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DECARBONISATION OPTIONS FOR THE DUTCH PAPER AND BOARD INDUSTRY

K. Rademaker, M. Marsidi

20 August 2019

MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for the Dutch paper and board industry

The Hague, 2019
PBL publication number: 3480
TNO project no. 060.33956

Authors
K. Rademaker and M. Marsidi

Acknowledgements
Special thanks to Corneel Lambregts (Royal VKP), Annita Westenbroek (KCPK) and Anton Wemmers (ECN part of TNO)

MIDDEN project coordination and responsibility
The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and ECN part of TNO. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to: K.M. Schure (PBL), Klara.Schure@pbl.nl, or A.W.N van Dril (TNO), Ton.vanDril@tno.nl

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This report was reviewed by by Corneel Lambregts (Royal Dutch Association of Paper and Board Factories) and Annita Westenbroek (Knowledge Center for Paper and Board). PBL and ECN part of TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

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Summary

This report describes the current situation for Dutch paper and board production and the options and conditions for its decarbonisation. There are 21 paper and board producing mills in the Netherlands (see Table 1). In 2017, they produced over 3 million tonnes of paper and board. Total board production was about 2.2 million tonnes and graphic paper accounted for 0.7 million tonnes. The mills of the Dutch paper and board industry are categorised according to their products:

• Graphic paper	• Folding boxboard
• Graphic paper made from recovered paper	• Sanitary paper
• Corrugated board	• Moulded fibre
• Solid board	• Specialty paper

Table 1 Overview of CO_2 eq emissions per Dutch paper mill

Production site	Location	EU ETS emissions 2015 [kt CO_2 eq]
Total		**1054.2**
DS Smith Paper De Hoop	EERBEEK	216
Smurfit Kappa Roermond Papier B.V.	ROERMOND	163
Sappi Maastricht B.V.	MAASTRICHT	151
Crown Van Gelder B.V.	VELSEN	143
Mayr-Melnhof Eerbeek B.V.	EERBEEK	68
Eska B.V.	HOOGEZAND	60
Solidus Solutions Board B.V.	BAD NIEUWESCHANS	37
Eska B.V.	SAPPEMEER	33
Solidus Solutions Board B.V.	OUDE PEKELA	24
WEPA Nederland B.V.	SWALMEN	23
Solidus Solutions Board B.V.	COEVORDEN	22
Essity Operations Cuijk B.V.	CUIJK	20
Papierfabriek Doetinchem B.V.	DOETINCHEM	20
Smurfit Kappa Parenco	RENKUM	19
Solidus Solutions Board B.V.	HOOGKERK	17
Huhtamaki Nederland B.V.	FRANEKER	13
Smart Packaging Solutions	LOENEN	13
Neenah Coldenhove	EERBEEK	10
Marsna Paper BV	MEERSSEN	3
Schut Papier	HEELSUM	0
VHP Security Paper B.V.	APELDOORN	0

Source: NEa, 2018

In 2015, final heat consumption by the Dutch paper and board industry was 11.9 PJ and final electricity consumption was 4.7 PJ. Combined heat and power plants (CHP) are an important part of the utilities in the Dutch paper and board industry, with a total heat production of 7.8 PJ and electricity production of 4.1 PJ, of which 1.3 PJ electricity was sold to the grid.

The most energy-intensive production process is that of the thermal drying of the paper web (drying step), which is responsible for around 81% of the steam/direct heat consumption in paper and board production (De Vries, 2016). The decarbonisation options, therefore, mostly focus on decreasing the CO_2 emissions related to this process.

There are several commercially available solutions that are relatively easy to implement:

- Electric boilers can be implemented without adjustments to the production process to replace natural gas boilers. However, electric boilers require significant investments in electricity grid connections, which, at current prices, hampers the use of electric boilers (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017);
- Biogas is another short-term alternative to decarbonising part of the paper industry's CO_2 emissions. Its application is limited by the amount of available local biomass suitable for on-site digestion or by the amount of available biogas/green gas from third parties;
- Using hydrogen instead of natural gas is another solution that requires relatively few adjustments to the production process. However, there is currently no infrastructure or large-scale production of green (electrolysis-based) or blue (natural-gas-based combined with CCS) hydrogen. Moreover, the hydrogen price is expected by the industry to be high, which will hamper the use of H_2.

In addition, there are several promising decarbonisation technologies currently under development, among which:

- Compression refining is currently in the pilot phase of development. This option can significantly reduce the CO_2 emissions from graphic paper mills. An estimated reduction of around 5% to 10% of the drying energy is possible, in addition to a halving of the electricity consumption that is related to refining. However, a significant acceleration of the development is required if this technology is to be implemented within the coming 10 years;
- Heat pumps are an efficiency option, as they convert low temperature waste heat into high temperature heat. High temperature heat pumps that provide the steam pressure and temperature levels required for paper and board production are still under development. Once developed, this option should be able to decarbonise most of the direct CO_2 emissions from the paper and board industry. A disadvantage of this technology is that connecting these heat pumps calls for certain adaptations to the production system;
- Air-laid technology produces paper without the use of water. Its low energy consumption and high production capacity are reasons to considers this technology. The input of fluff pulp makes this technology currently only suitable for products using virgin fibres rather than recovered paper;
- Ultra-deep geothermal energy has the potential to produce steam for paper and board mills. Its economic feasibility varies per location. In June 2017, a Green Deal was signed between Alliander, Parenco and QNQ to start a project around ultra-deep geothermal energy (Alliander, 2018). The possibility of applying geothermal heat varies per region;
- Microwave drying is a potential electrification technology for the drying process in paper and board production. The application of this technology in the paper and board industry is currently still at a low technology readiness level (TRL);

Various other technological options are under development, both within the sector (e.g. enhanced dewatering) and the general technologies that might be applicable in several sectors (e.g. vapour recompression).

FULL RESULTS

Introduction

This report describes the current situation for Dutch paper and board production and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Scope

Data on 2015 regarding the Dutch paper and board industry were provided by the association of the Dutch paper and board industry (VNP) and by the Centre of Competence Paper and Board (KCPK). This data set was used as a basis for the analysis of the current Dutch paper and board energy and material flows, and equipment and machinery. In addition, extensive literature research was conducted to cross-reference the calculated energy and material consumption and to identify and analyse potential decarbonisation options.
This study encompasses all 21 Dutch paper and board production locations. The Dutch paper and board association (VNP) has 22 members, 21 of which are production locations[1]. Of the 21 production locations, 19 are part of the European Emissions Trading Scheme (EU ETS); the remaining two—'Schut Papier' and 'VHP Security Paper B.V.'—are not part of the EU ETS.

