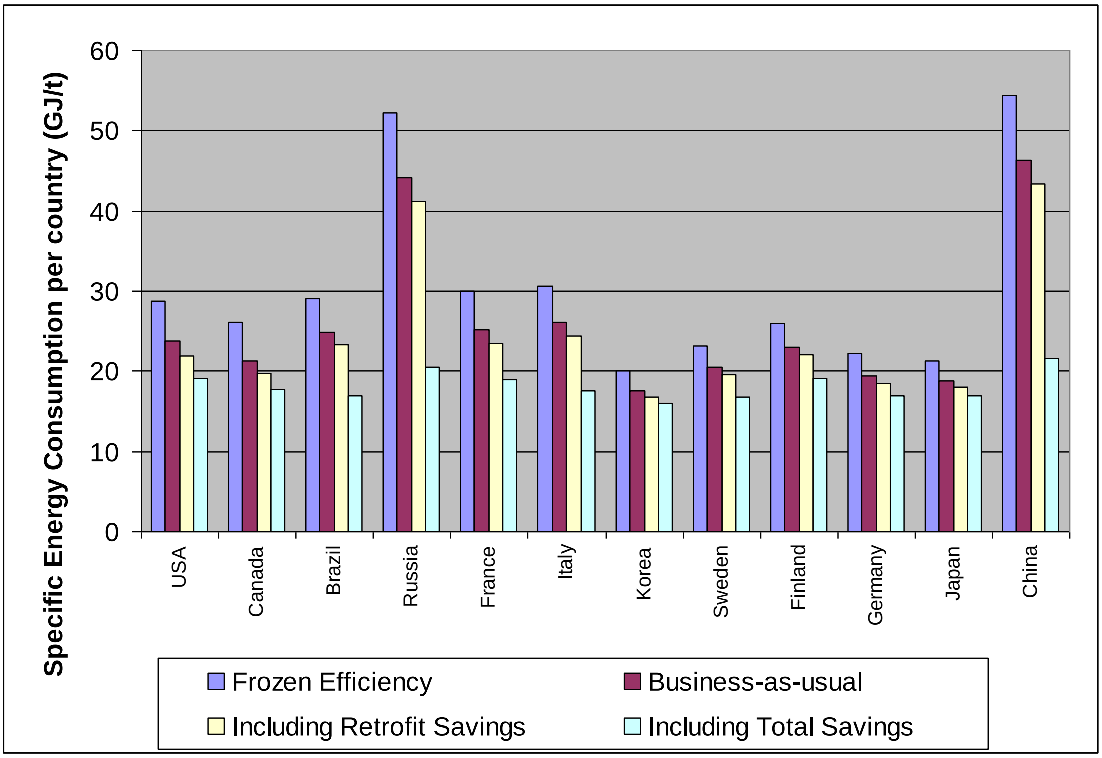


Figure 13 Specific Energy Consumption per country

The most efficient countries where room for improvement is limited are the Scandinavian countries, Germany , Japan and Korea. Finland and Sweden seem to have grater SEC values compared to Japan and Korea but this difference occurs due to the parameters mentioned above. The countries whith the highest SEC values are China and Russia. These are also the countries with the greatest energy reduction potential.

8.4 Sensitivity analysis

A number of parameter values in the model can be potential sources of uncertainty. A crucial assumption made in this work is the selection of the electricity and fuel prices values. The electricity and fuel prices selected are assumed to be constant since estimating future prices until year 2030 is difficult if not impossible. However this assumption is not depicting reality since prices changes constantly. Therefore a sensitivity analysis has been conducted and the results are presented in Table 14.

The electricity and fuel prices have been increased and decreased by 25% in order to examine the differences in the final outcome. The differences between the energy reduction potential and the CO_2 emissions reduction potential are inconsiderable since most emissions of pulp and paper industry derive from energy consumption. Furthermore, the differences between the two examined scenarios are also small. If the electricity and fuel prices increase the following years the additional energy and emissions reduction benefits are insignificant. Most of the measures examined in this study are beneficial and can already be implemented in pulp and paper industries. Therefore an increase in electricity and fuel prices is not expected to change drastically the CCE prices of the expensive measures. On the other hand, a reduction in electricity and fuel prices can be crucial considering the energy and CO_2 emissions reduction potential. The CCE values of some measures are below zero with current prices; however a decrease in these prices will reduce the economic benefits from electricity and fuel reduction. As a result some of these measures will not be beneficial for the industries and will not be implemented. In essence a 25% reduction in prices is expected to reduce the energy and CO_2 emissions reduction potential by 10 to 12% in both scenarios.

Table 14 Sensitivity analysis

Increase, Decrease in Electricity and Fuel Prices	**Frozen Efficiency scenario**		**Business-as-usual scenario**	
	Changes in the results			
	Energy	CO2 emissions	Energy	CO2 emissions
25.0%	3.7%	3.9%	3.3%	3.4%
-25.0%	-11.9%	-12.2%	-10.2%	-10.5%
Reduction of discount rate				
10%	8.2%	8.3%	5.9%	5.9%

In this project 30% discount rate is taken into account in order to express the capital restraints and the measures limitation with short payback periods and high internal rates of return that are more desirable in the pulp and paper industry.

However a decrease in the discount rate selected can significantly affect the outcome of this research. Therefore a discount rate of 10% has been introduced in order to investigate what will be the impacts in the overall energy and emissions savings potential. By changing the discount rate to 10% the CCE values of measures with high investment costs have been reduced. As a result measures that were not beneficial are expected to be implemented if a discount rate of 10% is selected. The estimated differences that occur due to this selection are presented in table 14.

Chapter 9

9. Discussion

In this chapter the assumptions made in this work and the importance of those assumptions will be presented. The main scope of this study is to forecast the energy and CO_2 performance of the pulp and paper industry. In such studies a significant amount of assumptions should be made, these assumptions are strongly related to uncertainties in the final outcome. Furthermore, the case study of this report is covering a complex industry; as a result the data needed to fully describe the industry is extremely hard to be gathered. From these data limitations additional assumptions need to be made and thus additional uncertainties derive.

A projection of the 2030 pulp and paper demand had been made in order to assist to forecast energy and CO_2 emissions abatement potential for year 2030. For estimating the pulp and paper demand until 2030 some assumptions have been made. Firstly the 'intensity of use' hypothesis has been considered and thus the pulp and paper demand on 2030 was estimated based on the GDP and population growth rate. For determining the GDP growth rate a literature survey have been made, however determining GDP growth rate entail assumptions and leads to uncertainties in the results.

The specific energy consumption of each country has been estimated using literature survey, in order to investigate the regional characteristics of the various countries and estimate the intermediate SEC values. Then these SEC values where cross checked by using the energy consumption of the pulp and paper industry aggregate values -which have been taken from the IEA database- combined with the production data taken from the FAO statistics database. However in some countries the available information in literature is not adequate and the SEC values calculated from the IEA database and the FAO statistics database. In these case no cross check of the estimated values was made and thus uncertainty in these values occur.

Uncertainty also occurs in the outcome of the cost effectiveness of the examined measures. The main assumption made in this task was the selection of electricity and fuel prices. Cost effectiveness of measure is strictly related to electricity and fuel prices. Both lack of coherent prices in all pulp and paper industries and the lack of crucial information for determining future prices is creating uncertainty. An additional assumption made is related to the applicable share of production of each measure in the examined countries. Available information for determining what is the exact potential for further penetration of those measures in each country do not exist and thus assumptions were made. Finally the implementation of a measure in a specific process may lead to changes in other processes of the industry. These changes in cost and performance have not been taken into account in this research.

The quality of the database used also entails uncertainty as described by the database developers. In both IEA and FAO statistics databases the system boundaries are not identical in all countries and regions. Furthermore, data breaks occur in some cases. Especially in data related to biomass use the uncertainty is grater since reporting methods vary among countries and in some cases the biomass used in pulp, paper and print production is often allocated to other non-specified industries.

Determining the business-as-usual scenario is also based on assumptions and thus possible uncertainty derives from the business-as-usual scenario outcomes. Pulp and paper industry is a complex industry with significant differences in mills structure and pulp and papers product types among countries. These differences lead to differences in the energy performance and the development of each country. Due to the complex nature of pulp and paper industry, estimating a single scenario that would be suitable in all countries without including uncertainties is difficult if not impossible.

