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Climate innovations in the paper industry: Prospects for decarbonisation

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Preface

This report is written as part of the REINVENT project and funded through the European Union Horizon 2020 Research and Innovation Programme under agreement no. 730053. The work has benefited from results, discussions and insights from several colleagues and other projects, notably GIST (Green Industrial Transitions) and STEPS (Pathways to Sustainable Plastics) funded by the Swedish Energy Agency and the Swedish Foundation for Strategic Environmental Research, respectively.

Summary

The European pulp and paper industry (PPI) directly emits 31.9 Mton CO_2 (2016) and indirectly 12.3 and 5 Mton CO_2 from purchased electricity and transport respectively. It also accounts for 68 Mton of biogenic CO_2 emissions. The PPI is a mature industry with overall stagnating market demand in the past ten years and relatively high levels of recycling. Forest countries like Sweden and Finland dominate the production of virgin fibres whereas paper production in other countries relies more on recycled fibre and purchased pulp.

Decarbonisation across all sectors is expected to increase the competition for biomass feedstock for fuel in heat and power production, biofuels for transport, bio-based materials and chemicals, and perhaps wood for construction. This development implies new interdependencies between the PPI and other sectors. Decarbonisation of the PPI itself can be achieved through energy efficiency, fuel switching and electrification (assuming decarbonised power). This decarbonisation is ongoing and carbon intensity has been steadily declining for decades.

Two other decarbonisation pathways are important to consider. One is the transition to biorefineries and a bioeconomy where several other products than pulp and paper are produced (including liquid fuels, lignin, textile fibres and bio-composites). The other is the transition to a closed-loop carbon society where biogenic CO_2 becomes an important feedstock through carbon capture and use (CCU). For the biorefinery pathway the PPI must develop in new directions, operate in new markets, and form partnerships with other actors. So far, there is less of a clear direction for this pathway and it appears that low levels of collaboration between the chemical industry and the forestry industry constitute a barrier.

For the PPI, decarbonisation is an opportunity but increased competition for feedstock is also a threat. Feedstock scarcity in the EU as well as globally is a serious problem in scenarios where the heat, power and transport sectors use biomass for energy at scale. The limits to biomass may necessitate the use of biogenic CO_2 (e.g., from chemical recovery boilers and waste incineration) as feedstock for the production of organic compounds (e.g., liquid fuels and plastics) in a fossil free society. This pathway is relatively unexplored but our preliminary analysis shows that biogenic CO_2 is also a scarce resource unless demand for organic compounds, in particular liquid fuels, is reduced considerably. It requires large amounts of emissions-free electricity for hydrogen production and implies completely new value chains and collaborations between the forestry, energy and chemicals industries.

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1 Introduction

Meeting the climate target agreed upon in Paris, i.e. limiting the global average mean temperature increase to well below 2 °C, will require deep greenhouse gas (GHG) emission reductions over the next few decades. For industry, as well as the energy and transport sectors, these emissions will have to be reduced to almost zero by 2050. This report focuses on the pulp and paper industry (PPI) which belongs to the energy intensive industries, a group that also includes producers of for example cement and iron and steel. Compared to other energy intensive industries, the PPI has a fairly low carbon intensity. This is due to the high share of bioenergy which accounted for 59 % of the fuel use in 2016 (CEPI, 2018). The remaining 41% in the fuel mix is fossil fuels, so there is still some way to go in order to be "decarbonised". *Decarbonisation* is used in this report to describe the transition to zero/very low GHG emissions although the word is a misnomer in this context since carbon is typically the main element in wood (biomass).

The PPI handles large volumes of wood and thus has an important role in the development of the bio-based economy. The PPI has so far focused primarily on producing pulp and paper, but the industry is showing a growing interest in developing forest biorefineries with a more diversified product portfolio that also includes for example chemicals and transportation fuels. The development of forest biorefineries is considered to be central to the decarbonisation of the transportation and chemical/plastic sectors. Because of the knowledge, experience and infrastructure of handling biomass in the PPI, this industry presumably has a key role in the realisation of forest biorefineries.

This report has two objectives: i) to investigate the prospects for decarbonising the European pulp and paper industry and ii) to investigate the prospects for this industry to contribute to the decarbonisation of other sectors. To meet these objectives the report addresses the following questions:

- What are the options and capabilities of the PPI to decarbonise and what are the implications of these options?
- What are the options and capabilities of the PPI to develop forest biorefineries?
- To what extent can forest biorefineries contribute to the decarbonisation of other sectors?

The geographical focus of this report is primarily the EU. However, some of the statistics presented in this report have been gathered by the Confederation of European Paper Industries (CEPI) and therefore have a slightly different geographical coverage (based on membership in this organisation) which includes Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

2 Context and historical trends

The global production of paper and board amounted to 414 Mt in 2016 (CEPI, 2018). About 22% of this was produced in Europe. The paper production includes a large variety of products that are primarily used for printing, packaging or hygiene. Pulp for paper and paper are the core products of the European PPI, but the production of dissolving pulp (e.g., for textiles), chemicals intermediates and biocomposites is growing.

The European PPI is a mature industry characterised by few investments in greenfield projects and stagnating production volumes. European paper and board production peaked in 2007 after decades of steady growth (Figure 1). The production then fell sharply during the financial crisis in 2008, after which it has recovered but stabilised at a lower level than pre-crisis. The development differs greatly between different paper grades. The production of newsprint has almost halved since around 2005 while that of packaging papers have increased markedly (Figure 1; Paper Advance, 2018). The European consumption follows the same pattern, but involves lower volumes since Europe is a net exporter of paper and board.

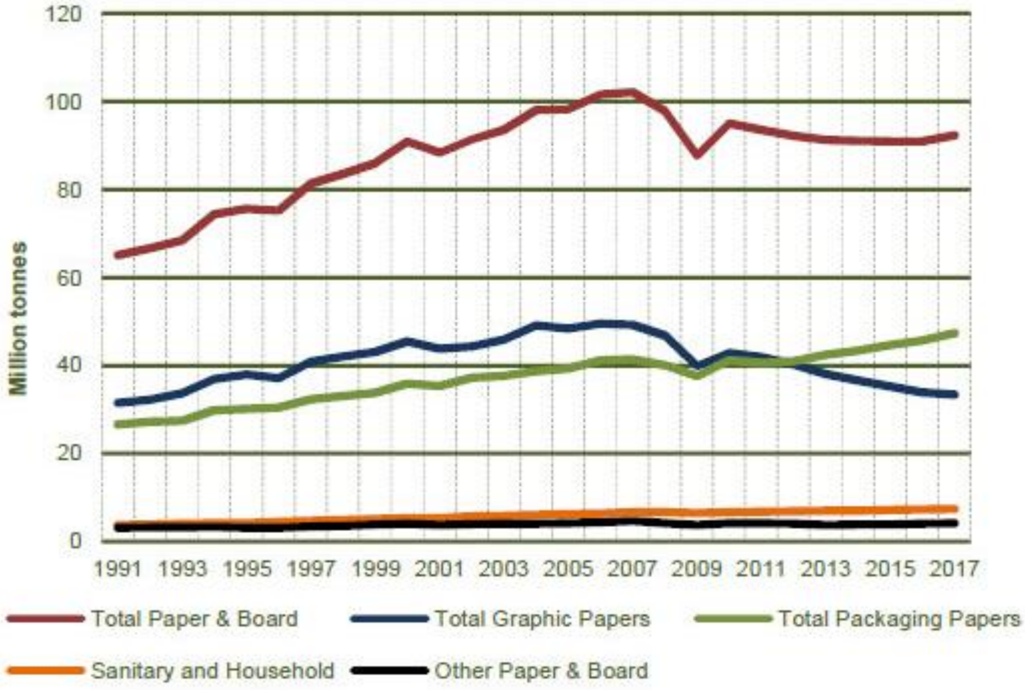

Figure 1: The production of paper and board in the EU (CEPI region) (Paper Advance, 2018).

The European PPI has experienced strong downward pressure on margins and profitability over the past couple of decades. Important drivers behind this development are increased competition from Asia and South America and the shrinking demand for newsprint and other graphic paper caused by the digitisation of media. Total turnover amounted to 82,000 M € in 2017 (CEPI, 2018).

Partly, as a response to these pressures, the European PPI has undergone significant consolidation since the turn of the century. This has led to a steady decline in the number of companies and mills while each production unit has increased in size. Another effect of this, as well as of increased automation, is the decline in people employed. About 177,000 people were employed in the European PPI in 2017, which is less than half the amount in 1990 (CEPI, 2018).

During the past 50 years, the fuel consumption in the PPI has gradually shifted towards more biomass and natural gas. Meanwhile, the use of coal has decreased and fuel oil has almost been phased out (CEPI, 2018). Electricity consumption has increased alongside industrial production and an increasing share of the electricity is produced internally via CHP. The pulp and paper processes have become increasingly energy efficient over time. The specific primary energy consumption decreased from 15.8 to 13.0 TJ/kt of paper between 1991 and 2016. Over the same time period the specific electricity consumption decreased from 1.2 to 0.9 MWh/kt of paper (CEPI, 2018). Another trend is the growing use of recovered paper in paper, which has almost doubled since 1991 (CEPI, 2018).