Reading guide

Chapter 1 describes the current situation of paper and board production in the Netherlands. A description of the production processes, specific energy and material consumption, and equipment cost is provided in Chapter 2. This is followed by an overview of the main paper and board products and their applications in Chapter 3. Chapter 4 discusses possible decarbonisation options and, finally, Chapter 5 provides an assessment of the decarbonisation options.

[1] Kimberly-Clark is excluded from this study. As there are no data provided by the VNP, it is assumed this is not a production location

1 Paper and board production in the Netherlands

This chapter provides information regarding the types of paper and board produced in the Netherlands, which types are produced by which mills, and the total production capacity per type.

1.1 Paper and board production in the Netherlands

The pulp and paper industry forms the fourth largest industrial user of energy, worldwide. Asia has the largest share of the paper production (42%), followed by Europe (28%) and North America (23%). China is the largest producer of paper and board, followed by the United States, Japan, and Germany (Laurijssen, 2013).

In the Netherlands, total revenues of the paper and board industry in 2017 were around EUR 1,859 million, with a production of almost 3 million tonnes of paper and board (VNP, 2018). In 2017, total CO_2 emissions from the sector were slightly over 1 Mt CO_2 eq (NEa, 2018).

1.2 Definition of paper and board types

Paper and board products consist mainly of cellulose and are used for a variety of applications such as writing materials and packaging. Paper and board are essentially the same material and have similar production processes. Generally, the distinction between paper and board is the *grammage* of the product (see Section 3.1).

For this study, the paper and board products produced in the Netherlands are categorised into 8 types[2]:

- **Graphic paper**: Graphic paper covers printing and writing paper, magazine paper and specialty paper. Graphic paper is generally produced from primary fibre from chemical pulping[3], because consumers demand a certain whiteness and brightness that is difficult to obtain using recovered paper;
- **Graphic paper made from recovered paper**: Like graphic paper, but produced from recovered paper instead of virgin fibres. This type of graphic paper is used, among other things, for leaflets;

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[2] The categorisation and descriptions are based on the PhD thesis 'Energy use in the paper industry' (Laurijssen, 2013). Note however that the category 'newsprint' has been replaced by 'paper made from recovered paper', since newsprint is no longer produced in the Netherlands.

[3] The virgin fibres are imported as there are no chemical pulping facilities in the Netherlands.

- **Corrugated board**: Corrugated board consists of different combinations of layers of sheets produced from recovered pulp, mechanical pulp and chemical pulp. In the Netherlands, mainly recovered pulp is used. This type of paper has a wide variety of applications but is mostly used for packaging;
- **Solid board**: Solid board consists of 100% recovered paper and has multiple applications, such as book covers and food plates. Paper and board products that use recovered paper generally require deinking to remove unwanted impurities, but this is not required for solid board, because of the types of applications;
- **Folding boxboard**: Folding boxboard consists of different types of fibres and is typically used as packaging material of various food products. In the Netherlands, this paper grade consists of recovered paper and mechanical pulp. Because of its application, the outer layer needs to look representative. The outer layers therefore need to be either deinked or bleached;
- **Sanitary paper**: Sanitary paper can be produced from primary fibre or recovered fibre and is used to produce, for example, toilet paper and tissues. The primary fibre is generally produced through chemical pulping. Sanitary paper needs to be strong, absorbent and soft;
- **Moulded fibre**: Moulded fibre is a packaging material used as protection in egg boxes, among other things, and is composed mainly of recycled paper and cardboard[4];
- **Specialty paper**: Specialty paper covers a wide range of products that cannot be categorised using the above paper and board type definitions and are generally produced in relatively low volumes.

The companies and their paper type category are provided in Table 2.

Table 2 Paper type per company

Paper type	Plant name	City
Corrugated board	DS Smith Paper De Hoop	EERBEEK
	Smurfit Kappa Roermond Papier B.V.	ROERMOND
Folding boxboard	Mayr-Melnhof Eerbeek B.V.	EERBEEK
Graphic paper	Crown Van Gelder B.V.	VELSEN
	Sappi Maastricht B.V.	MAASTRICHT
Graphic paper from recovered paper	Smurfit Kappa Parenco	RENKUM
Moulded fibre	Huhtamaki Nederland B.V.	FRANEKER
Sanitary paper	Essity Operations Cuijk B.V.	CUIJK
	WEPA Nederland B.V.	SWALMEN

[4] http://www.cdl-moulded-fiber.com/en/history-of-moulded-fibre.html

Paper type	Plant name	City
Solid board	Eska B.V.	HOOGEZAND
	Eska B.V.	SAPPEMEER
	Smart Packaging Solutions	LOENEN
	Solidus Solutions Board B.V.	BAD NIEUWESCHANS
	Solidus Solutions Board B.V.	COEVORDEN
	Solidus Solutions Board B.V.	HOOGKERK
	Solidus Solutions Board B.V.	OUDE PEKELA
Specialty paper	Marsna Paper BV	MEERSSEN
	Papierfabriek Doetinchem B.V.	DOETINCHEM
	Schut Papier	HEELSUM
	VHP Security Paper B.V.	APELDOORN
	Neenah Coldenhove	EERBEEK

1.3 Production volumes and CO_2 emissions

The annual production capacity of the Dutch paper and board mill ranged from 5,000 to 600,000 tonnes in 2015. An overview of the 2015 production capacity per product type is presented in Table 3. Large mills typically produce products in bulk, whereas mills with lower production capacity tend to produce more specialised products.