Finally the list of measures examined was also limited. The measures examined in this study are the state-of-the-art techniques which are commercially available and can penetrate the market. Therefore some of these measures are already applied and the potential for further expansion in the market is limited. On the other hand the number of available techniques listed in the literature is surprisingly large. Therefore a selection of the most promising that can also be applied widely have been made. Thus an amount of measures that could affect the outcome of the energy and CO_2 savings potential was not included in this study. Additionally measures that are not commercially available nowadays have not been taken into account, but these measures may penetrate the pulp and paper market the following years increasing the savings potential in year 2030.

In order to compare the results of our research with similar studies the International Energy Agency's report "Energy Technology Transitions for Industry" have been used. The International Energy Agency's report "Energy Technology Transitions for Industry" use a different methodology in order to determine the global potential of energy consumption reduction. An energy efficiency improvement potential index has been conducted in this research. The global potential is determined by comparing the difference between current energy consumption and the estimated consumption if best-available-techniques would have been implemented. Another difference between our research and the IEA's report is that the results given are calculated for different time periods since this research has estimated the abatement potential for year 2030 while IEA's report refers to year 2010. On the other hand, in the frozen efficiency scenario current energy efficiencies are used and thus the result of this scenario can be compared with IEA's report. The total savings of the pulp and paper sector according to the "Energy Technology Transitions for Industry" is estimated at 20% of the energy demand, while in our research the global abatement potential was calculated at 20.4%. However, IEA results include the potential savings from an increase in CHP use globally. The reduction potential from CHP use is 3.57%. This difference in the result can be explained by the fact that in our report the pulp and paper production shares of the countries are different. China's industry share is expected to increase substantially until 2030. Since China's industry is the least energy efficient producer the reduction potential in our research is estimated to be greater.

Chapter 10

10. Conclusions

The pulp and paper industry has examined in this research in order to analyze the technical potentials of energy and CO_2 emission reduction up to 2030.

Considering the most dominant pulp and paper producing countries the paper production for 2030 is estimated to be 383 million tones, increased by 80 million tonnes compared to 2007. Concerning the domestic production, China is expected to significantly enlarge their capacity while the U.S.A. and Canada industries are expected to reduce in size. In essence the regions where pulp and paper industries are expected to growth rapidly the following years are Eastern Europe, most Asian countries except Japan and the Latin America.

Two different baseline scenarios have been examined in this research. These scenarios are the frozen efficiency scenario and the business-as-usual scenario. The main difference of these two scenarios is that in the frozen efficiency scenario the new stock efficiency is operating with similar efficiency to the base year (2005) while in the business-as-usual scenario the new stock consists of efficient state-of-the-art equipment.

In the Frozen efficiency scenario the overall energy consumption is estimated to rise at 14.1 EJ or increased by 67% compared to 2003. On the other hand, in the business-as-usual scenario the overall energy demand is 12 EJ. Compared to the frozen efficiency scenario the energy demand is reduced by 2.1 EJ or 14.8%.

The overall energy savings potential in the Frozen efficiency scenario is estimated to be 2.8 EJ, which represents 20.4% of the global energy demand of the pulp and paper industry in year 2030. These savings leads to 129.8 mtonnes CO_2 emissions reduction. In the business-as-usual scenario the energy reduction potential is 745PJ or else the energy consumption is reduced by 6.2%. The CO_2 abatement potential in this scenario is 35.6 mtonnes.

According to our results the greatest abatement potential, which is approximately 55%, is located in China's pulp and paper industry due to two different reasons. Firstly the domestic industry is expected to drastically increase and become the dominant paper producer. Secondly the fact that China's pulp and paper mills are operating highly inefficiently.

The overall abatement potential can be increased if new technologies, that are not currently commercially available, implemented in pulp and paper mills. These technologies are black liquor gasification, lignin production from black liquor, biomass gasification with synfuels production, and CO_2 capture and storage. Additional research is needed in examining the implementation potential of these technologies and their possible energy and CO_2 abatement potential.

Data limitations regarding the pulp and paper industry limits the possibility of having a better insight in pulp and paper sector. The high complexity of industry's structure and the low quality of existing data makes it very difficult to investigate the available abatement potential. Thus, additional effort should be made in existing data quality and on data reporting.

Furthermore, the affect of other parameters crucial in pulp and paper industry should be further examined. These parameters are the CHP use and the integrated-stand alone mills ratio. The increase of the CHP use in pulp and paper industry and the possible reduction of stand alone mills global capacity will reduce the energy consumption in the sector. These two parameters and their abatement potential have not been examined in this report and additional research could contribute in providing more adequate results.

References

Akimoto K., Sano F., Homma T., Oda J., Nagashima M., Kii M.., 2010, Estimates of GHG emission reduction potential by country, sector, and cost, Energy Policy, Volume 38, Issue 7, Large-scale wind power in electricity markets with Regular Papers

Alami R., 1997, Impact of Refining Intensity on Energy Reduction in Commercial Refiners: Effect of Primary Stage Consistency. TAPPI Journal

Alsema E., 2001, Sector Study for the Paper and Board Industry and the Graphical Industry, Utrecht Center for Energy Research, NWS-E-2001-02

Baker E., Clarke L., Shittu E., 2008, Technical change and the marginal cost of abatement, Energy Economics, Volume 30, Issue 6, Technological Change and the Environment,

Beaumont N.J, Tinch R., 2004, Abatement cost curves: a viable management tool for enabling the achievement of win-win waste reduction strategies?, Journal of Environmental Management, Volume 71, Issue 3,

Blok K., 2007, Introduction to energy analysis, Techne Press Amsterdam

China Energy Databook v. 7.0, October 2008

Confederation of European Paper Industries (CEPI), 2001, Special Recycling Statistics, Confederation of European Paper Industries Brussels.

Confederation of European Paper Industries (CEPI), 2006, Europe Global Champion in Paper Recycling: Paper Industries Meet Ambitious Target, Press Release, July. Brussels.

Confederation of European Paper Industries (CEPI), 2007, CEPI Annual Statistics 2007, CEPI publications

Confederation of European Paper Industries (CEPI), 2008, Key statistics 2008 – European Pulp and Paper Industry, CEPI publications

Criqui P., Mima S., Viguier L., 1999, Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model, Energy Policy, Volume 27, Issue 10,

Ecofys, 2009, Methodology for the free allocation of emission allowances in the EU ETS post 2012 - Sector report for the pulp and paper industry, retrieved April 2010 from http://ec.europa.eu/environment/climat/emission/pdf/bm/BM%20study%20-%20Lime.pdf

Energy Research Center of Netherlands (ECN), 2007, GHG Marginal Abatement Cost curves for the Non-Annex I region

European Commission, Integrated Pollution Prevention and Control (IPPC), 2001, Reference Document on Best Available Techniques in the Pulp and Paper Industry, retrieved July 2009 from http://eippcb.jrc.es/reference/pp.html

Farahani S., Worrell E., Bryntse G.,2004, CO2-free paper?, Resources, Conservation and Recycling, Volume 42, Issue 4, Farla J., Blok K., Schipper L., 1997 Energy efficiency developments in the pulp and paper industry : A cross-country comparison using physical production data, Energy Policy, Volume 25, Issues 7-9, Cross-country comparisons of indicators of energy use, energy efficiency and CO2 emissions

Focus on Energy (FOE), 2005, Pulp and Paper - Energy Best Practice Guidebook

Food and Agriculture Organization of the United Nations, Forestry Statistics, retrieved September 2009 from http://faostat.fao.org/site/626/default.aspx#ancor

Francis D., Towers M., Browne T., Energy Cost Reduction in the Pulp and Paper Industry – An Energy Benchmarking Perspective, Natural Resources of Canada taken October 2009 from http://www.oee.nrcan.gc.ca/publications/infosource/pub/cipec/pulp-paper-industry/index.cfm?attr=24

Graus, W., 2008, International comparison of fossil power efficiency and CO2 intensity, Ecofys

Henley E. J., Williams R.A., Mathematics in Science and Engineering, Elsevier, 1973, Volume 98, Chapter 5 Sensitivity Analysis, ISBN 9780123408501

Holik H., 2006, Handbook of Paper and Board, Wiley-VCH Publications, ISBN: 978-3-527-30997-9

Hoogwijk M., Rue du Can S., Novikova A., Urge-Vorsatz D., Blomen E., Blok K., 2010, Assessment of bottom-up sectoral and regional mitigation potentials, Energy Policy, Volume 38, Issue 6, The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers,