Historically, pulp and paper mills have caused major environmental problems at the local level due to various emissions to air and water (Söderholm, 2009). These emissions have been dramatically reduced over the past decades as a result of fuel shifts, the installation of end-of-pipe technologies and changes in process technologies, including a shift to closed water cycles, chlorine-free bleaching of pulp and a shift from sulphite to sulphate pulping (Kivimaa et al., 2008). The shift to chlorine-fee bleaching technologies that took place in the 1980s and 90s resulted in dramatic reductions in the emissions to water of chlorinated organic compounds (AOX) [1]. This major technology shift was initially driven by environmental regulation and industrywide R&D collaboration in Sweden and Finland (Söderholm et al., 2017). The shift was also driven by the market for chlorine-free paper products that emerged in the mid-1980s following the news that dioxins, which are examples of AOX, could be formed in the manufacturing of bleached chemical pulp (Söderholm et al., 2017).

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[1] AOX stands for absorbable organic halides. These compounds are generated during the bleaching process and formed as a result of the reaction between residual lignin among the wood fibres and chlorine compounds used for bleaching.

3 The pulp and paper production system

This section first provides an overview of the pulp and paper production system from a value chain perspective and then describes the pulp and paper processes, and the energy use and GHG emissions in the PPI.

3.1 Overview of the value chain

Figure 1 illustrates the value chain for paper and board, starting with acquisition of raw materials (mainly wood) and ending with a final consumption and waste management. The figure includes the main material flows except for water consumption and discharges.

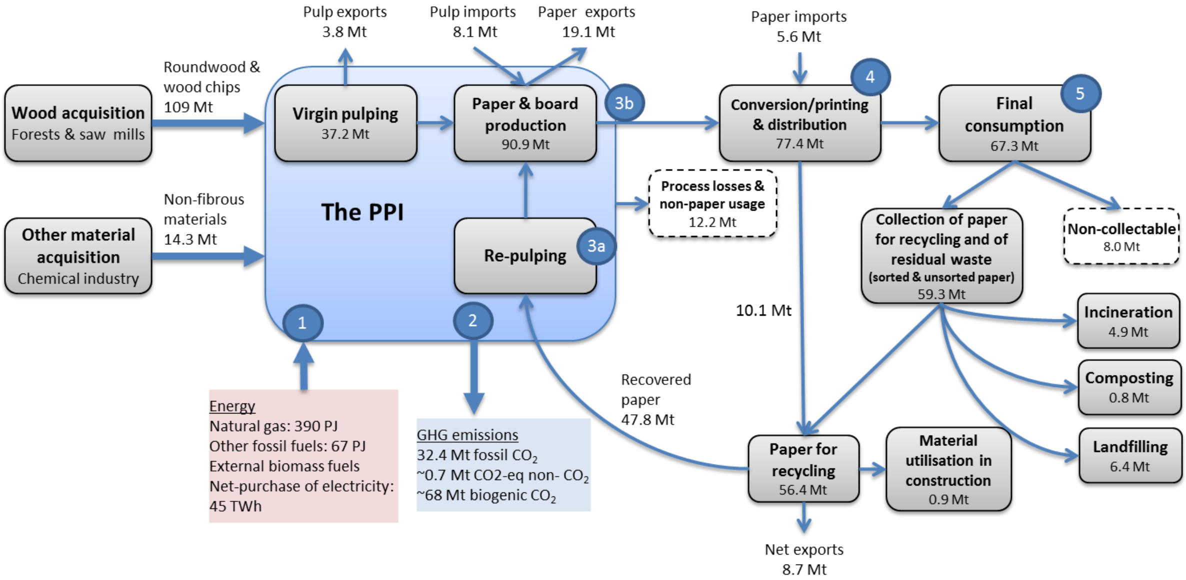

Figure 2: Sketch of the material flows (Mton, in 2016) in the value chain of paper and board (CEPI, 2017a, 2017b and 2018). Water intake (3397 Mm^3 in 2016) and discharge are excluded. The encircled numbers refer to the following mitigation options: (1) energy efficiency, (2) emission efficiency and reduction, (3a) materials efficiency in manufacturing, (3b) materials efficiency in product design, (4) product service efficiency and (5) service demand reduction, which are described in Section 4.

The European PPI almost exclusively uses wood as virgin fibre source. The wood consumption amounted to 109 Mt in 2016 and consisted of roundwood from forestry and wood chips from saw mills (CEPI, 2017a). About 91% of the wood consumption originated from Europe and the remaining 9% were imported from mainly Russia and Belarus. The raw material consumption of the PPI also includes non-fibrous materials (14.2 Mt), which mainly consist of calcium carbonates, starches and clays that are used as coating and filler in paper production.

Paper making starts with debarking and chipping of the roundwood into small pieces and pretreatment of wood chips. In the following pulping process, the wood is separated into fibres by chemical or mechanical means for production of pulp (see section 3.2). Wood is composed of cellulose (~40-50 %), hemicelluloses (25-35 %), lignin (18-35%) and extractives, including organic compounds and ash (4-10%) (Petterssen, 1984). The next step is paper production, which can be based on either virgin wood pulp or pulp from recovered paper (see Section 3.3). Pulp and paper mills can be either integrated or separate operations. An integrated paper mill produces pulp on-site while a non-integrated pulp mill produces market pulp that is dried and pressed before it is transported to a paper mill.

Paper and boards are often intermediate products that are converted and/or printed into final products by downstream companies. Some products, such as tissue and office papers, are often distributed directly to consumers without further conversion (Hänninen, 2014). The majority of paper and board products are for single use and thus they are used for a short period of time before becoming waste that is collected as part of residual waste or as separate fractions for recycling. About 12% of the final consumption of paper was not collected in 2016 (CEPI, 2017a); this includes toilet paper as well as paper and board that are accumulated in society. Most of the paper for recycling is utilised within the European PPI. However, all of the fibres in the recovered paper that is circulated back to the PPI do not end up in new paper since some fibres may be of too poor quality. Paper can be recycled 4 to 8 times on average (Ervasti et al., 2016). Consequently, continued injection of virgin fibre and other materials into the system is required in order to replace the materials lost during each recycling round. Considerable amounts of paper for recycling were exported to China in 2016. Furthermore, a small amount of recovered paper is used for material purposes in other sectors, primarily construction and buildings.

Based on CEPI's definition, the recycling rate in the EU 28 amounted to 72% in 2016 (CEPI, 2017a). This recycling rate is calculated as the ratio between the amount of paper collected for recycling (used in the European PPI or exported) and the market supply of paper and board in Europe. The recycling rate does not take into account the fact that Europe is a net importer of paper and board via packaged goods from Asia and there is no estimate of this indirect import of paper (Ervasti et al., 2016).

3.2 Pulp production

Pulp can be produced from virgin fibre via chemical or mechanical pulping and from recovered paper. The processes differ significantly and result in pulp with different properties that are suitable for different types of paper products. Table 1 shows the production and consumption of pulp from virgin fibre in Europe. Sweden and Finland accounted for 31% and 29%, respectively, of the virgin wood pulp production in 2016 (CEPI, 2017a). Europe is a net importer of wood pulp and most of the pulp imports come from Latin America (CEPI, 2017a).

Table 1: Virgin pulp production and consumption in Europe in 2016 (CEPI, 2017a).

	Production (Mt)	**Consumption (Mt)**
Chemical pulp in total	26.8	31.1
Sulphite pulp	1.8	1.6
Sulphate (kraft) pulp	25.0	29.4
Mechanical and semi-chemical pulp	10.1	10.1
Other pulp	0.3	0.4
Total	37.2	41.5

Chemical pulping is the dominating pulping process based on virgin fibre. In this process, fibres are extracted from the wood in a digester under pressure with the use of cooking chemicals (which dissolve the lignin) and then separated by washing. Around 50% of the wood (primarily cellulose) is converted into pulp while lignin, many other organic substances and the cooking chemicals end up in the spent pulping liquor (so-called black liquor). The black liquor is heated to evaporate water and increase the solids content. The black liquor is then burned in a chemicals recovery boiler which produces steam for electricity production and process heat. The cooking chemicals are recovered from the bottom of the boiler as a smelt which is then dissolved in water to form green liquor. The cooking chemicals are regenerated in the causticizer where the green liquor is reacted with calcium hydroxide (produced from calcium oxide). The precipitate from the causticizer is called lime mud and burned in the lime kiln to regenerate the calcium oxide. The chemical pulping process leaves the fibres fairly intact which makes this pulp suitable for high-quality paper products. There are two main processes for chemical pulping: sulphate (kraft) pulping and sulphite pulping. Sulphate (kraft) pulping is the most common process; sulphite pulping is mainly used for production of specialty paper and non-paper products. A special grade of bleached sulphite pulp is known as dissolving pulp which is used for production of cellulose derivatives and textiles (e.g., viscose).

Mechanical pulping uses mechanical shear to separate the fibres and is usually integrated with paper production. The majority of the lignin remains with the fibres; around 95 % percent of the wood ends up in the pulp. Mechanical pulp is mainly used for weaker papers such as newsprint and these papers turn yellow and brittle with time due to their lignin content. There are two main processes for mechanical pulping: thermo-mechanical pulping (TMP) and stoneground wood pulping. Pulp is also produced in processes that combine chemical and mechanical pulping technologies.