Table 3. Production capacity and CO_2 emissions in the paper and board industry in 2015

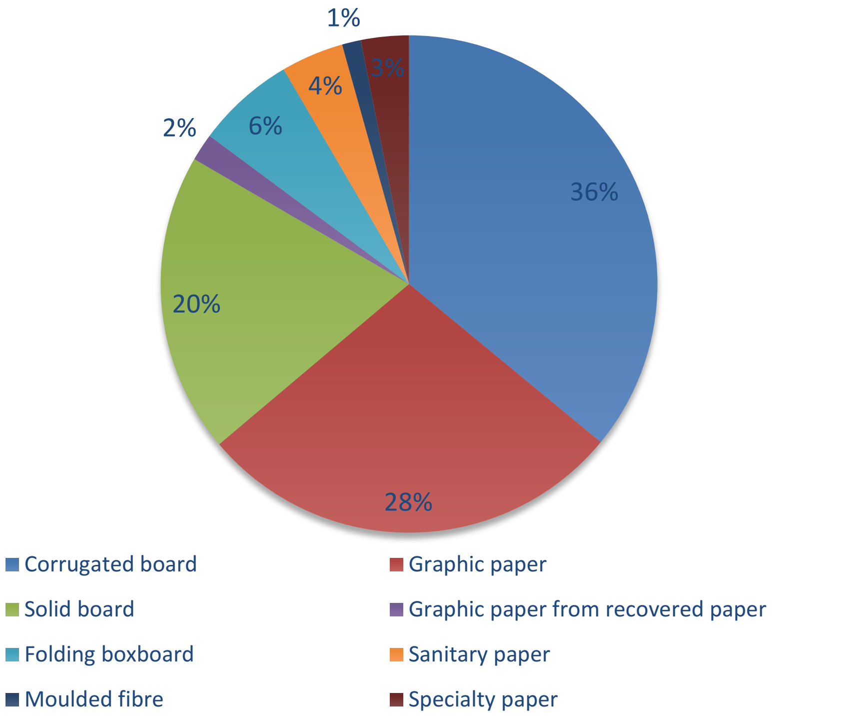
Paper machine; main output	Sum of EU ETS emissions 2015 [kt]	Sum of production capacity [t/year]
Corrugated board	379	950,000
Folding boxboard	68	140,000
Graphic paper	294	520,000
Graphic paper from recovered paper	19	280,000

Paper machine; main output	Sum of EU ETS emissions 2015 [kt]	Sum of production capacity [t/year]
Sanitary paper	43	105,000
Solid board	206	730,000
Moulded fibre	13	35,000
Specialty paper	33	110,000
Grand Total	**1,054**	**2,870,000**

Source: adapted VNP data

In 2015, the total in greenhouse gas emissions from the Dutch paper and board industry, corresponding to a total production capacity of 2,870 kt paper and board, was 1,054 kt CO_2 eq. The graphic paper mills using virgin fibres, with a total production capacity of 520 kt per year, were responsible for 294 kt CO_2, and the graphic paper mills using recovered paper, with a total production capacity of 280 kt per year, emitted 19 kt CO_2[5]. The corrugated board mills, with a cumulative production capacity of 950 kt per year, emitted 379 kt CO_2. Solid board, produced by 6 mills in the Netherlands with a total production capacity of 730 kt per year, emitted 206 kt CO_2. Folding boxboard (a capacity of 140 kt per year) emitted 68 kt CO_2. The sanitary paper producing companies in the Netherlands had a combined production capacity of 105 kt paper per year and emitted 43 kt CO_2. In the Netherlands, moulded fibre production, with a capacity of 35 kt per year, emitted 13 kt CO_2. Finally, the aggregated group of mills producing 'specialty paper', with a production capacity of 110 kt paper, emitted 33 kt CO_2. The breakdown of the CO_2 emissions per paper and board type are illustrated in Figure 1.

Figure 1 Breakdown of CO_2 emissions (kt) per paper and board type in 2015



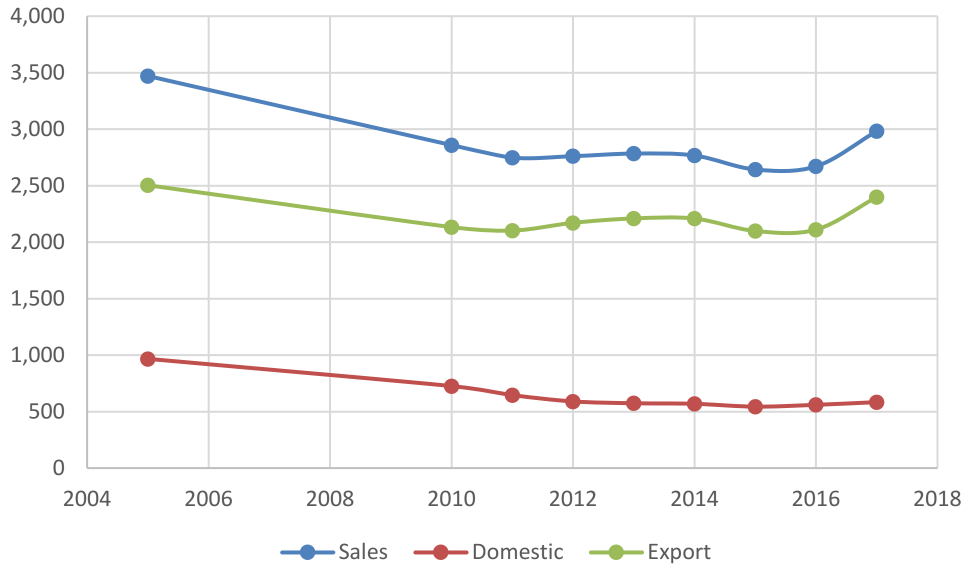
[5] The relatively low CO_2 emission level compared to the production level is due to the large amount of bio-energy used by these paper mills.

1.4 Production and sales trend

The Dutch paper and board industry suffered from a decline in sales, between 2007 and 2010, as a result of the closing of paper mills Favini and Stora Enso Wapenveld. In 2009, producer of newsprint paper Parenco was also forced to scale down its production, closing one of its production lines. In 2015, graphic paper producer Innovio Papers closed (EUWID, 2015). As of 2016, Dutch paper and board sales began to rise again.

Figure 2 shows the downward trend in sales between 2007 and 2010 and the increase as of 2016.

Figure 2 Annual total sales figures for the Dutch paper and board industry (x 1,000 tonne.