Ince, P.J., 1998. Long-range outlook for U.S. paper and paperboard demand, technology, and fiber supply–demand equilibria. In: USDA Forest Service, Forest Products Laboratory Proceedings

Institute for Prospective Technological Studies (IPTS), 2006, Development of a Model of world Pulp and Paper Industry, retrieved October 2009 from ftp.jrc.es/EURdoc/eur22544en.pdf

Institute of Paper Science and Technology (IPST), 2006, Pulp and Paper Industry Energy Bandwidth Study

International Energy Agency (IEA), 2007**,** Key World Energy Statistics 2007

International Energy Agency (IEA), 2008, Key World Energy Statistics 2008

International Energy Agency (IEA), 2008, Report: Tracking Industrial Energy Efficiency and CO_2 Emissions, retrieved October 2009 from http://www.iea.org/w/bookshop/add.aspx?id=298

International Energy Agency (IEA), 2009, Key World Energy Statistics 2009

International Energy Agency (IEA), 2009, Energy Technology Transitions for Industry,

International Energy Agency (IEA), 2010, Beyond 20/20 Database, Izquierdo S., Dopazo C., Fueyo N, 2008, Supply-cost curves for geographically distributed renewable-energy resources, Available online 16 October 2009, ISSN 0301-4215,

Jokinen J., 2006, Energy Efficiency Developments in the North and South American and European Pulp and Paper Industry, presented in IEA workshop at October 2006

Kallio, A., M., I., Moiseyev, A., Solberg, B., 2004, The Global Forest Sector Model EFI-GTM. The Model Structure. European Forest Institute, Internal Report No. 15,

Kramer K., Masanet R., Xu T., Worrell E., 2009, Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry, Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-2268E

Mannaerts H., 2000, Substance Throughput Related to Economic Activity Model
A partial equilibrium model for material flows in the economy, CPB Netherlands Bureau for Economic Policy Analysis, The Hague,

Martin N., Anglani N., Einstein D., Khrushch M., Worrell E., and Price L.K., 2000, Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the U.S. Pulp and Paper Industry, retrieved September 2009 from http://www.osti.gov/bridge/servlets/purl/767608-u2AeNa/native/767608.pdf

McKitrick R., 1999, A Derivation of the Marginal Abatement Cost Curve, Journal of Environmental Economics and Management, Volume 37, Issue 3,

Office of Energy Efficiency (OEE), 2010, National Energy Use Database, retrieved January 2010 from
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablestrends2/egen_ca_1_e_4.cfm?attr=0

Poyry (2009), Know How Wire Supplement, ISSN: 0780, Publisher: Poyry PLC

Sixta H., 2006, Handbook of Pulp, 2 Volume Set, Wiley-VCH Publications, ISBN: 978-3-527-30999-3

Smith M., 1997, The U.S. Paper Industry and Sustainable Production : An Argument for Restructuring Urban and Industrial Environments, The MIT Press, ISBN-10: 0-262-19377-9

Szabo L., Soria A., Forsstrom J., Keranen J.T., Hytonen E., 2009, A world model of the pulp and paper industry: Demand, energy consumption and emission scenarios to 2030, Environmental Science & Policy, Volume 12, Issue 3

Tessier, P., G. Broderich, C. Desrochers and S. Bussiere, 1997, Industrial Implementation of Motor Load and Freeness Control of Chemimechanical Pulp Refiners. TAPPI Journal,

Tomberline D., Zhu S., Buongiorno J., 1998, The Global Forest Products Model (GFPM): Users manual and guide to installation. Working Paper No: GFPOS/WP/02. FAO Forestry Policy and Planning Division,

United Nations database (UN), 2008, World Population Prospects: The 2008 Revision Population Database, retrieved April 2010 from http://esa.un.org/unpp/index.asp

van Ruijven B., Urban F., Benders R., Moll H., van der Sluijs J., de Vries B., van Vuuren D., 2008, Modeling Energy and Development: An Evaluation of Models and Concepts, World

Development, Volume 36, Issue 12, Special Section: Social Movements and the Dynamics of Rural Development in Latin America (pp. 2874-2952),

van Vuuren P., 1970, Energy systems and climate policy: Long-term scenarios for an uncertain future, The Netherlands Environmental Assessment Agency

van Vuuren D., Strengers B., De Vries H., 1999, Long-term perspectives on world metal use—a system-dynamics model, National Institute of Public Health and the Environment, Bureau for Environmental Assessment,

Worrell E., Ramesohl S., Boyd G., 2004, Advances in Energy Forecasting Models based on Engineering Economics, Annu. Rev. Environ. Resour. 2004. 29:345–81
doi: 10.1146/annurev.energy.29.062403.102042

Worrell E., Biermans G.,2005, Move over! Stock turnover, retrofit and industrial energy efficiency, Energy Policy, Volume 33, Issue 7,

Zhuang Z., 2006, China’s Pulp and Paper Industry: A Review, Georgia Institute of Technology

Appendices

Appendix I. Fuel type used per country

	Electricity generation by fuel and average efficiency of electricity generation for each fuel type per country								
	Coal	n	N. Gas	n	Oil	n	Hydro	Nuclear	Other
Usa	51,9%	36,3%	16,3%	51,3%	3,1%	36,3%	6,7%	20,4%	1,6%
Canada	17,7%	33,8%	6,2%	38,1%	1,3%	43,1%	59,9%	13,5%	1,4%
Russia	13,8%	23,4%	33,4%	26,4%	1,6%	23,5%	4,1%	10,4%	36,7%
China	78,3%	31,5%	0,9%	42,5%	2,5%	33,6%	16,0%	2,3%	0,0%
Brazil	2,7%	30,0%	4,3%	42,0%	3,0%	35,0%	40,1%	4,6%	45,4%
Japan	26,2%	41,5%	25,2%	44,9%	8,6%	45,6%	9,2%	30,2%	0,6%
Korea	37,7%	36,8%	16,6%	51,3%	5,7%	39,7%	1,3%	38,7%	0,1%
Finland	29,9%	39,0%	13,9%	48,8%	0,4%	43,4%	20,0%	30,2%	5,6%
Sweden	1,5%	32,0%	0,5%	36,5%	0,6%	30,7%	41,0%	52,8%	3,7%
Germany	51,0%	38,2%	8,3%	46,6%	0,6%	36,5%	3,7%	29,8%	6,6%
France	4,6%	39,4%	2,0%	47,6%	0,8%	45,4%	10,7%	81,7%	0,2%
Italy	18,4%	37,7%	43,8%	54,6%	18,9%	47,9%	14,1%	0,0%	4,8%

Appendix II.

Table A. Cost of Conserved Energy values for each measure per country (Frozen efficiency scenario

	USA	Canada	Russia	China	Brazil	Japan	Korea	Finland	Sweden	Germany	France	Italy
Refiner improvements	-3,8	-3,4	-2,8	-6,3	-6,9	-12,7	-6,6	-5,5	-3,6	-8,4	-7,9	-17,3
Heat recovery in TMP	-1,1	-1,1	0,3	1,5	-2,0	-0,2	-5,4	-3,3	-10,3	-2,2	-4,1	-4,1
Continuous digesters including modifications	2,9	2,5	1,5	2,5	1,4	3,5	-1,2	1,0	-6,4	1,5	0,1	0,0
Lime kiln modifications	-5,0	-4,6	-1,0	-0,5	-6,4	-5,9	-11,0	-8,2	-15,8	-7,3	-9,7	-11,9
Extended nip press (shoe press)	1,3	1,1	0,8	1,6	-0,1	1,3	-2,7	-0,6	-7,2	-0,2	-1,6	-2,4
Reduced air requirements	-2,1	-2,0	-0,4	0,0	-3,3	-2,9	-6,2	-4,3	-9,7	-3,8	-5,4	-6,9
Waste heat recovery	5,1	4,5	2,1	3,1	3,4	5,5	1,2	3,4	-4,2	3,6	2,4	2,3
Energy efficient vacuum systems for dewatering	-6,9	-6,2	-3,8	-7,6	-9,8	-16,2	-9,8	-8,9	-6,1	-11,6	-11,3	-21,2
Efficient motor systems	-5,2	-4,7	-3,3	-6,9	-8,3	-14,4	-8,1	-7,1	-4,8	-9,9	-9,5	-19,1
Pinch analysis	-3,7	-3,4	-0,8	-0,5	-4,7	-4,3	-7,9	-6,0	-11,3	-5,3	-7,1	-8,6
Install and Use Real Time Energy Monitoring Systems	-3,0	-2,8	-0,6	-0,2	-4,0	-3,6	-7,2	-5,2	-10,6	-4,6	-6,3	-7,7
Boiler improvements	-3,5	-3,2	-0,7	-0,4	-4,5	-4,1	-7,7	-5,8	-11,1	-5,1	-6,8	-8,3
Steam trap maintenance	-3,4	-3,1	-0,7	-0,3	-4,4	-4,0	-7,6	-5,6	-11,0	-5,0	-6,7	-8,2