Recovered paper is used as fibre source in the **re-pulping process**. The recovered paper is soaked in large containers where the fibres disintegrate. The following steps involve removal of various additives (contaminants); for high-quality paper de-inking is necessary. Another possible step is fractionation which separates the fibre stream into two or more flows on the basis of fibre properties such as fibre length. The quality of each fibre stream can thus be adjusted to suit the product requirements. The re-pulping process is always integrated with paper production. Newsprint and case materials (type of packaging) are almost exclusively produced from recovered paper (CEPI, 2017).

3.3 Paper production

The European production of paper and board amounted to 91 Mt in 2016 and included a variety of paper products and grades (CEPI, 2017a). About half of the production consisted of packaging paper (e.g. carton boards and case materials) and 37% of graphic paper, including newsprint. The rest was mainly sanitary and household papers, primarily various tissues. The paper production is geographically more spread out than pulp production from virgin fibres. The largest producing countries are Germany (25% of total production), Sweden (11%) and Finland (11%) (CEPI, 2017a). Europe is a net exporter of paper with Asia as the main export market.

Table 2: Paper and board production and consumption in Europe in 2016 (CEPI, 2017a).

	Production (Mt)	**Consumption (Mt)**
Newsprint	6.5	6.0
Other graphic papers	27.4	20.8
Sanitary and household	7.3	7.0
Total packaging papers	44.7	39.8
Other paper & board	4.0	3.7
Total	90.9	77.4

The European paper production in 2016 was based on 41.5 Mt of virgin pulp and 47.8 Mt of recovered paper[2] (CEPI, 2017a) is this. The paper making process starts with stock preparation. In this step the pulp (sometimes different kinds of pulp) is mixed with water and additives and transformed via different processes (e.g. screening, cleaning and refining) into a slurry with properties suitable for entering the paper machine. The pulp slurry is then sprayed onto a flat wide screen which moves very quickly through the paper machine in which the paper properties are developed. The paper machine contains different sections in which water is removed by different means, including vacuum, pressing and drying. Steam-heated cylinders is the most common technology used in the drying section. After drying, some types of paper are coated with calcium carbonates, clays or starches in order to provide a certain quality (weight, gloss etc.).

3.4 Energy use

Fuel consumption in the European PPI amounted to 1165 PJ in 2016. The fuel consumption was dominated by biomass (59%), but also includes natural gas (33%), coal (4%), fuel oil (2%) and other (2%) (CEPI, 2018). The electricity consumption in 2016 amounted to 96 TWh, of which 51 TWh was produced internally (CEPI, 2018).

Pulp and paper production is energy intensive, but the energy balance and character of the energy use vary greatly between different pulp and paper mills depending on the pulping process, type of paper product and if the pulp and paper production processes are integrated or separated processes. The specific energy use is lower in integrated pulp and paper production since there is no need for drying of the pulp and due to better opportunities for heat integration between the processes. The pulping and paper production processes typically require process heat of less than 200°C, although steam generators in boilers operate at around 500°C and lime kilns around 1000°C or higher (ÅF, 2011).

The mechanical pulping process mainly uses electricity as energy input and the process yields waste heat (steam) that is typically used for paper drying. Chemical pulping, on the other hand, uses large amounts of process heat, but less electricity. The process heat in chemical pulp production is mainly generated by burning black liquor in the chemical recovery boiler but also by burning bark or forestry residues in biomass boilers. Because of the use of internal by-products for production of electricity and process heat, modern non-integrated kraft pulp mills are self-sufficient in energy, and sometimes net exporters of electricity and biomass fuels. Many chemical pulp mills, however, still use fossil oil or gas in the lime kiln although a number of lime kilns have been converted to biomass fuels (ÅF, 2011).

In paper production, most of the energy is used in the drying section of the paper machine. Drying accounts for up to 70% of the fossil energy use in the European PPI (CEPI, 2011).

3.5 Greenhouse gas emissions

The GHG emissions from the PPI mainly consist of CO_2 emissions, but also of small amounts of methane and nitrous oxide. In 2016, the European PPI emitted 31.9 Mt CO_2 from burning of fossil fuels in boilers (including the emissions from on-site outsourced energy facilities) and lime kilns, and 0.7 Mt CO_2-eq of other GHG (CEPI, 2017; EEA, 2017). Process-related CO_2 emissions are also generated in the calcination process in the lime kilns. These CO_2 emissions are primarily of biogenic origin since the carbon contained in the calcium carbonate originates from wood and only small external inputs of sodium carbonate are made to the lime kiln in order to make up for losses (Miner and Upton, 2002).

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[2] Note that all of the recovered paper does not end up in new paper since the recovered paper also contains non-fibrous material and fibre of too poor quality.

The production of pulp and paper also generate CO_2 emissions in other sectors such as the energy and transportation sectors. The indirect CO_2 emissions related to the purchased electricity amounted to 12.3 Mt CO_2 in 2016 (CEPI, 2017a). Earlier estimates of the indirect CO_2 emissions related to transportation indicate that these could amount to around 5 Mt CO_2 per year (CEPI, 2011).

The biogenic CO_2 emissions in the European PPI are estimated to 68 Mt in 2016 (calculated based on 685 PJ of biomass use and an emission factor of 100 kg CO_2/GJ biomass) and are thus twice as large as the fossil CO_2 emissions.

4 Options for decarbonisation

This section describes a number of mitigation options that relate to different parts of the PPI value chain and that are indicated in Figure 2. The focus here is on how the pulp and paper production in itself can be decarbonised and not on the important role that the PPI can play in decarbonising other sectors.

4.1 Energy efficiency

4.1.1 Energy efficiency measures within pulp and paper mills

Energy efficiency improvements can contribute to the decarbonisation of the PPI. Energy efficiency has always been important for the PPI since it enables reduced energy costs and continuous improvements have been made over the past decades. Further improvements can be achieved by gradual replacement of machinery to more efficient equipment, improved process control and optimisation, and waste heat recovery (Suhr et al., 2015). Each mill typically has its unique energy balance with heat and electricity needs, and often CHP production. Heat recovery can be achieved by heat integration and installation of industrial heat pumps which lifts the temperature of waste heat with input electricity[3] to a temperature high enough for reuse (see more in Section 4.2.2 on electrification). Energy management systems are an important tool for identifying and implementing energy measures since these systems lead to a systematic way of working with this issue (Stenqvist et al. 2011). CEPI (2017c) estimates that energy efficiency improvements via increased automation and digitalisation and investments in state-of-the-art production processes could lead to a reduction of the annual GHG emissions of 7 Mt CO_2 by 2050 compared to 2015.

A gradual shift to state-of-the-art technologies can bring important improvements in energy efficiency, but emerging and radical technologies will be necessary in order to achieve substantial energy savings in the PPI. Within mechanical pulp production research efforts focus on improving the efficiency of refining and grinding as well as pretreatment of wood chips. Pretreatment of wood chips has the potential to reduce use of energy as well as chemicals in chemical pulping processes. Two emerging technologies for kraft pulp mills are microwave pretreatment and the reuse of green liquor for pretreatment of wood chips. For mechanical pulping, biological pretreatment and chemical pretreatment with new chemicals are being developed (Kong et al., 2016). There is also research on a new, radical pulping concept which is based on the use of deep eutectic solvents produced by plants. These solvents can dissolve the lignin at low temperature and atmospheric pressure and thus replace chemical and mechanical pulping. The benefit of this pulping technology is that it would deliver 40% energy savings and enable the extraction of cellulose from waste (CEPI, 2013).

Since drying is the largest energy use in paper production, the PPI has always looked for new ways of producing paper with less water, more efficient ways of dewatering paper and improved drying technologies. One example is the development of the extended nip press for dewatering (Luiten, 2001). Another example that has been developed for a long time is impulse drying (Nilsson et al., 1995; Luiten, 2001; Laurijssen et al., 2010). One emerging concept is to use vapour combined with largely dry fibres to form paper and board. Other emerging concepts are to suspend the fibres in a highly viscous solution instead of water (referred to as DryPulp) and drying with supercritical CO_2 or superheated steam (CEPI, 2013).

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[3] one unit of electricity typically yields 3-5 units of process heat.

4.1.2 Industrial clustering

Industrial clustering represents an opportunity for energy and resource savings in the PPI and other sectors by enabling heat integration and efficient use of waste streams, including CO_2. In practice the opportunities for industrial clustering are limited for existing installations and there can be significant local planning difficulties (WSP et al., 2015). Within the forest sector, there is a potential for further mergers of pulp and paper mills and of co-location with saw mills. There is also potential to further develop industrial clustering of the PPI with waste management. Such clustering is especially attractive for paper mills in countries that lack opportunities to recover heat from waste incineration in district heating networks. There is also an opportunity to develop integrated biorefinery complexes together with other sectors such as the chemical industry; this is further described in Section 5.1.

4.2 Emission efficiency and reduction

4.2.1 Fuel switch, replace fossil fuels with biomass

Biomass can replace fossil fuels in the production of process heat in boilers and in the lime kilns and has increasingly been doing so for the past 20-30 years. CEPI (2011) estimates that replacing the remaining use of oil and gas in lime kilns with biomass, would save 3-4 Mt of CO_2. This can be done by firing pulverised biomass directly in the lime kiln or by gasifying the biomass and firing the resulting producer gas in the lime kiln. In theory, all process heat in the PPI could be supplied by biomass combustion. The opportunities for using bioenergy, however, differ between different types of mills depending on their availability of internal by-products and residues and location. Chemical pulp mills have access to large volumes of residues that are used for energy purposes while paper mills that use recovered paper as fibre source have little residues.