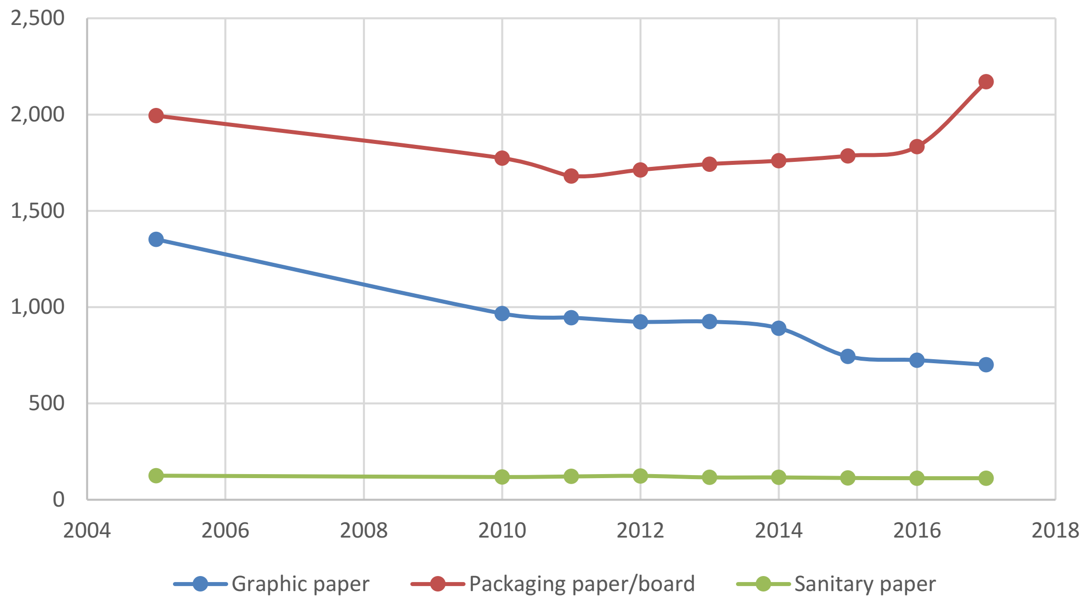


Source: VNP (2018)

The increase in sales as of 2016, resulted from an increasing demand for packaging paper (see Figure 3), including corrugated board, solid board, folding boxboard, and moulded fibre. In response to market developments, graphic paper mill Parenco invested in converting its second production line to produce packaging paper (Smurfit Kappa Parenco, 2019). Sappi Maastricht, also a graphic paper mill, is following a similar strategy (VNP, 2017)[6] and aims to produce Solid Bleached Board (VNP, 2018).

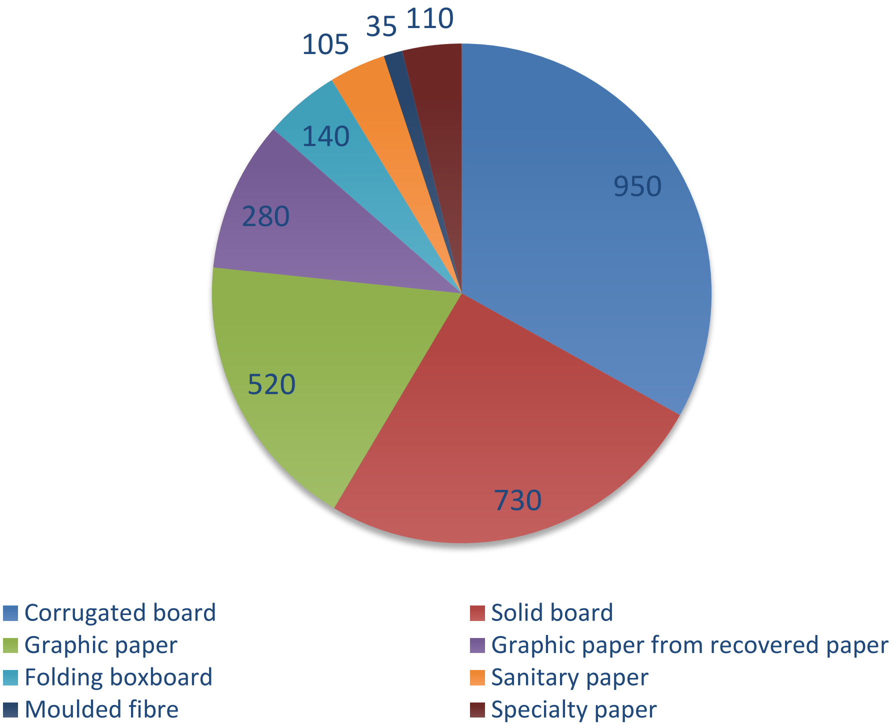
6 http://vnp.nl/nieuws/laatste-nieuws/ombouw-machine-sappi-maastricht-versterkt-positie-concern/

Figure 3 Production levels of the Dutch paper and board industry, per paper type (x1,000 tonne, source: (VNP, 2018)



In 2015, the total paper production was 2,639 kt, with a revenue of EUR 1,737 million (2017 revenues were EUR 1,859 million). As can be seen in Figure 4, the highest production level was that of corrugated board. Sanitary paper formed the smallest share of paper production in the Netherlands. According to VNP's annual report on 2017, about 70% of the production volume was sold to the European market, 10% outside the European Union and 20% within the Netherlands (VNP, 2018). Graphic paper had the largest export share, with 91% in 2015 and only 9% of the market sales going to Dutch consumers. Likewise, board was mainly exported (75%). With 37%, sanitary paper had the largest percentage of product sold to domestic consumers, in 2015 (VNP, 2018).

Figure 4 Production capacity in the Netherlands, in 2015, in kt per paper type



Source: adapted VNP data

1.5 Employment

Table 4 provides an estimation of the employees per mill in 2015. Results have been rounded to the nearest 50.

Table 4 Estimated employees per mill (FTE) in 2015

Plant	Employees	City
Smurfit Kappa Parenco	200	RENKUM
Crown Van Gelder B.V.	300	VELSEN
Sappi Maastricht B.V.	400	MAASTRICHT
Essity Operations Cuijk B.V.	100	CUIJK
WEPA Nederland B.V.	50	SWALMEN
DS Smith Paper De Hoop	200	EERBEEK
Smurfit Kappa Roermond Papier B.V.	250	ROERMOND
Solidus Solutions Board B.V.	100	BAD NIEUWESCHANS
Solidus Solutions Board B.V.	100	COEVORDEN
Solidus Solutions Board B.V.	100	OUDE PEKELA
Solidus Solutions Board B.V.	100	HOOGKERK
Smart Packaging Solutions	50	LOENEN
Eska B.V.	150	HOOGEZAND
Eska B.V.	150	SAPPEMEER
Mayr-Melnhof Eerbeek B.V.	200	EERBEEK
Marsna Paper BV	50	MEERSSEN
VHP Security Paper B.V.	100	APELDOORN
Schut Papier	50	HEELSUM
Neenah Coldenhove	150	EERBEEK
Huhtamaki Nederland B.V.	200	FRANEKER
Papierfabriek Doetinchem B.V.	150	DOETINCHEM