Table B. Energy savings potential for each measure per country (Frozen efficiency scenario

	USA	Canada	Russia	China	Brazil	Japan	Korea	Finland	Sweden	Germany	France	Italy
Refiner improvements	0,01	0,06	0,05	0,00	0,00	0,00	0,00	0,03	0,02	0,01	0,02	0,01
Heat recovery in TMP	0,04	0,27	0,25	0,01	0,02	0,02	0,01	0,13	0,14	0,08	0,07	0,06
Continuous digesters including modifications	0,76	0,53	1,78	0,23	0,50	0,19	0,03	0,33	0,49	0,09	0,33	0,09
Lime kiln modifications	0,03	0,02	0,07	0,00	0,02	0,00	0,00	0,01	0,01	0,00	0,01	0,00
Extended nip press (shoe press)	0,91	0,82	0,89	1,48	0,52	1,02	0,47	0,49	0,37	0,46	0,61	0,56
Reduced air requirements	0,45	0,41	0,58	1,09	0,26	0,25	0,12	0,24	0,18	0,23	0,30	0,28
Waste heat recovery	0,21	0,19	0,28	0,46	0,16	0,08	0,07	0,08	0,06	0,07	0,19	0,18
energy efficient vacuum systems for dewatering	0,06	0,05	0,08	0,10	0,05	0,02	0,02	0,02	0,02	0,02	0,06	0,06
Efficient motor systems	1,25	1,13	1,63	2,03	1,14	0,70	0,65	0,94	0,70	0,88	1,08	1,24
Pinch analysis	0,51	0,46	1,16	0,83	0,46	0,14	0,13	0,14	0,10	0,13	0,55	0,63
Install and Use Real Time Energy Monitoring Systems	1,90	1,72	2,97	4,33	1,39	0,85	0,78	0,81	0,61	0,77	1,64	1,41
boiler improvements	0,65	0,59	1,69	1,32	0,44	0,36	0,33	0,35	0,26	0,33	0,52	0,48
Steam trap maintenace	1,91	1,72	2,73	1,24	1,39	0,85	0,79	0,82	0,61	0,77	1,64	1,41

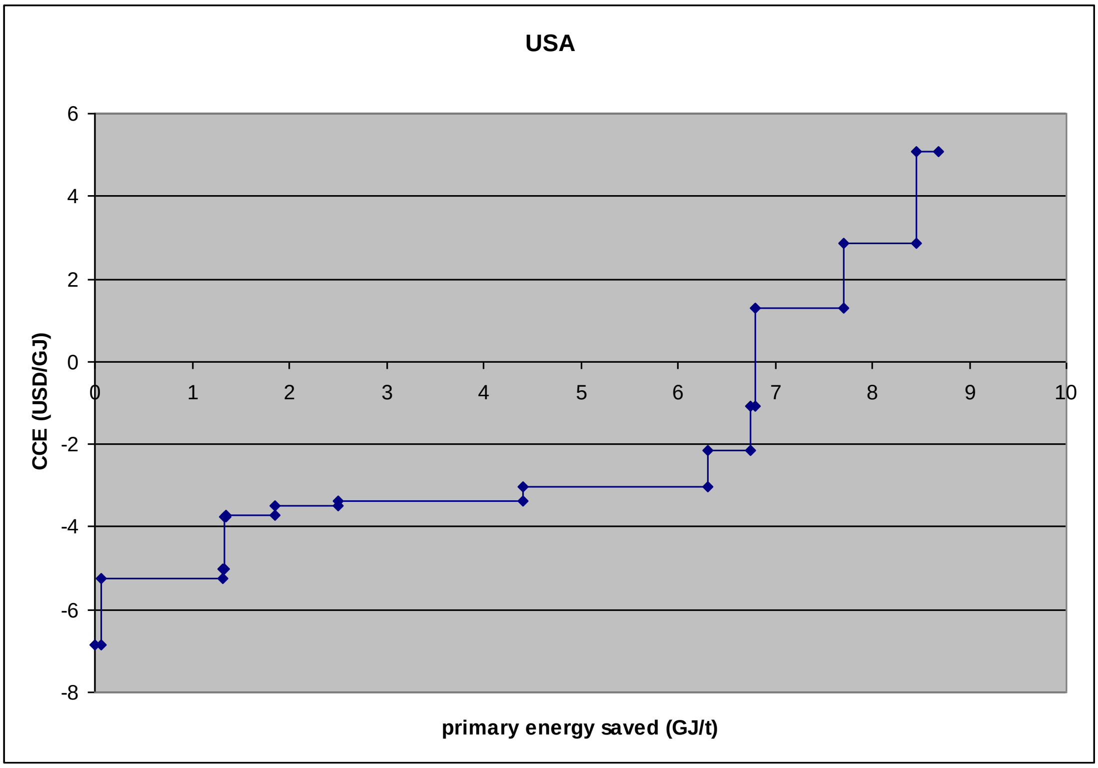
Table C. Cost of Conserved Energy values for each measure per country (Business-as-usual scenario)

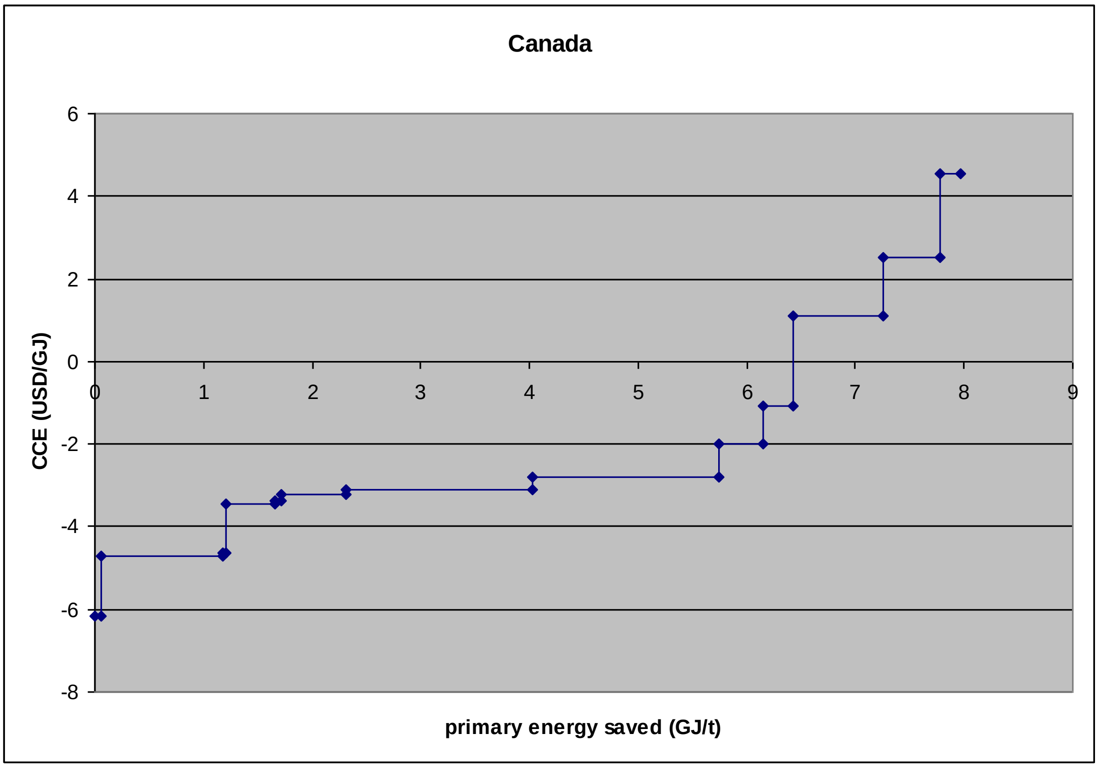
	USA	Canada	Russia	China	Brazil	Japan	Korea	Finland	Sweden	Germany	France	Italy
Energy efficient vacuum systems for dewatering	-6,9	-6,2	-3,8	-7,6	-9,8	-14,4	-11,0	-3,3	-15,8	-11,6	-11,3	-21,2
Efficient motor systems	-5,2	-4,7	-2,7	-6,3	-8,3	-12,7	-8,1	-0,6	-11,3	-8,4	-9,5	-19,1
Lime kiln modifications	-5,0	-4,6	-0,5	0,1	-6,4	-16,2	-9,8	-8,9	-11,0	-7,3	-9,7	-11,9
Refiner improvements	-3,8	-3,4	-1,8	-5,1	-6,9	-3,6	-7,2	3,4	-11,1	-9,9	-7,9	-17,3
Pinch analysis	-3,7	-3,4	-0,5	-0,1	-4,7	-5,9	-7,9	-8,2	-10,6	-5,3	-7,1	-8,6
Boiler improvements	-3,5	-3,2	-0,3	0,1	-4,5	-4,3	-7,7	-7,1	-10,3	-5,1	-6,8	-8,3
Steam trap maintenance	-3,4	-3,1	-0,3	0,2	-4,4	-4,1	-7,6	-6,0	-9,7	-5,0	-6,7	-8,2
Install and Use Real Time Energy Monitoring Systems	-3,0	-2,8	-0,1	0,5	-4,0	-4,0	-6,6	-5,8	-7,2	-4,6	-6,3	-7,7
Reduced air requirements	-2,1	-2,0	0,5	1,0	-3,3	-2,9	-6,2	-5,5	-6,4	-3,8	-5,4	-6,9
Heat recovery in TMP	-1,1	-1,1	1,4	2,8	-2,0	-0,2	-5,4	-5,6	-6,1	-2,2	-4,1	-4,1
Extended nip press (shoe press)	1,3	1,1	2,8	4,0	-0,1	1,3	-2,7	-5,2	-4,8	-0,2	-1,6	-2,4
Continuous digesters including modifications	2,9	2,5	3,9	5,6	1,4	3,5	-1,2	-4,3	-4,2	1,5	0,1	0,0
Waste heat recovery	5,1	4,5	5,3	7,1	3,4	5,5	1,2	1,0	-3,6	3,6	2,4	2,3