4.2.2 Electrification

Electricity can replace steam and fuels for heating purposes and thus promote decarbonisation of the PPI assuming the use of low-carbon electricity. It is possible to produce steam and hot water from electricity via electric boilers and industrial heat pumps. Electric boilers can supply heat of low and medium temperature (up to 400°C) and could thus in theory replace all fuel fired boilers in the PPI. Industrial heat pumps are currently limited to supplying heat at up to 100°C, but enhanced industrial compression heat pumps that are under development are expected to be able to supply heat of up to 150°C (Kleefkens and Spoelstra, 2014). New concepts that are in the research stage could possibly supply heat of up to 200°C (ibid). Plasma generators may be an option for replacing fuel in lime kilns, an option currently explored by the cement industry.

Within paper drying there is an opportunity to replace the use of steam or fuel by introducing electro-thermal technologies such as infrared drying and impulse drying (Laurijssen et al., 2010). These are commercially available technologies, but not widely adopted. One reason is that the drying technology is important for the paper quality and thus the technologies are not interchangeable.

In theory, electrification of the PPI could also be achieved by the restructuring of the industry towards more mechanical pulping. In reality, the strategy is constrained by the lower quality of mechanical pulp.

4.2.3 Bio-CCS

The technology of carbon capture and storage (CCS) provides an opportunity for achieving negative CO_2 emissions in the PPI due to its large use of bioenergy. CCS has been demonstrated for combustion facilities but is currently only applied at commercial scale in oil and gas extraction. The opportunity for implementing CCS varies between different mills depending on their size, pulping technology, location etc. Due to economies of scale, CCS is mainly attractive for large point sources of CO_2 (~> 0.5 Mt/y) or at point sources within industrial clusters. Kraft pulp mills have large biogenic CO_2 emissions from the chemical recovery boiler and present the best opportunity for heat integration of a post-combustion CO_2 capture process (Jönsson and Berntsson, 2012). These mills are, on the other hand, often not located in industrial clusters with large CO_2 emissions (Jönsson and Berntsson, 2012).

4.3 Materials efficiency in manufacturing and product design

Increasing the use of recovered paper in paper production (# 3a in Figure 2) saves wood and energy resources since re-pulping requires less energy input than chemical and mechanical pulping. There is a certain potential to increase the recycling of paper by increasing the source separated paper collection and improving the sorting technologies. A recycling rate of 80% (equal to using the fibres on average five times) has been suggested to be a realistic goal considering the consumption of non-recoverable paper such as tissue (Miranda et al, 2010). The utilisation of recycled paper in the European PPI can also be increased by reduced exports of recovered paper. In 2018 China banned the imports of various recyclables, including unsorted paper. The European exports of unsorted paper for recycling are therefore likely to decrease in the future. Unsorted paper and recovered paper that has been separated from collected co-mingled waste are, however, often of poor quality (Miranda et al., 2010). Changes in the collection and sorting of waste are therefore necessary in order to increase the utilisation of these types of recovered paper in PPI.

The quality of recovered paper differs between different paper grades. In order to handle these variations, there is a European list of standard grades of recovered paper and board (EN 643) which defines grades and combinations of the types of recovered papers that are acceptable for recycling. The main potential for an extended use of recovered paper lies in the production of graphic paper, for which the quality requirements have always been high (Miranda et al, 2010). There is also a potential for saving wood resources and energy by producing more lightweight products or by modifying the material composition (with fibres, fillers etc) of the paper products (# 3b in Figure 2).

4.4 Product service efficiency and service demand reduction

Paper and board primarily serve the purpose of information dissemination, packaging or hygiene. There is certain potential to provide these services more efficiently (# 4 in Figure 2). One example is information dissemination via digital media, a shift that is already taking place. In the case of hygiene, there is no apparent alternative to tissue but an opportunity to improve the efficiency via product design. Also packaging could in many cases be achieved with less material. There are other material options than paper and board for packaging, for example plastics. Plastics is, however, not a desirable alternative since it is largely based on fossil feedstock.

Decarbonisation can also be facilitated by reducing the demand for the services provided by paper and board (# 5 in Figure 2). Such a strategy could be applied on packaging, but appears less desirable with regard to hygiene and information dissemination. An important function of packaging is to preserve or protect the content. It is therefore important that strategies for reducing the demand for packaging do not compromise the quality or functionality of packaging. The demand for packaging is strongly related to overall consumption and consumption patterns. In recent years, growth in e-commerce has been an important driver for increased use of packaging (Hänninen et al, 2014). Demand for packaging can be reduced by changes in logistics and storing as well as reduced consumption of physical goods.

5 The PPI in the bio-based economy

Section 5.1 presents the key biorefinery technologies that could be integrated into the PPI. Focus is on technologies that enable production of chemicals, fuels, and cellulosic fibres while the opportunity to export heat and electricity is not discussed. In Section 5.2 we discuss the potential supply of forest biomass in relation to the potential demand for bio-based products in other sectors.

5.1 Biorefinery pathways/technologies

There are a number of biorefinery technologies that can be integrated into an existing pulp and paper mill. Below we discuss some important technologies that are currently under consideration (they are also summarised in Table 3). Some of the technologies can be combined, while others are mutually exclusive. The conditions for integrating these technologies differ between existing mills depending on their process, design, age etc., but in most cases they are suitable mainly for chemical pulp mills.

Table 3: Biorefinery technologies/pathways that can be integrated in pulp mills and thus transform them into biorefineries. Some technologies can be combined while others are mutually exclusive. The list has been developed from Karltorp and Sandén, (2012), Pettersson et al. (2012) and Ericsson (2017).

Technology pathway	**Product**	**Comment**
Thermal gasification (of black liquor or solid biomass) and synthesis	Synthesis gas that can be upgraded to chemicals/fuels such as methanol, methane, DME, Fischer-Tropsch fuels	Black liquor gasification leads to reduced steam and electricity production and enables increased capacity in pulp production.
Lignin extraction and refining	Solid fuels, carbon fibres, activated carbon, phenols, lignin oil (various biofuels)	Decreases steam and electricity production and enables capacity increase in pulp production.
Hemicelluloses extraction (from wood chips or pulping liquor) and refining	Ethanol, butanol, acetic acid, xylitol	Decreases steam and electricity production and enables capacity increase in pulp production.
Conversion of cellulose to alternative products (via a number of technologies)	Dissolving pulp, textile fibres, ethanol, biocomposites	Displaces pulp for paper production.
Separation and refining of extractives from bark or black liquor	Crude tall oil (fatty acids, triglycerides, rosin acids, phenolics, biodiesel), turpentine	Limited potential in terms of product volumes.
Anaerobic digestion of sludge	Biogas, solid biofuels, fertiliser	Limited potential in terms of product volumes.
Carbon capture and utilization (incl. hydrogen boosting of gasification and of biogas upgrading)	Methanol, methane, DME, Fisher-Tropsch naphtha and fuels (diesel, jet fuel, petrol)	The hydrogen production increases the electricity consumption.

Thermal gasification is a key technology for forest-based biorefineries since it enables the conversion of all parts of the wood into a synthesis gas (hydrogen and carbon monoxide) which then can be converted into various chemicals and fuels (see eg. Larson et al., 2006). The technology can be applied on black liquor as well as solid biomass such as forestry residues. Black liquor gasification is an alternative technology to the chemical of recovery boiler and enables production of syngas while recovering the inorganic chemicals. Replacing the chemical recovery boiler with black liquor gasification will change the energy balance of the mill. The recovery boiler is sometimes the bottleneck in chemical pulp mills. In such cases it is possible to increase the capacity of the mill without investing in a new recovery boiler through diverting some of the black liquor to a gasifier.

An alternative to black liquor gasification is to extract the lignin from the black liquor. Lignin contains complex organic polymers and can be used as a solid fuel or raw material for production of various chemicals and materials. In the LignoBoost process, 25-50% of the lignin is extracted from the black liquor via precipitation at low pH with CO_2; the lignin is then washed and dried (Moya and Pavel, 2018). Hemicelluloses, which mainly consist of macro-molecular sugars, can also be extracted from black liquor and then used as raw material for production of e.g. ethanol, fibre additives and hydrogels (Pettersson et al., 2012). Hemicelluloses can alternatively be extracted from the wood chips prior to cooking; this procedure is normally carried out before production of dissolving pulp. The extraction of hemicelluloses and lignin from black liquor reduces the steam production and can enable a capacity increase of the mill.

Cellulose can be used for a range of other products than pulp for paper, including for example textile fibres (sometimes via production of dissolving pulp), ethanol and biocomposites. There are two chemical processes for production of dissolving pulp, the modified sulphite processes and the pre-hydrolysis kraft process (Pettersson et al., 2012). The dissolving pulp can be used for production of for example viscose fibres for textiles. Ethanol can be produced from cellulose via acid or enzymatic hydrolysis followed by fermentation. Cellulose can serve as fibre source in biocomposites which are formed by fibres that are reinforced by a matrix of bio-based polymers (which can be produced from hemicelluloses). Biocomposites are used in applications such as automotive interior parts, furniture and decking.

Various extractives can be extracted from bark and wood chips or be recovered from black liquor. The evaporation of black liquor in the kraft process makes it possible to recover turpentine and soap (salts of fatty acids) as well as impure methanol (IRENA, 2018). The tall oil soap can then be reacted with acid to produce 'crude tall oil'. The crude tall oil can be processed into biofuels, and various chemical intermediates for production of adhesives, coatings etc.