Source: adapted VNP data

1.6 Total energy and material flows Dutch paper and board industry 2015

1.6.1 Total energy consumption

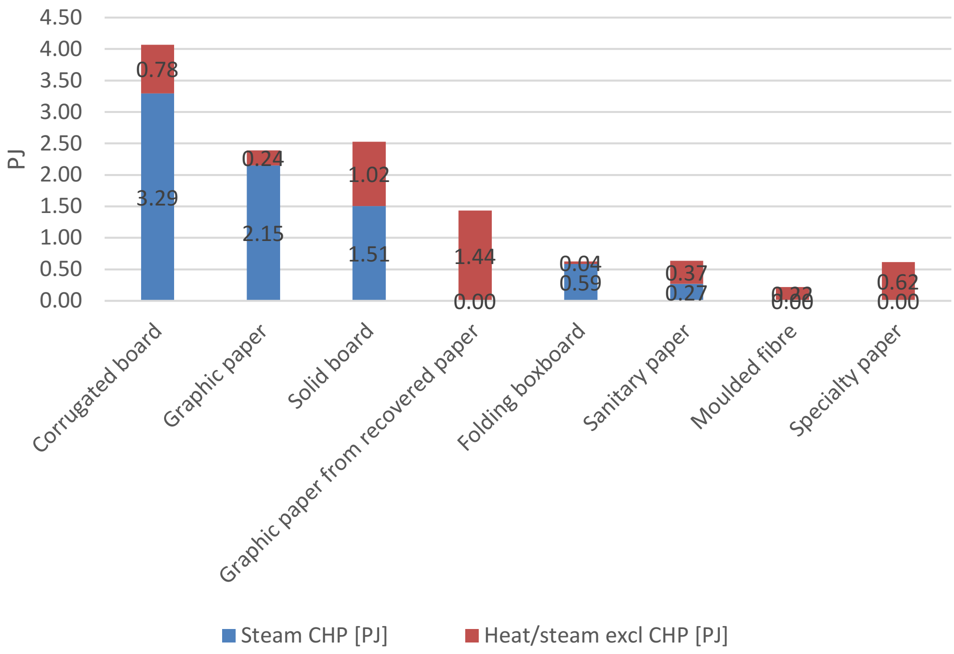
The energy consumption varies significantly per mill due to the differences in size. Bulk producing corrugated board and graphic paper mills are significantly larger, and therefore consume more steam/heat, compared to the more specialised paper mills that produce a larger variety of products in much lower quantities.

Almost all boilers and CHPs in the Dutch paper and board industry are natural-gas-fired. As for other fuels, Smurfit Kappa Parenco uses deinking sludge, biogas and imported biomass as fuel input (RVO, 2019). Smurfit Kappa Roermond Papier B.V. uses biogas produced by the on-site wastewater treatment plant (VNP, 2019), as do Eska B.V. (Eska, 2019), and Huhtamaki Nederland B.V. (RVO, 2014). DS Smith Paper De Hoop uses the biogas that is produced from their waste water by wastewater treatment plant Industriewater Eerbeek[7] (VNP, 2016).

Aside from steam production, natural gas is also used directly for drying instead of via steam: sanitary paper production uses hot air directly in the drying section in combination with steam (Yankee cylinder) and moulded fibre production uses hot air for drying in so called tunnel dryers.

Figure 5 shows the final consumption of steam/heat per product type in 2015. The total consumption of steam/heat was 12.5 PJ, most of which (7.8 PJ) was produced by CHP installations.

Figure 5 Overview of the amount of heat/steam used

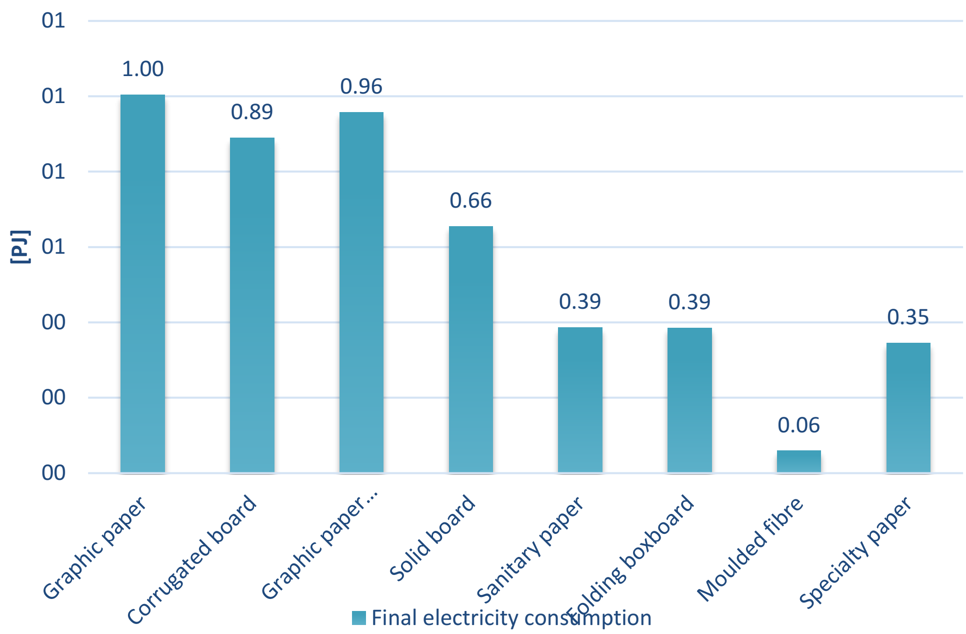


Source: adapted VNP data

[7] Industriewater Eerbeek also receives waste water from Neenah Coldenhove and Mayr-Melnhof Eerbeek B.V. (RVO, 2015)

Electricity is used to drive the paper machine, pumps and other electric equipment. Figure 6 shows the final electricity consumption per product type in 2015. The total electricity consumption was 4.7 PJ, of which 2.8 was from CHP installations.

Figure 6: Electricity consumption



Source: adapted VNP data

1.6.2 Total material consumption

Sanitary and packaging (corrugated board, solid board, moulded fibre) paper and board products use predominately recovered paper as feedstock in the Netherlands. The graphic paper producers, except for Smurfit Kappa Parenco, use mostly virgin fibres. Folding boxboard and specialty papers consist of a mixture of virgin and recovered fibres.

Chemicals are used for retention of materials or to provide certain properties to the end product (e.g. optical brightening, water resistance, writability). Note that graphic paper production uses a significant amount of fillers ($CaCO_3$) to save on expensive virgin fibre material[8].

Table 5 provides an overview of the material input per product type in 2015, as well as the total production output.