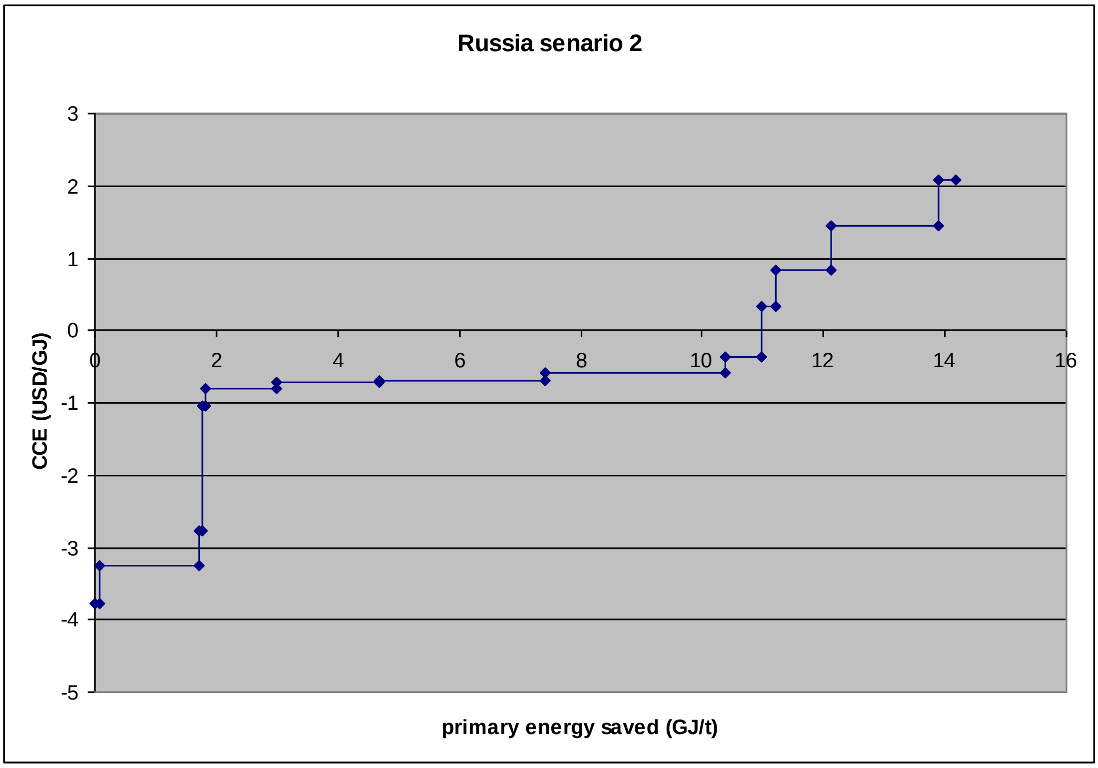
Table D. Energy savings potential for each measure per country (Business-as-usual scenario)

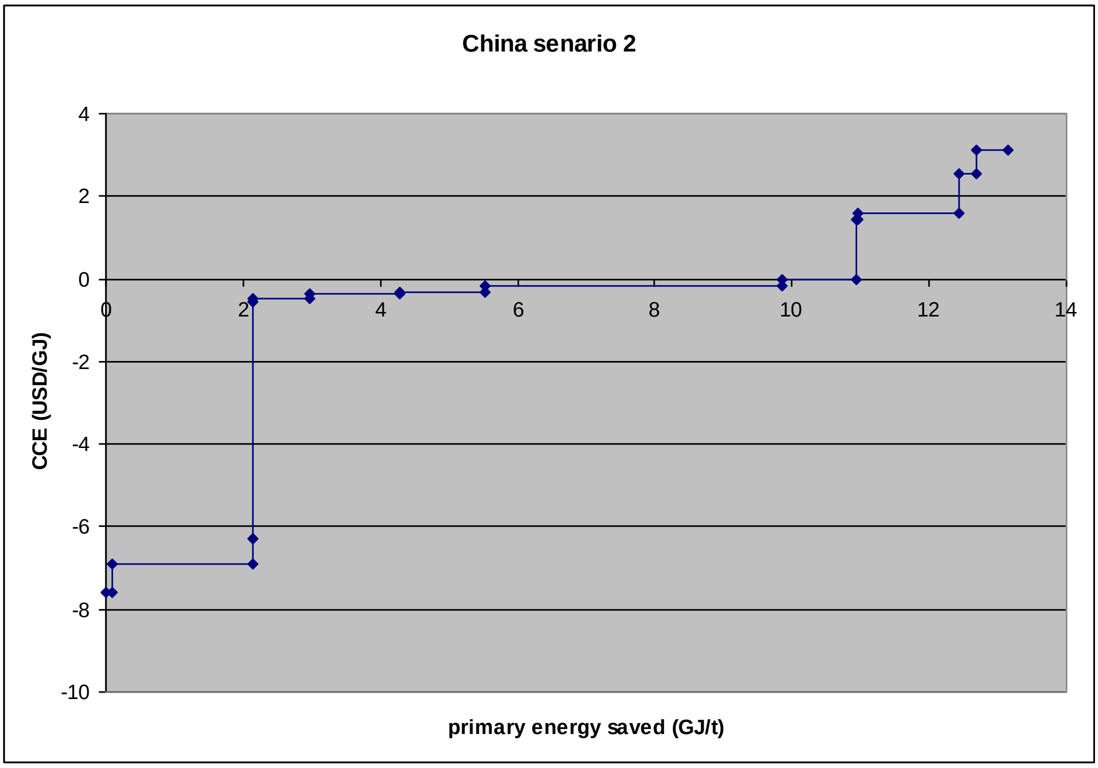
	USA	Canada	Russia	China	Brazil	Japan	Korea	Finland	Sweden	Germany	France	Italy
Energy efficient vacuum systems for dewatering	0,06	0,05	0,08	0,10	0,05	0,02	0,02	0,02	0,02	0,02	0,06	0,06
Efficient motor systems	1,25	1,13	1,63	2,03	1,14	0,70	0,65	0,94	0,70	0,88	1,08	1,24
Lime kiln modifications	0,03	0,02	0,07	0,00	0,02	0,00	0,00	0,01	0,01	0,00	0,01	0,00
Refiner improvements	0,01	0,06	0,05	0,00	0,00	0,00	0,00	0,03	0,02	0,01	0,02	0,01
Pinch analysis	0,51	0,46	1,16	0,83	0,46	0,14	0,13	0,14	0,10	0,13	0,55	0,63
Boiler improvements	0,65	0,59	1,69	1,32	0,44	0,36	0,33	0,35	0,26	0,33	0,52	0,48
Steam trap maintenance	1,91	1,72	2,73	1,24	1,39	0,85	0,79	0,82	0,61	0,77	1,64	1,41
Install and Use Real Time Energy Monitoring Systems	1,90	1,72	2,97	4,33	1,39	0,85	0,78	0,81	0,61	0,77	1,64	1,41
Reduced air requirements	0,45	0,41	0,58	1,09	0,26	0,25	0,12	0,24	0,18	0,23	0,30	0,28
Heat recovery in TMP	0,04	0,27	0,00	0,00	0,02	0,02	0,01	0,13	0,14	0,08	0,07	0,06
Extended nip press (shoe press)	0,00	0,00	0,00	0,00	0,52	0,00	0,47	0,49	0,37	0,46	0,61	0,56
Continuous digesters including modifications	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,00	0,49	0,00	0,00	0,00
Waste heat recovery	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00