At the pulp mills, wastewater is fed into a wastewater treatment plant where sludge containing organic and inorganic solids is separated from the wastewater (IRENA, 2018). The sludge can be fed to an anaerobic digester for production of biogas that can be used as fuel internally or sold for external fuel use after being upgraded to biomethane. The solid remnant after digestion contains a large amount of lignin, which after being dried and pelletised can be used as fuel. It can also be used as fertiliser (ibid).

A technology that is less frequently discussed in the biorefinery context is carbon capture and utilisation (CCU). This technology involves capturing of CO_2, for example from the flue gases of the recovery boiler, and then utilising the captured CO_2 as feedstock together with hydrogen for production of chemicals and fuels (see e.g. Quadrelli et al., 2015). Alternatively, the utilisation of CO_2 could be integrated in biorefinery technologies that generate CO_2 residue streams, for example upgrading of biogas or thermal gasification (Hannula, 2016). Using such CO_2 as feedstock would enable a higher share of biogenic carbon to be converted into chemicals and fuels. The concept requires investments in an electrolyser for production of hydrogen and possibly hydrogen storage, and increases the electricity consumption of the mill.

5.2 The availability of biogenic carbon versus potential demand

The potential biomass supply and the level of recycling of bio-based is products set an upper physical limit to the development of the bio-based economy. As regards the biomass supply, the discussion in this section is restricted to the forest sector although the agricultural sector can also play an important role with the use of residues and changes in land use (see e.g. EEA, 2006).

Forest land and other wooded land cover about 182 Mha in the EU28, corresponding to 43% of the land area (excluding lakes and large rivers) (Eurostat, 2016). The biomass volume in European forests is steadily increasing since the forested area is increasing and the removals are well below the net annual increment (i.e. growth). In 2015, the growing stock of roundwood in forests available for wood supply amounted to about 23,100 Mm^3 including bark and the net annual increment amounted to 720 Mm^3 solid volume including bark. The presented volumes refer to roundwood and do not include tops and branches, some of which could be extracted as logging residues when harvesting roundwood. The ratio of logging residues to stem wood varies for different tree species and is highest for spruce. Due to ecological restrictions, all logging residues should generally not be removed from a harvest site and in some cases residues should not be removed at all (Savolainen and Berggren, 2000).

The roundwood removal in the EU28 is less than the annual increment and amounted to 458 Mm^3 excluding bark (about 522 Mm^3 including bark) and consisted of 99 Mm^3 firewood and 359 Mm^3 industrial roundwood (Eurostat, 2016). Most of the industrial roundwood is used for production of sawn wood and pulp and paper, but some is also used for production of particle boards etc. An important part of the harvested industrial roundwood passes through saw mills where about 50% of the saw logs are converted to sawn wood; the remaining 50% becomes wood chips and sawdust which are sold to the PPI, the wood fibre industry and the energy sector.

The size of the annual increment suggests that it is possible to increase the removals to at least 650 Mm^3 (including bark), which corresponds to 90% of the current annual increment in forests available for wood supply. This level of roundwood harvest could furthermore enable the extraction of about 100 Mm^3 of logging residues[4] when considering ecological constraints.

So how much roundwood is required for the production of sawn wood and paper, the two main products from forest biomass? The case presented in Box 1 shows that about 270 Mm^3 of wood including bark is required to maintain the current production levels (90 Mt of paper and 100 Mm^3 of sawn wood). The calculations in this case disregard international trade of forest products, and assume higher utilisation of recovered paper than today and that paper only consists of cellulose and fillers (mechanical pulping is disregarded in order to simplify the calculations).

Hence, in theory 380 Mm^3 of roundwood could be available for other purposes, including the production of chemicals and transportation fuels, or increased production of paper and sawn wood for construction. Other potentially available resources include logging residues and by-products (e.g. bark and black liquor) from the forest industry. It should be noted that black liquor and much of the bark are currently used within the forest industry for production of process heat and electricity.

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[4] Assuming an extraction of logging residues that corresponds to 15% of the roundwood harvest, which is a conservative estimate.

Box 1: Biogenic carbon flows related to paper and sawn wood

How much roundwood is in theory required to sustain the current annual production of sawn wood and paper and what is the potential amount of other outputs? In order to answer these questions we made some back-of-the-envelope calculations (see Appendix) which focus on the material demand of the products (i.e. disregard the energy balance). Figure 3 illustrates the calculated carbon flows associated with the production of 100 Mm^3 sawn wood and 90 Mt paper and board, which is roughly the current annual production level.

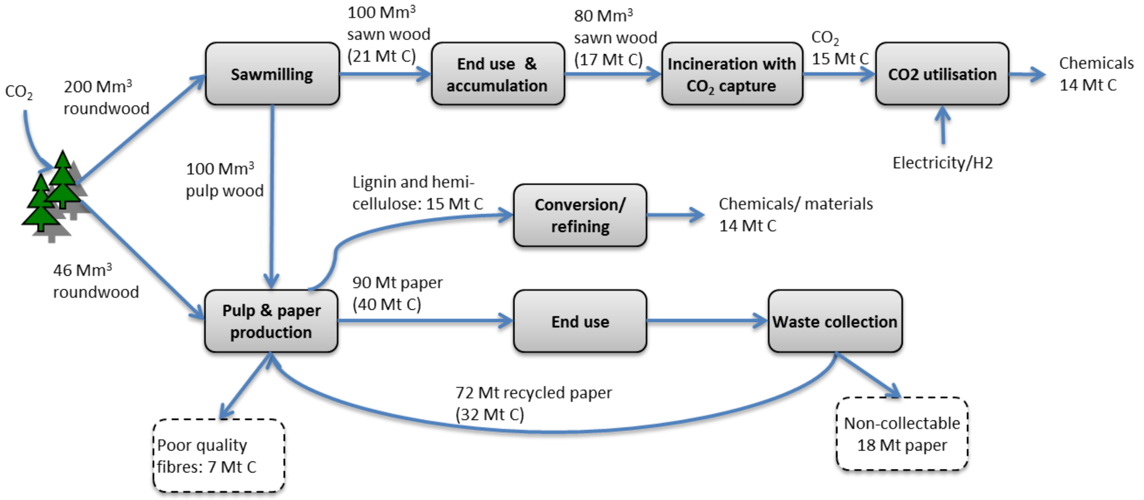

Figure 3: The estimated material and carbon flows associated with the production of 100 Mm^3 sawn wood and 90 Mt paper and board.These calculations were based on the following assumptions: the annual production amounts to 100 Mm^3 sawn wood and 100 Mt paper and board; 50% of the stem wood input to saw mills is converted to sawn wood and 50% to pulpwood; bark adds 14% to the volume of roundwood excluding bark; paper consists of 90% fibres and 10% fillers; 80% of the annual paper production is collected for recycling; the re-pulping involves 20% fibre losses (fibres of poor quality are removed); roundwood consists of 50% cellulose (the remaining 50% is hemicelluloses and lignin); the CO_2 capture rate from incineration is 90%; the CO_2 conversion rate to chemicals is 95%. The following conversion factors were used: 1 m3 of wood = 0.42 t solid matter on average; 1 t dry matter = 0.49 t pure carbon

Figure 4 illustrates how the potential supply of forest biomass (as biogenic carbon) relates to the potential demand for biogenic carbon. The ‘supply-side’ shows the biogenic carbon that is available in the potential biomass removals, that is required for the sawn wood and paper production and that is available for other purposes. The last category includes biogenic carbon in residues, by-products, residual roundwood, as well as CO_2 from incineration of sawn wood at its end of life. The potential demand for biogenic carbon for transportation fuels is represented first by the current use of fuels in the EU transportation sector (including aviation and shipping), and second by a scenario where two thirds of the current fuel use in road transportation has been phased out while fuel use remains the same in aviation and shipping. In 2016 liquid biofuels accounted for about 5% of the fuel use in the EU road transportation sector and less for the transportation sector as a whole, which is heavily dominated by fossil fuels (EC, 2018). The potential demand for biogenic carbon for plastics is represented by the use of plastics in the EU in 2017, which amounted to 49 Mt (Plastics Europe, 2018).