[8] http://www.tappi.org/content/events/11papercon/documents/277.519%20doc.pdf

Table 5: Material consumption and production figures for the Dutch paper and board industry, in 2015

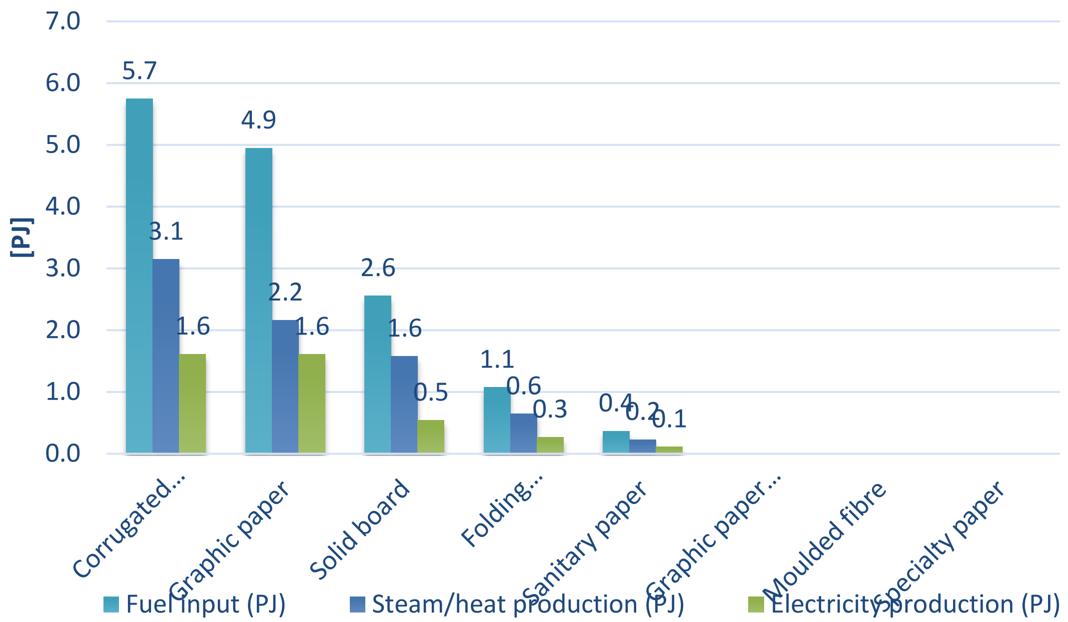
Paper machine; main output	Recovered paper [kt]	Cellulose [kt]	Fillers and chemicals [kt]	Total material input [kt]	Total production 2015 [kt]
Corrugated board	882	0	38	920	890
Folding boxboard	69	130	14	214	133
Graphic paper	0	302	187	489	478
Graphic paper from recovered paper	239	0	30	270	252
Sanitary paper	103	0	1	104	97
Solid board	643	0	3	646	646
Moulded fibre	37	0	0	37	35
Specialty paper	75	20	3	99	99
Total	1,936	432	274	2,642	2,495

Source: adapted VNP data

1.6.3 Combined Heat and Power installations

In 2015, 10 paper mills used combined heat and power (CHP) installations to cover (part of) their steam demand. The total thermal capacity of these installations was 496 MW_{th} and the total electrical capacity was 217 MW_e. The total fuel input was 14.7 PJ. The total electricity production was 4.1 PJ and the total steam/heat production was 7.8 PJ.

Figure 7: Fuel input per paper type and associated outputs of the CHP installations



Source: adapted VNP data

Decommissioned units
According to Statistics Netherlands (CBS), in 2015 there were 25 CHP installations in the Dutch paper and board industry with a total electrical capacity of 309 MW_e[9] instead of 217 MWe. The difference can be explained by the fact that the Dutch paper and board industry had previously invested heavily in combined heat and power installations to meet their energy demand. Due to unfavourable natural gas and electricity prices, some of these installations have been decommissioned and therefore no longer appear in the database of the VNP but are still included in the statistics of CBS. Therefore, in 2015, there was only an active CHP capacity of 217 MWe in the Dutch paper and board industry (see Table 6).

Table 6: Overview of CHP capcity per paper type, in 2015

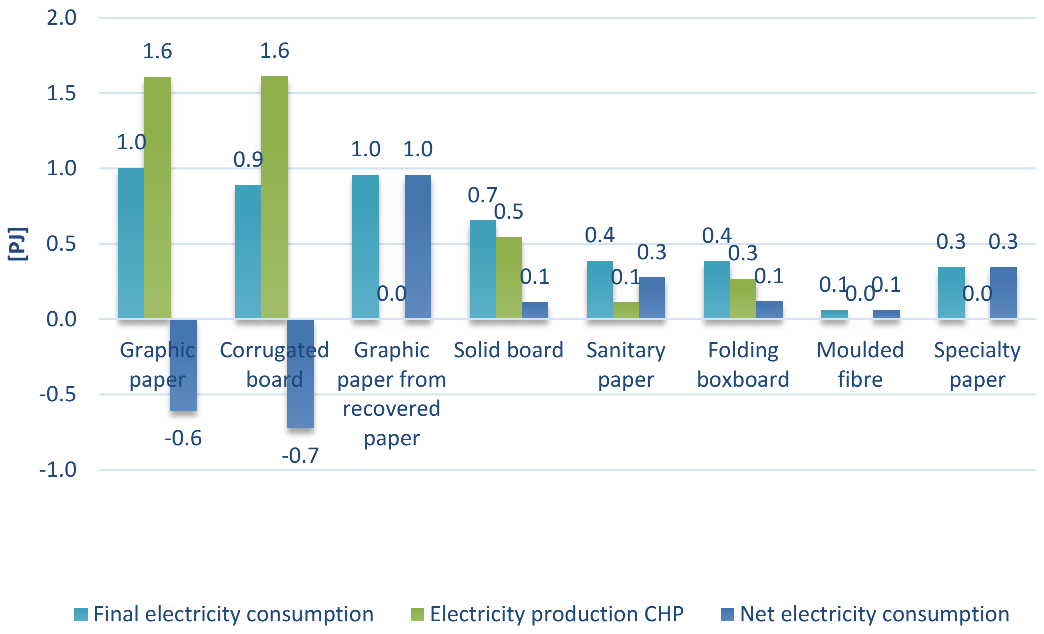
Paper machine; main output	Electrical capacity CHP [MW_e]	Thermal capacity CHP [MW_{th}]
Graphic paper	93	213
Corrugated board	84	131
Solid board	24	115
Folding boxboard	13	22
Sanitary paper	4	15
Graphic paper from recovered paper	0	0
Moulded fibre	0	0
Specialty paper	0	0
Total	217	496

Source: adapted VNP data

Electricity sold to the grid
The final electricity consumption in the Dutch paper and board industry was 4.7 PJ in 2015 and the total electricity generation by CHP installations was 4.1 PJ. The CHP installations of the graphic paper and corrugated board mills exceeded their final electricity consumption; the excess electricity produced was sold to the grid (see Figure 8). The net consumption of electricity (electricity consumption minus electricity produced) from the grid was 0.5 PJ.