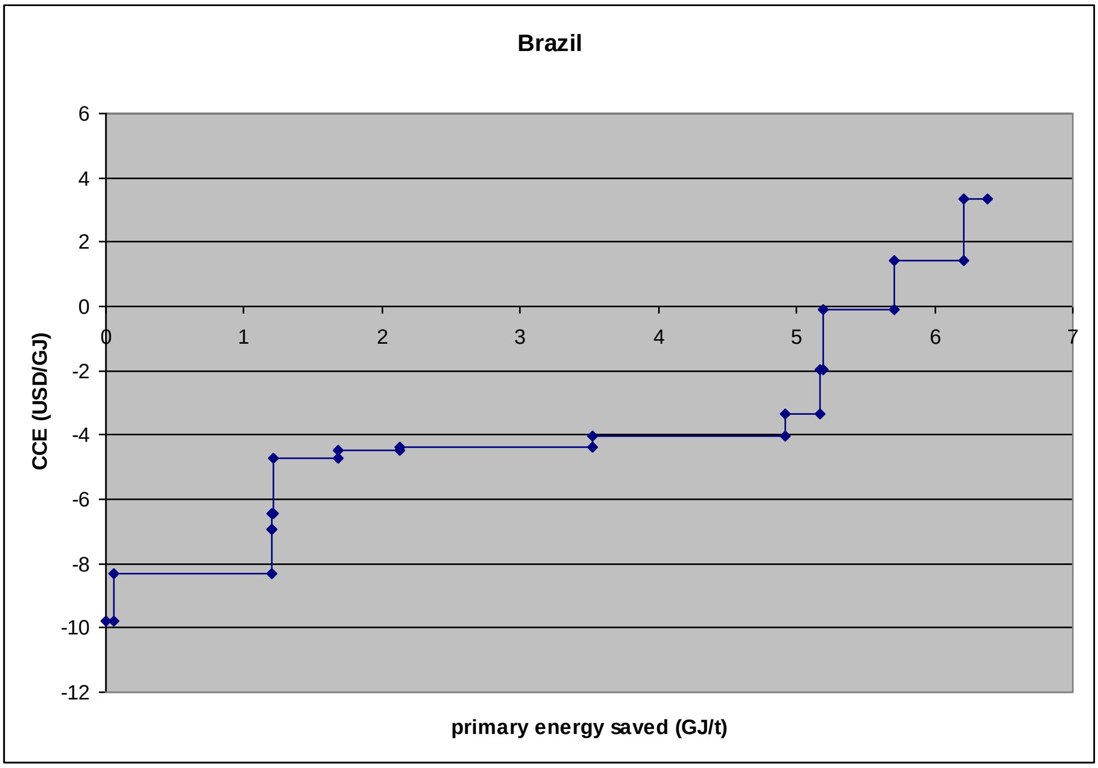
Appendix III. Marginal Abatement Cost Curves per country