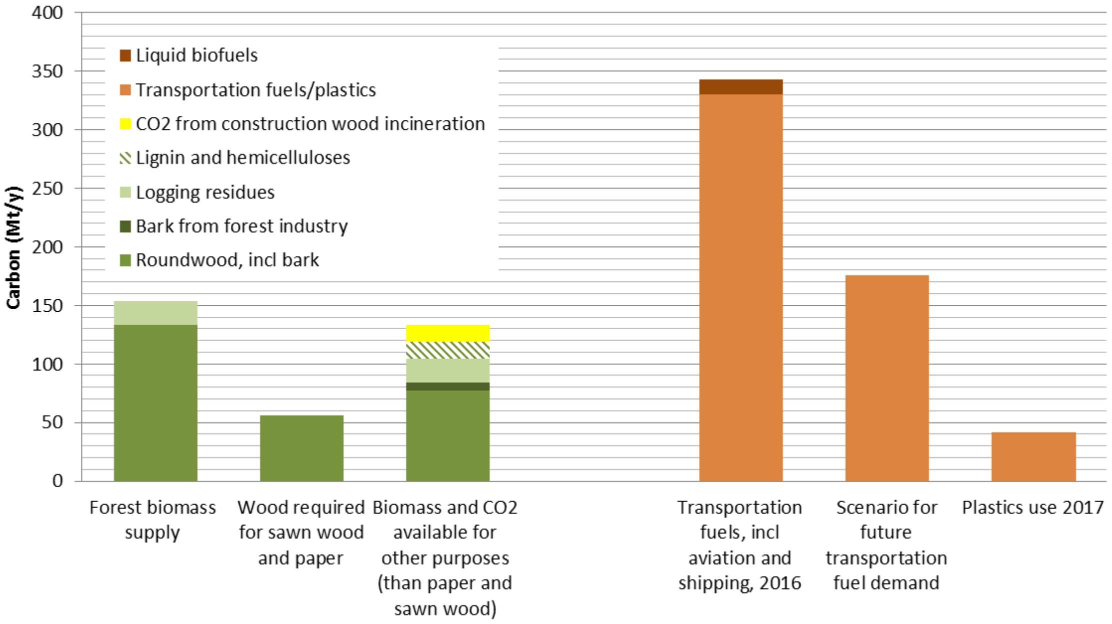

Figure 4: The potential supply of biomass (expressed as biogenic carbon) and the potential demand for biogenic carbon for production of transportation fuels and plastics, based on the current consumption and a scenario for the transportation sector. The 'supply-side' shows the biogenic carbon available in the potential biomass removals, the biogenic carbon that is required for the sawn wood and paper production and the biogenic carbon that is available for other purposes. The carbon content in transportation fuels was calculated based on the reported CO_2 emissions from the sector (EC, 2018). The transportation fuel scenario assumes that two thirds of the fuel use in road transportation has been phased out while fuel use in shipping and aviation remains the same. The demand for carbon for plastics use in 2017 was calculated based on statistics from Plastics Europe (2018) and the assumption of 85% carbon content in plastics.

The demand for bio-based materials could also increase in other sectors as a consequence of decarbonisation efforts. Wood is sometime proposed as a substitute for steel and concrete in buildings but we have not found any estimates of the potential demand for wood that could result from such substitution. Today, large amounts of biomass are used as fuel for heat and power production. This biomass use amounted to 5.2 EJ in 2016 (Eurostat, 2017), which corresponds to about 140 Mt C[5]. The CO_2 emitted from large-scale biomass combustion could be used by applying CCU technologies.

When comparing the potential supply and demand in Figure 4, it should be noted that the conversion of biomass into biofuels, chemicals and plastics generally involve considerable carbon losses, in particular carbon that ends up as CO_2 (or in various residue streams). This CO_2 can be used by applying CCU technologies (see e.g. Ericsson, 2017). Such concepts can close carbon loops and reduce emissions but require potentially large inputs of electricity. One Mt of CO_2 converted to methanol would require 136 kt hydrogen, which in turn requires 6.5 TWh electricity[6].

The estimates presented in Figure 4 point to the size and importance of the transport sector as a potential future user of biogenic C and CO_2. The current plastics production relies almost entirely on new fossil feedstock for carbon and recycling rates are low. A future plastics system could close the loops on carbon

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[5] The carbon content was calculated based on a CO_2 emission factor for biomass of 100 kg CO_2/GJ (~27 kg C/GJ).
[6] Assuming hydrogen has an energy density of 120 MJ/kg and that the electrolyser has a conversion efficiency of 70%. Assuming a 95% conversion of the CO_2 would yield 14.3 MJ (725 kt) of methanol.

by increasing mechanical as well as chemical recycling and that way the need to replenish the system with new biogenic carbon can be reduced to perhaps 20-30 Mt/y (Bauer et al., 2018). This could involve using hydrogen from electrolysis and carbon dioxide from incineration and gasification to produce new hydrocarbons via methanol synthesis.

6 Capabilities for decarbonisation and biorefinery development

This section addresses various aspects that impact the capabilities of the PPI to decarbonise and to develop forest biorefineries. The structure of this section draws on the frameworks presented in Wesseling et al. (2017) and Bulkeley and Stripple (2018).

6.1 Industry structure

The PPI is characterised by high capital intensity, long investment cycles and strong economies of scale. High capital utilisation is therefore an important factor for profitability and it is on average around 90% for the European production of pulp and paper (CEPI, 2018).

The PPI is highly diversified in terms of technology, fibre source and products, something that affects the choice of location and amount of by-products. Pulp (and paper) mills which use virgin fibre are generally located in forested areas and sometimes co-located with saw mills. They are often on the coast and near rivers where timber was traditionally transported through log driving. Non-integrated paper mills and paper mills which use recycled fibre are, on the other hand, often located near the consumers.

Individual forest industry companies are often specialised towards certain types of pulp and/or paper products. Some pulp and/or paper producers are part of forest industry groups that also produce e.g. sawn wood, wood pellets, dissolving pulp, textile fibres and tall oil. The PPI consist of a wide mix of companies ranging from companies with one or a handful of mills in one country to multinational companies that have production sites across Europe as well as other regions.

The European PPI is a mature industry that is dominated by brownfield investments. The investment level in the European PPI has increased over the past few years after a period of fairly low investments around 2010. The reinvestment ratios (capital investment in relation to depreciation) amounted to about 1.2 and 1.3 in 2014 and 2015, respectively (PWC, 2016). Total investments in the European PPI amounted to 5500 M € in 2017, which corresponds to the levels in 2000-2005 (CEPI, 2018).

6.2 Innovation strategies and networks

The R & D investments among pulp and paper producers tend to be low, typically less than 1% of the turnover (Kivimaa, 2008). The technical development in the PPI has traditionally been mainly incremental and much of the innovation has occurred in production processes, and less in products. Due to high capital intensity, new technologies typically need to fit into existing processes (Wesseling et al., 2017). The requirements of high capital utilisation (continuous operation) also present a barrier to more radical innovations and their diffusion.

Forest research institutes traditionally play an important role in the R & D in this industry. Innovations are also often developed in cooperation with, or outsourced to, technology providers (Wesseling et al., 2017). Valmet, Metso and Andritz are examples of important technology providers to the PPI. Forest research institutes and some universities have been active in biorefinery innovation for decades while forest industry companies have become increasingly engaged in this field more recently (Bauer et al., 2016).

Biorefineries span across different industries and areas of expertise. The development of forest biorefineries does not necessarily require new knowledge, but a combination of knowledge held by different actors. The strategic competences of the PPI in this regard are wood acquisition and wood processing while it lacks the knowledge, infrastructure and distribution channels related to chemicals and transportation fuels. Collaboration across industry sectors and with public actors is therefore considered necessary for the development of biorefineries (Karltorp and Sandén, 2018).

Establishing new partnerships between forest industry companies and potential partners in other industries is often a challenging task (Bauer et al., 2016). One major barrier to such partnerships is profit-sharing (Näyhä and Pesonen, 2014) and the level of collaboration is low between the chemical and forestry industries (Bauer et al, 2018).

6.3 Government policy

For decades the PPI has been subject to increasingly strict environmental regulations concerning local air pollutants and waterborne pollutants. Policies that target GHG emissions in industry were, on the other hand, largely absent until 2005 when the European emission trading system (EU ETS) was introduced. An exception to this is that the PPI in for example Sweden and Finland was subject to national carbon taxes for a period before that (Ericsson et al., 2004). The EU ETS has so far put limited pressure on industry to decarbonise due to the low prices on emission allowances. Various national policy instruments targeting energy efficiency and renewable electricity production (e.g. biomass-based CHP in the PPI) have probably contributed more to the emission reductions that have been achieved in the PPI over the past 10-20 years (for the case of Sweden see Ericsson et al., 2011). EU waste legislation has also indirectly contributed to the decarbonisation of the PPI by enabling and promoting increased recycling of paper.

Government policies that target biorefinery development have mainly focused on funding of research, development and demonstration while policies supporting the market for biorefinery products have been weak or ambiguous. Many of the previously mentioned biorefinery technologies have been developed for decades with support from national or EU public funding (Karltorp and Sandén, 2012). More recent initiatives include the EU funding of demonstration plants within the Horizon 2020 programme and the NER 300 program. NER 300 granted funding to a number of biorefinery demonstration plants across Europe. Many of these plants were, however, never built due to the uncertain market for biofuels which made industrial co-funding hard to motivate (Åhman et al., 2018).

The EU biofuel market is promoted by a 10% renewable energy sources (RES) target for transportation fuels to be achieved in each member state by 2020 (as part of the 2009 RES directive) and by the fuel quality directive which requires reduction of the GHG intensity of transportation fuels by minimum of 6% by 2020. These targets are implemented in the member states via national tax schemes and mandatory blending targets etc. The 10% target has been highly contested among certain countries and stakeholders and was in 2015 complemented with a 7% cap on biofuels from food crops (iLUC[7] directive). In 2018, the EU agreed upon an overall RES target for 2030, but it contains no specific target for the transportation sector. There have so far been no similar targets or policies instruments supporting the market demand for bio-based chemicals and plastics.