9 Source: Elektriciteit; productie en productiemiddelen, Statistics Netherlands (CBS) (preliminary data for 2015).

Figure 8: Electricity consumption and production per product type



Source: adapted VNP data

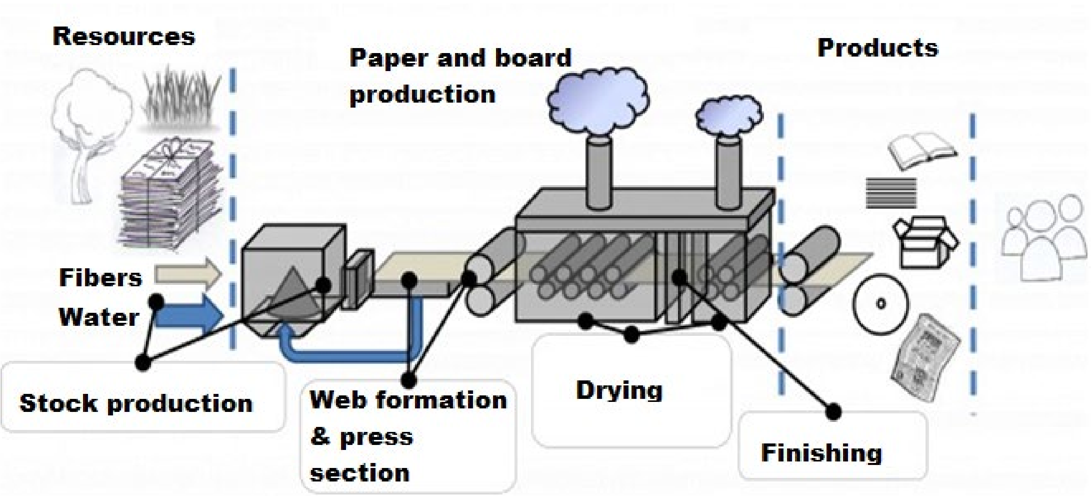
2 Paper and board production processes

This chapter provides insights regarding the production processes of the paper and board mills in the Netherlands. This includes the specific energy/material consumption and capacity and cost of equipment. The VNP has provided a data set on the energy and material consumption of the paper mills in 2015 that was used to analyse the specific energy and material consumption for each paper type. The presented energy consumption in this chapter is provided in round figures, for reasons of confidentiality.

2.1 Stock preparation and drying

In general, the paper and board production steps the Netherlands can be split into two steps: Preparation of the pulp, which is referred to as 'stock preparation' or 'stock production', and the conversion of pulp into the paper or board, which is referred to a as 'paper machine'. This conversion includes the spraying of the pulp onto the wire for the formation of the web, mechanical drying in the press section, thermal drying in the drying section, and the cutting of rolls. Figure 9 shows a schematic of typical paper and board production facility.

Figure 9: Schematic representation of the paper making process



Source: adapted figure from De Vries, KCPK (2016)

Pulp production

Paper and board mills use either virgin fibres (pulp produced from trees) or fibres from recovered paper (recycled paper and board) as main input material. In Europe virgin pulp is mainly produced in Finland, due to access to large forests (Thompson, Swain, Kay, and Forster, 2001). In the Netherlands, only one mill, Mayr-Melnhof Eerbeek B.V. (HBM, 2015), produces (part of) its own pulp directly from wood. The rest of the pulp used by Dutch paper and board mills is either imported virgin fibre pulp or pulp made from recovered paper. The energy used to convert the recovered paper into pulp is part of the stock preparation process. Therefore, there is virtually no energy consumption related to pulp production in the Netherlands.

Stock preparation

In stock preparation, fibres are dissolved in water producing a mixture with a typical dry matter content (dmc) of 1% (De Vries, 2016). When needed, the fibres are treated to enhance their properties (e.g. improved bonding ability).

The use of recovered paper and board often means that cleaning steps are required to remove plastics, small metal parts, ash and other impurities. De-inking and dispersion are sometimes also required to remove ink and other small particles, depending on the requirements for the end product.

The main stock preparation steps are:

- Cleaning: Removal of unwanted elements through various sorting and screening steps;
- Deinking: Ink removal; this is necessary for paper grades where brightness and cleanliness are important, for example, for newsprint, tissue or light topliner of recovered paper-based carton boards (Laurrijssen, 2013).;
- Dispersion: Reducing impurities that could not be removed to a size small enough not to harm the paper quality (Laurrijssen, 2013);
- Refining: Paper grades produced from virgin fibres sometimes require a refining step. The fibres are beaten to roughen their surface which enhances the fibre properties. Currently, refining is done using rotating disks pressed on a stator (Laurrijssen, 2013)[10].

Paper machine

Paper and board is produced from pulp using the following processes:

- Forming: Formation of the paper web;
- Pressing: Mechanical removal of water;
- Pre-drying: Thermal removal of water;
- Coating (if applicable): Surface property adaptations by applying e.g. starch;
- After-drying (if applicable): Thermal removal of water after coating.

During the formation, pulp (1% dmc) is spread over a wide wire to let the fibres form paper. Most of the water is removed during this phase by gravitational forces. After the forming section, the dry matter content is around 20% to 25% (Laurrijssen, 2013). The paper is then mechanically pressed in the press section to remove as much water as possible. The dry matter content of the resulting paper web is then 50%–55% (De Vries, 2016). The remaining water content of the paper web is thermally dried by rolling the paper web over steam cylinders (multi-cylinder system, the most commonly used drying technology in paper and board production), blowing hot dry air into the web (done in combination with a large steam cylinder in so-called yankee dryers, typically used in the production of sanitary paper), or by using hot air convection in tunnel drying (typically used for the production of moulded fibre).

Table 7 provides an overview of typical steam temperatures and pressures used to produce various product types.

[10] Refining is energy intensive requiring on average 150 kWe/t (range varying from 80 kWe/t to 1,500 kWe/t) (Clumpkens, 2018).