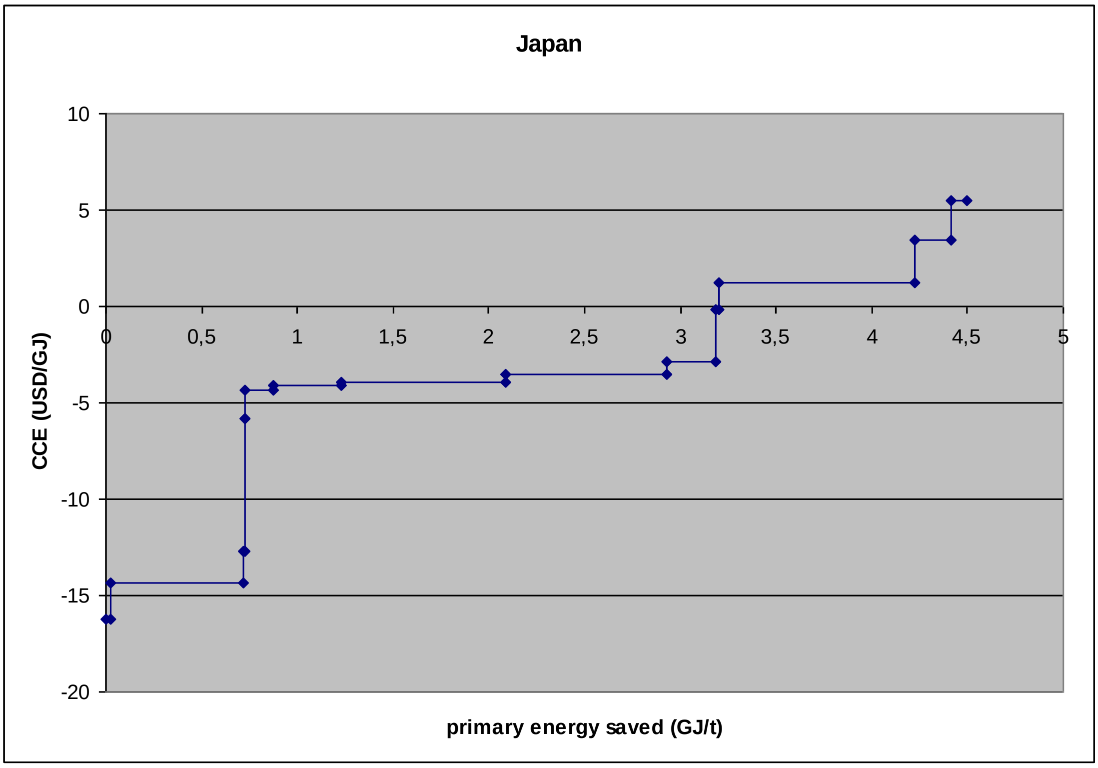


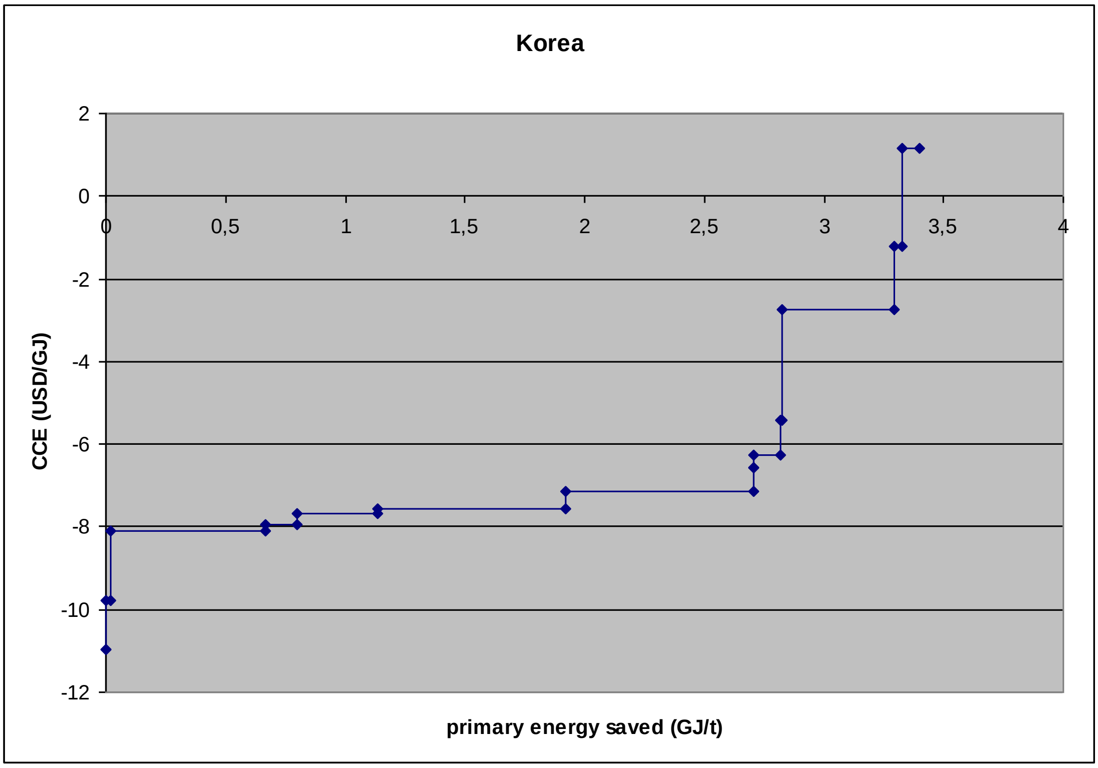


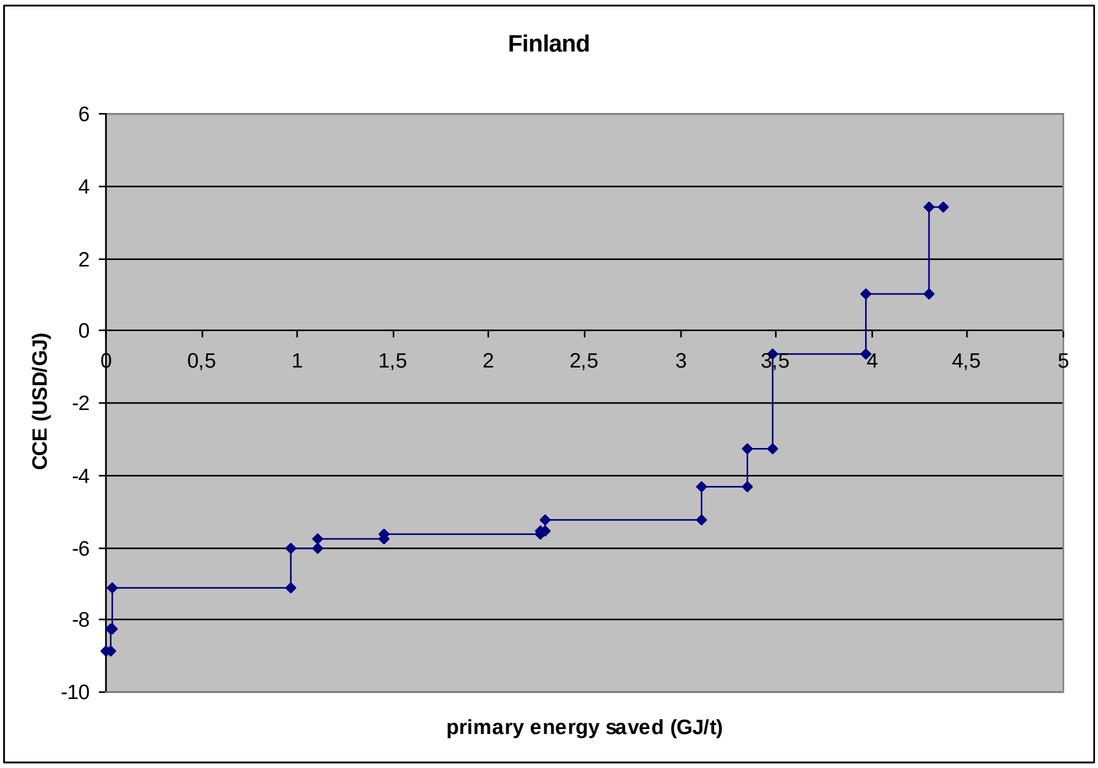

Russia senario 2
CCE (USD/GJ)
3
2
1
0
-1
-2
-3
-4
-5
0
2
4
6
8
10
12
14
16
primary energy saved (GJ/t)

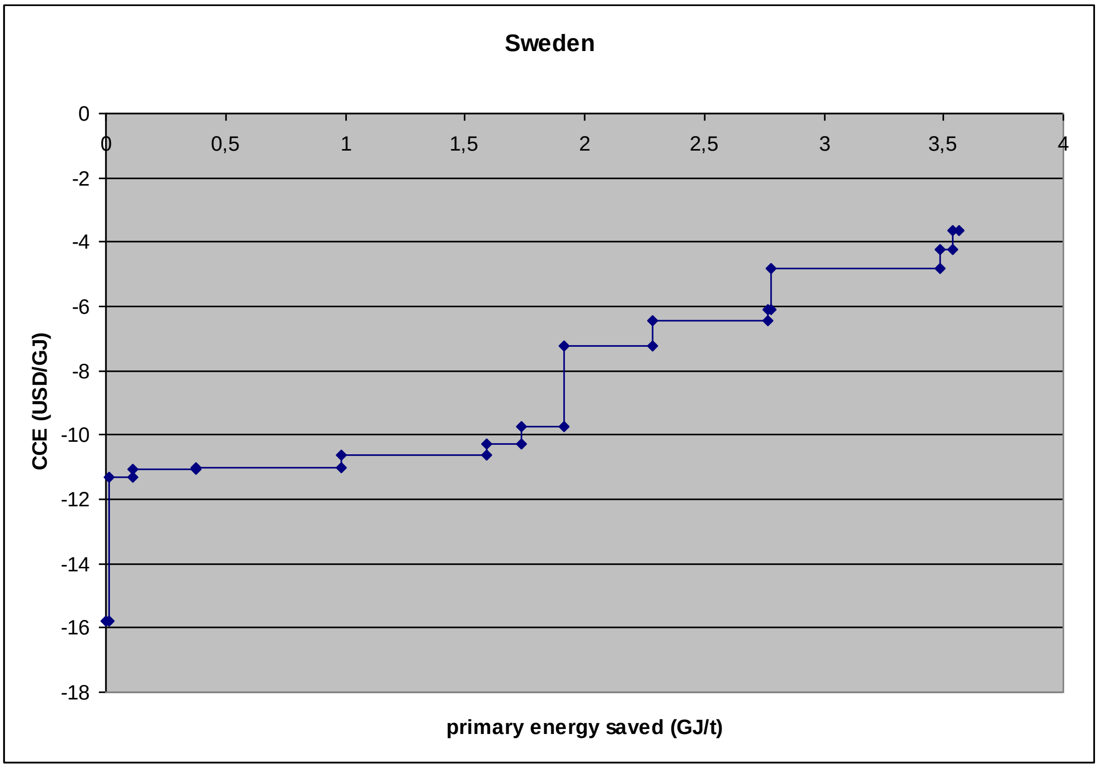

China senario 2
CCE (USD/GJ)
4
2
0
-2
-4
-6
-8
-10
0
2
4
6
8
10
12
14
primary energy saved (GJ/t)