Prices of EU emission allowances started to increase during 2018, but are still relatively low. Biomass-fired combustion plants are not included in the EU ETS, which means that this instrument provides no incentive for bio-CCS or CCU of biogenic CO_2. It should also be noted that CEPI has a sceptical attitude towards bio-CCS since "the incentives needed to drive bio-CCS would create a perverse incentive to burn wood" (CEPI, 2011). Climate and RES policies present opportunities for the PPI which rely on a

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[7] iLUC denotes indirect land-use changes

renewable raw material and to a high extent on bioenergy. At the same time, these policies are perceived as a threat by the PPI which fears competition for biomass from the energy sector and in the future potential demand from the chemicals sector if fossil feedstock is phased out.

6.4 Markets

The markets for pulp and paper are partly global and partly regional depending on product. The paper consumption at global level is still growing, but at decreasing growth rates while the consumption in Europe has stagnated (CEPI, 2018). It appears unlikely that the paper consumption in Europe will grow much in the future, but also unlikely that it will sharply decline (Hänninen et al., 2014). The demand for graphic paper is expected to continue to decline in the future due to the digitisation of media. On the other hand, the market for paper packaging is strong and expected to grow as demand for 'renewable' packaging increases. The market for hygiene paper products could potentially also grow (Hänninen et al., 2014).

Biofuels accounted for about 5 percent of the energy use in the EU road transportation sector in 2016 and less for the transportation sector as a whole (EC, 2018). The biofuels use is dominated by two types of biodiesel; i) fatty acid methyl esters (FAME) that are primarily produced from rapeseed oil and ii) hydrogenated vegetable oil (HVO), a drop in fuel that is produced from various vegetable oils including tall oil. The biofuels consumption also includes alcohols which are mainly produced from sugar and starch-based crops (EurObserv'ER, 2017). Only a small proportion of the biofuels consumed today origin from forest biomass. The European market for biofuels emerged in the late 1990s and grew until about 2014, after which it has been stagnant (Eurostat, 2018). The market has been highly influenced by EU targets and national policy instruments since biofuels are not competitive with the pricing of fossil fuels. The potential market for biofuels in the transportation sector is very large in relation to biomass resources (as indicated in Figure 4) and will apart from policies be influenced by the development of other technologies, including electrification, and the demand for transportation.

There is also a potentially large market for bio-based chemicals and plastics (see Figure 4). Today, bio-based plastics mainly exist on niche markets and account for about 1% of the global production of plastics (European bioplastics, 2018). The bio-based plastics are mostly made of carbohydrate rich plants such as maize or sugarcane. Biocomposites partly compete with plastics and present yet another potentially large market. The production of biocomposites is growing and amounted to about 410 kt in Europe in 2017 (nova-Institute, 2017a).

The potential market for cellulose-based textile fibres is large and has not received much attention in the discussions around the bio-based economy. The proportion of cellulose-based textile fibres has been continuously decreasing for decades, mainly because of the limits of the cotton production and the progress and cost reductions in synthetic fibres such as polyester (Dammer et al., 2017). There is thus great potential for developing cellulose textile fibres from wood.

7 Current initiatives

In 2011 CEPI launched the Forest fibre industry 2050 roadmap to a low carbon economy. The roadmap presents the sector's vision of achieving a CO_2 emission reduction of 80% by 2050 compared to 1990 while producing 50% more value (CEPI, 2011). The roadmap also discusses strategies for achieving this, highlighting fuel shifts to biomass and various options for improved energy efficiency and implementation of biorefinery technologies.

Following the roadmap, CEPI launched the Two Team Project (2012-2013) which aimed to identify the most promising breakthrough technologies to cut the carbon footprint of pulp and paper making (CEPI, 2013). This initiative brought together two teams and set them to compete using a method of open innovation. Eight breakthrough technology concepts were identified and further discussed, among which the pulping concept based on the use of deep eutectic solvents (previously mentioned in Section 4.1.1) was appointed winner.

A mapping by nova-Institute (2017b) shows that there were 25 wood-based biorefineries in Europe in 2017. Most of these are located in Finland (8), Sweden (6) and Austria (3). Some of them are integrated with pulp and paper production while others are stand-alone biorefineries that refine (waste) streams, such as crude tall oil, from the PPI. Below we describe important current initiatives that involve pulp (and paper) mills. The initiatives were identified from the biorefinery mapping by nova-Institute and further investigated via the companies' websites. The magazine Process Nordic and the website pulpapernews.com were used to identify the most recent initiatives.

The production of dissolving pulp and textile fibres from wood has grown during the past few years. Lenzing group is the largest producer in this segment in Europe with a handful of production sites, including the biorefineries in Lenzing, Austria, and Paskov, Czech Republic, which also produce various chemicals from the extracted hemicellulose. Other examples of pulp mills that have undergone profound transformation are the Borregaard biorefinery in Sarpsborg, Norway and Domsjö Fabriker, Örnsköldsvik, Sweden, both of which have sulphite-based processes. The Borregaard biorefinery produces specialty cellulose and a variety of chemicals from the hemicelluloses and lignin, including for example ethanol and vanillin. Domsjö Fabriker produces for example specialty cellulose (for e.g. textiles), lignin, biogas and ethanol (from hemicelluloses). There is currently no ethanol production from cellulose in the PPI. However, 2017 saw the opening of the Cellulonix ethanol plant in Karajaani, Finland, which is co-located with a sawmill and produces ethanol from sawdust.

Many pulp and paper companies are diversifying into biocomposites. One example is Stora Enso which recently started a biocomposites mill with the product brand name DuraSense combining wood fibres, polymers (fossil- or bio-based) and additives. Its annual production capacity is 15 000 tonnes, making it the largest wood fibre-based biocomposite plant in Europe. Södra produces a similar composite since 2011 called DuraPulp using only biobased polymers.

Considerable investments are currently being made to transform the Metsä fibre pulp mill in Äänekoski to a biorefinery (referred to as bioproducts mill by the company). Pulp will still be the main product, but the biorefinery will also produce for example tall oil, turpentine and biocomposites. The transformation also includes construction of a biogas plant and of a bark gasifier, which will supply producer gas to the lime kiln. The bark gasifier being built at the biorefinery in Äänekoski is possibly the only example of industrial-scale gasification in the PPI. Furthermore, Finnpulp Oy plans a new bioproducts mill (greenfield project) in Kuopio, Finland. The construction is scheduled to start in 2019. The annual pulp production capacity of the bioproducts mill is 1.2 Mt. The mill will also produce 60,000 tons of tall oil and 1 TWh bioelectricity to the domestic power grid (Finnpulp, 2018).

Lignin extraction is applied at industrial scale since 2015 in the Stora Enso Sunila pulp mill in Finland. The mill produces high purity kraft lignin from black liquor via the "Lignoboost" technology. Some of the lignin is used internally as fuel in the lime kiln and some is sold as raw material. The Lignoboost technology was first demonstrated in 2007 at the Nordic Paper pulp and paper mill in Bäckhammar, Sweden. That site now also hosts a pilot plant that produces lignin oil via RenFuel's process. Furthermore, technology provider RenFuel, the oil company Preem and the pulp and paper company Rottneros are now investigating the possibility to invest in an industrial scale plant for production of lignin oil at one of Rottneros's pulp mill. The lignin oil will then be refined into drop-in biofuels at one of Preem's refineries.

The processing of crude tall oil for production of biodiesel has increased over the past few years. One example is UPM Lappeenranta biorefinery, Finland, which produces bio-based naphtha and biodiesel (HVO) via hydro-treating and refining of crude tall oil. In Sweden, "tall diesel" is produced at SunPine's biorefinery which processes crude tall oil into a number of products. The tall diesel is then further refined at one of Preem's refineries. The forest products company SCA and the energy company St1 have formed a partnership with aim to construct a new facility to produce advanced biofuels from tall oil with a capacity of 100 kt per year. The planned production site will be St1's refinery in Gothenburg.

Södra and Statkraft plans to build a demonstration plant for liquid biofuels in Tofte Norway (the location of Södra's closed down pulp mill). The investment will be made through the joint company Silva Green Fuel AS, in partnership with technology provider Steeper EnergyAps. The demonstration plant is expected to be in operation by spring 2019. Furthermore, Södra is currently investing in methanol production at its Mönsterås pulp mill. Around 5 Mt of fuel quality methanol will be produced from impure methanol that is recovered from the black liquor evaporators.

CCU is currently being demonstrated in a number of European power-to-gas pilot plants that produce methane, usually with biogas as source of CO_2 (Bailera et al., 2017). The forest industry is not involved in any these projects. Carbon capture from flue gases has been demonstrated but is not applied at industrial scale. CO_2 is, however, sometimes captured from ethanol production plants in which the fermentation process generates an almost pure CO_2 stream. This is done for example at the biorefinery Domsjö Fabriker. The captured CO_2 is used for carbonated beverages.

8 Overall analysis and assessment of pathways

This section presents an overall assessment of the prospects for decarbonising the European PPI and for it to contribute to the decarbonisation of other sectors. For the purpose of this assessment, the transition of the PPI is broken down into three pathways: i) decarbonisation of the PPI itself, ii) the development of forest biorefineries and iii) CCU in the context of societal decarbonisation. The pathways do not represent different ways forward, but should rather be seen as complementary and partly sequential.

8.1 Decarbonisation of the PPI

The GHG emissions and carbon intensity in the European PPI have steadily declined over the past decades, but natural gas is still an important fuel, especially for paper drying. A few years ago CEPI presented its vision of achieving 80% less CO_2 emissions in the PPI by 2050 compared to 1990 (CEPI, 2011). This vision shows that the PPI considers deep emission reductions to be possible.

Decarbonisation of the PPI is technically fairly uncomplicated since the processes require process heat of low and medium temperature. Such process heat can be supplied from biomass combustion, waste incineration, electric boilers and high temperature heat pumps (with further technical development). Energy efficiency improvements and increased utilisation of recycled paper can also contribute to the decarbonisation. Furthermore, the PPI also has the opportunity to reach negative GHG emissions via bio-CCS, but this option has so far gained little traction in the PPI. The PPI in co-operation with equipment manufacturers appears to have the capabilities, knowledge and resources to continue these efforts towards decarbonisation. An exception to this is bio-CCS, the implementation of which would require new partnerships, CCS infrastructure and large investments.

The barriers to more rapid decarbonisation are primarily economic. Natural gas is and has been a convenient and economically attractive fuel in many paper mills that have few by-products and access to the natural gas infrastructure. The industry is also characterised by long capital stock turnover rates which leads to a few opportunities for replacement investments. Another barrier is that investments related to decarbonisation compete for financing with other investments within the pulp and paper companies or groups.

The decarbonisation options that are available to the PPI impact other sectors in different ways. A fuel switch to biomass may reduce the availability of biomass for other purposes and sectors. A shift to electro-thermal processes will increase the use of electricity while decreasing the potential for CHP production, thus making the PPI more reliant on purchased electricity. Energy efficiency measures reduce the demand for fuel and electricity and may thus make more biomass available for other sectors and facilitate the transformation of pulp mills to biorefineries.

8.2 Development of forest biorefineries

Forest biorefineries are a central element in the bio-based economy and the PPI, which handles large volumes of biomass, could assume a critical role in their realisation. The vision of a bio-based economy is widely embraced by European policymakers who see this as a strategy for decarbonisation and economic growth (EC, 2012). The EU, as well as national governments, have therefore provided considerable funding of research, development and demonstration in this area. The vision of a bio-based economy is largely aligned with the interests of the PPI and CEPI's vision of creating more value in the PPI. The industry nevertheless also expresses certain ambivalence to the bio-based economy (depending on how this concept is interpreted) due to the fear of competition for raw material, especially with the heat and power sector.

The opportunity to transform into a biorefinery differs greatly between pulp and paper mills depending on their feedstock, pulping process, location etc. Chemical pulping generates large amounts of by-products that can be converted to various bio-based products. Much of these by-products are currently used for production of process heat and electricity. Energy efficiency improvements and electrification of processes could increase their availability for other purposes. The opportunities for integrating biorefining technologies are, however, not necessarily restricted by the availability of by-products since forestry residues and roundwood could also be used as feedstock.

The transformation into forest biorefineries has to some extent already started. The mapping of current initiatives indicates that many pulp and paper companies are diversifying their product portfolios. A handful of pulp and paper mills have made a shift into becoming biorefineries that produce dissolving pulp and/or various chemicals and bio-based materials. Most initiatives, however, involve less radical changes such as the production of biocomposites and extraction of tall oil, which is then often processed by downstream companies. There is currently no initiative that involves black liquor gasification, which was previously at the centre of much of the research, development and demonstration efforts related to forest biorefineries. This technology has so far not been applied at industrial/commercial scale. Instead, recent developments suggest that the PPI prefers lignin extraction, which involves fewer changes in the core processes and thus less risk.

The current initiatives reveal emerging partnerships between pulp and paper producers and energy and oil companies. Partnerships with major chemical producers appear, on the other hand, to be lacking. As mentioned previously, collaboration across industry sectors is considered necessary for the development of biorefineries since pulp and paper companies lack the knowledge, infrastructure and distribution channels related to transportation fuels and chemicals. This includes finding new roles and business models along new value chains.

Uncertain market conditions for the biorefinery products pose a major barrier to investments in biorefinery technologies. The market for transportation biofuels has been promoted by EU targets and national policy instruments. The incentives and stability of these policies have, however, not been strong enough to motivate major investments in forest biorefineries. The controversies surrounding biofuel policies and land-use impacts have also led to uncertainties concerning future market conditions. Bio-based plastics and chemicals mainly exist on niche markets since these products have not been promoted by political targets or policy instruments. The niche markets for bio-based plastics are created by marketing initiatives among companies which use plastics in their consumer products. The markets for bio-based chemicals and plastics are thus lagging behind the market for transportation biofuels. Since biofuels and bio-based chemicals largely involve the same technologies and platform chemicals, there is an opportunity for bio-based chemicals and plastics to partly piggyback on the infrastructures and technologies for biofuels.

8.3 CCU in the context of societal decarbonisation

Achieving deep GHG emission reductions will increase the demand for biogenic carbon for various products, including for example transportation fuels, chemicals, plastics and textiles. These emerging or growing markets will add to the current forest product markets for paper and board, sawn wood etc. At the same time biogenic carbon from forestry as well as agriculture is a limited resource. The resource constraint is particularly evident in relation to the potential future demand for transportation fuels and highlights the need for other decarbonisation strategies that reduces the demand for carbon-based transportation fuels (see Section 5.2). Furthermore, most scenarios towards limiting global mean temperature rise below 1.5°C highlight the need for removing CO_2 from the atmosphere, primarily via bio-CCS (Rogelj et al., 2018). The PPI is, however, showing little interest for bio-CCS and this technology would make less biogenic carbon available for various products.

CCU offers a way to economise with the biogenic carbon, but requires considerable input of electricity. CCU is thus only relevant in a low-carbon electricity system. From an economic point of view, electricity must be less expensive than the bio-based chemicals/fuels produced. It is a situation opposite from today where hydrocarbons are used to produce electricity. In this CCU pathway electricity is used to produce hydrocarbons from electrolytic hydrogen and biogenic CO_2-sources (e.g., pulp mills, ethanol production and biogenic waste incineration/gasification).

The pathway entails strong integration with the electricity sector and probably electricity demand flexibility in electrolysers for grid balancing. To think about how this pathway may unfold becomes rather speculative. The early movers and niche markets may be in power-to-liquids through non-PPI companies like Carbon Recycling International, Enerkem, and Sunfire. It is also possible that polymer producers that currently use fossil feedstock invest in chemical recycling of plastics (e.g., gasification) where the yield can be boosted with hydrogen. With current fossil feedstock and carbon pricing this is not economical and preliminary assessments indicate that the cost of polymers from CCU may be 2-3 times higher than current polymer prices (Bauer et al, 2018).

There are no indications that this CCU pathway option is considered or discussed in the PPI. It is related to bio-CCS, but with CCU the biogenic CO_2 is seen as a resource rather than a pollutant. Most of the interest in CCU appears to come from parts of the chemical industry and the energy sector where one motivation is CCU as an energy storage option (Nikoleris, 2018). For the PPI to engage will require a shift in perceptions and that biogenic CO_2 is seen as a feedstock that can be turned into green products. A possible short term niche application in the PPI could be to increase biomethane yields through hydrogenation in mills with biogas production.

9 Conclusion

It appears relatively straightforward to decarbonise the PPI in Europe through continued efforts in recycling, energy efficiency, fuel switching and electrification. Current fossil fuel use only amounts to 477 PJ (132.5 TWh). This is not to say that it is an easy task but technologies are largely available and new ones are developed. The PPI also has the capabilities, e.g., resources and knowledge, to implement the necessary changes. Inertia is mainly caused by equipment turn-over rates, relative fuel and electricity prices, and the profitability of investments. A larger and more challenging issue is how the PPI, or the forestry industry as a whole, can contribute to the decarbonisation of other sectors and how biogenic carbon can be used in a fossil-free society. One step in this direction is the development of forest biorefineries as part of the broader vision of a bioeconomy. So far, this has not involved radical change in the PPI. Most examples involve taking by-products or diverting small streams to produce fuels, chemicals and biocomposites that can replace fossil-based products. This development has limited potential for decarbonising other sectors due to the relatively small volumes of by- and co-products that are available. The cellulose fibre remains the core product even in the relatively radical shift from paper production to textiles fibre production. For deep decarbonisation of other sectors, notably switching to biomass feedstock for fuels, organic chemicals and plastics, the availability of biogenic carbon (in biomass or as biogenic CO_2) becomes an issue. Future demand in such applications, e.g., for transport fuels and plastics, will make biogenic carbon a scarce resource in Europe. A scenario where biogenic carbon is captured and used (CCU) as feedstock implies large demands for hydrogen, completely new value chains and more closed carbon loops. The CCU option is mainly explored and discussed by actors in the chemical and energy sectors, so far not including the PPI.

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11 Appendix: Carbon flow calculations

Carbon content in 100 Mm^3 sawn wood = 100 × 0.42 × 0.49 Mt C= 21 Mt C

Carbon content in 90 Mt paper = 90 × 0.9 × 0.49 Mt C= 40 Mt C

C utilisation in recycled fibre = 90 × 0.8 × 0.8 × 0.49 Mt C= 25 Mt C

Total wood input to the PPI = (40-25) ÷ 0.5 ÷ 0.49 ÷ 0.42 Mm3= 146 Mm^3 excluding bark

Total wood input to saw mills and the PPI = (100 ÷ 0.5) +43 Mm3 = 243 Mm^3 excluding bark

Potential output of lignin and hemicelluloses = 146 × 0.5 × 0.42 × 0.49 Mt C= 15 Mt C