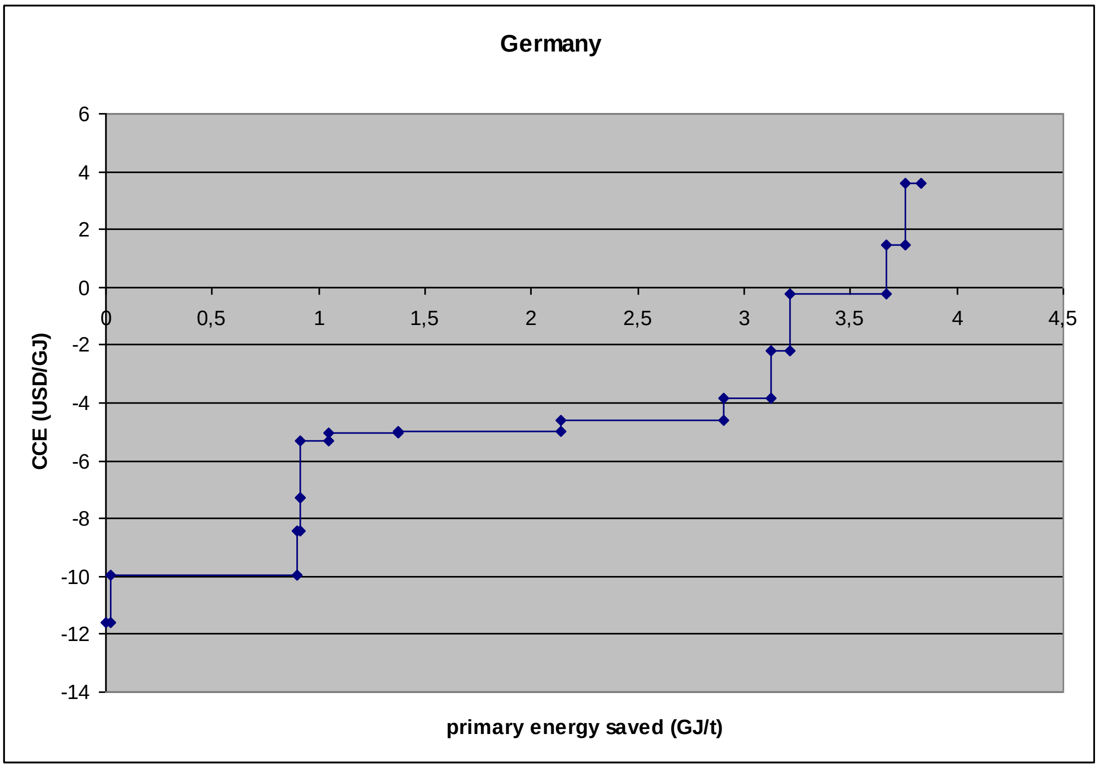

Brazil
CCE (USD/GJ)
6
4
2
0
-2
-4
-6
-8
-10
-12
0
1
2
3
4
5
6
7
primary energy saved (GJ/t)

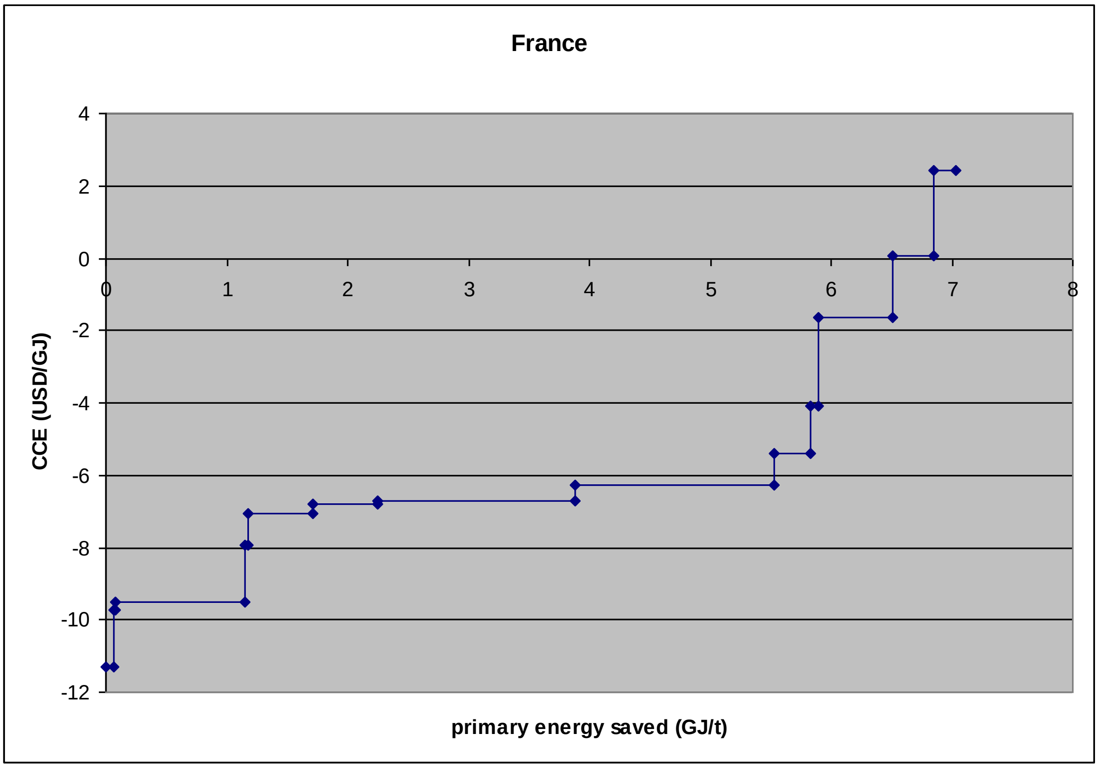

Japan
CCE (USD/GJ)
10
5
0
-5
-10
-15
-20
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5
primary energy saved (GJ/t)

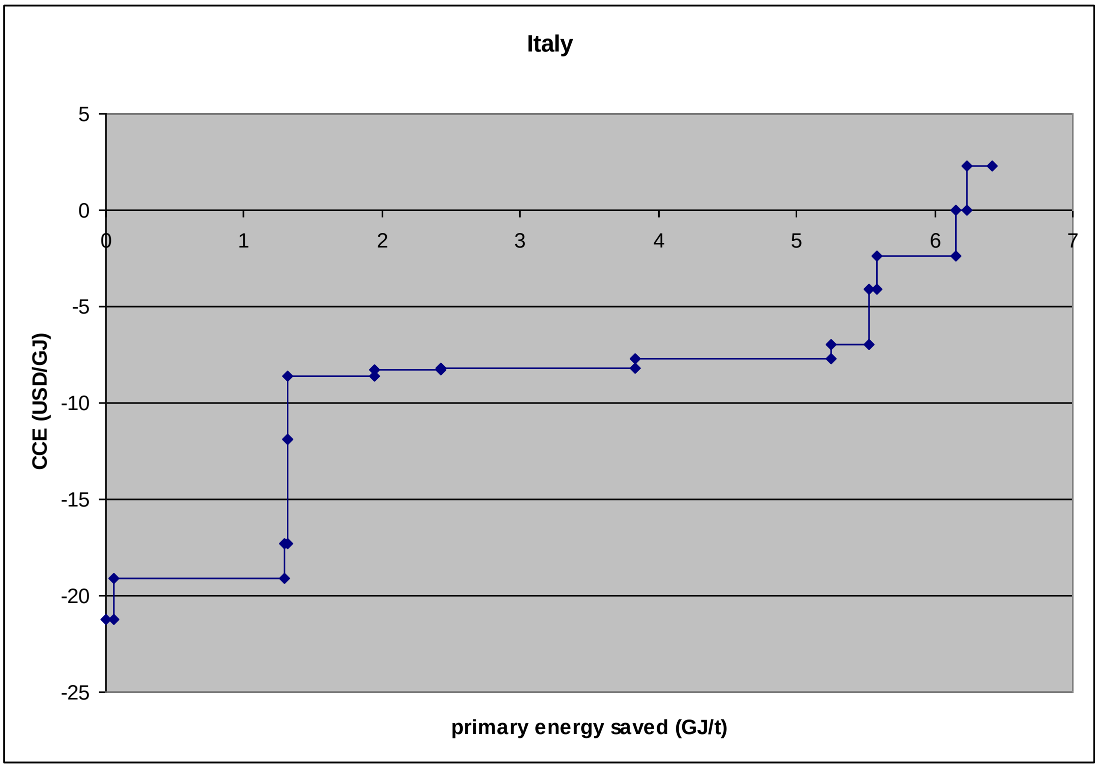

Korea
CCE (USD/GJ)
primary energy saved (GJ/t)
2
0
-2
-4
-6
-8
-10
-12
0
0,5
1
1,5
2
2,5
3
3,5
4


Finland
CCE (USD/GJ)
primary energy saved (GJ/t)
6
4
2
0
-2
-4
-6
-8
-10
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5


Sweden
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
0,5
1
1,5
2
2,5
3
3,5
4
CCE (USD/GJ)
primary energy saved (GJ/t)


Germany
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
CCE (USD/GJ)
primary energy saved (GJ/t)


France
CCE (USD/GJ)
4
2
0
-2
-4
-6
-8
-10
-12
0
1
2
3
4
5
6
7
8
primary energy saved (GJ/t)


Italy
CCE (USD/GJ)
5
0
-5
-10
-15
-20
-25
0
1
2
3
4
5
6
7
primary energy saved (GJ/t)