Table 7: Specific steam temperatures and pressures, per paper type

Paper type	Steam temperature drying section (max) [C]	Steam pressure drying section (max) [barg]
Graphic paper	150	5
Graphic paper from recovered paper	150	5
Corrugated board	180	10
Solid board	180	10
Folding boxboard	180	10
Sanitary paper	165	7
Moulded fibre[11]	n/a	n/a
Specialty paper[12]	150	5

Source: adapted VNP data

Depending on the requirements of the product an extra coating can be applied to the product after the (pre) dryer. Since the coating introduces extra moisture to the paper web, after-drying is needed. This can be done using infra-red drying ('no contact' drying) or multi-cylinder drying (De Vries, KCPK, 2016).

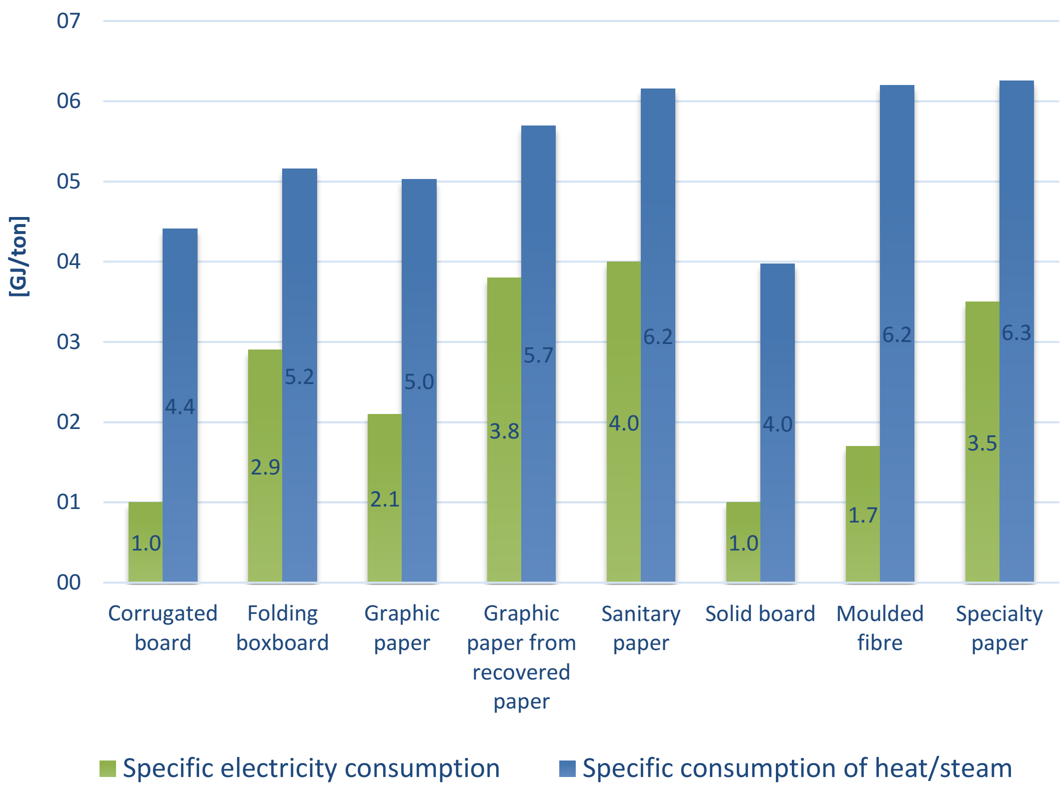
Being a hygroscopic product, the moisture content of the final paper product is still 4%–8%, despite thermal drying (De Vries, KCPK, 2016).

2.1.1 Specific energy consumption

The energy consumption per tonne of product (specific energy consumption) varies per paper type. For all paper types, the consumption of steam is greater than that of electricity. In terms of electricity, the average energy demand per paper type varies from 1.0–4.0 GJ/t product, while, in terms of steam (or direct heat for the tunnel and Yankee driers), the range for the average energy demand per paper type is 4.0–6.3 GJ/t product. Figure 10 illustrates the specific energy consumption per paper type.

11 Moulded fibre production does not use steam for drying (De Vries, 2016).
12 There is no data available for specialty paper but it is assumed the temperature and pressure used is the same as for graphic paper.

Figure 10: Specific energy consumption per energy input per paper type in 2015



Source: adapted VNP data

The process step with the highest energy consumption is the drying step. The specific energy consumption for the drying step varies per product type and depends on the dry matter content of the pulp before going into the drying section, the need for coating, the use of multi-cylinder drying or yankee dryers, and the amount of energy recovered from the heat coming out of the drying section (Laurijssen, 2013). After evaporation of the water in the drying section, the energy (in the form of waste heat) can be partially recovered via heat exchangers if there is a drying hood. The heat can be used with heat exchangers for heating of the drying air, process and cleaning water, and (during colder months) heating of the buildings. The amount of heat that can be recovered depends on the quality (dew point) of the waste heat.

The specific electricity consumption varies depending on the need for cleaning steps during stock preparation and for refining. Sanitary paper and graphic paper made from recovered paper use a relatively large amount of electricity because of the deinking/dispersion steps of these mills. Solid board and corrugated board production, on the other hand, use relatively little electricity because they have little to no need for refining and require less extensive cleaning steps.

Note that the SEC presented in Figure 10 is based on the data of one specific year, in which also different mills producing the same paper type are aggregated. A range of the specific energy consumption is provided in Table 8.

Table 8: SEC ranges for various product types

Product type	Range specific electricity consumption (GJ/t)	Range specific steam consumption (GJ/t)
Graphic paper from recovered paper	3.6–4	5.4–6
Graphic paper	2–2.1	4.8–5.2
Sanitary paper	3.4–4.6	6.1–6.2
Corrugated board	0.7–1.3	4.1–5
Solid board	0.6–1.2	2.9–4.4
Folding boxboard	2.8–3	4.9–5.5
Moulded fibre	1.6–1.8	5.9–6.5
Specialty paper	2.8–>5	4.7–>8

Source: adapted VNP data

The waste heat leaving the drying section has a dew point that varies from 25 ºC to 74 ºC, depending on the use and configuration of a drying hood. Some of the mills use the waste heat to heat the process water, buildings, and cleaning water. There is no mill-specific data available on waste heat dew point and volumes, but, based on discussions with internal experts and KCPK, it is assumed that mills with an annual production of 100 kt or more have a drying hood and a waste heat dew point of at least 55 ºC (Laurrijssen, 2013) and, currently, use half of their waste heat to heat the dryer ventilation air, process water and the machine hall[13], with the remaining waste heat dissipated into the atmosphere at 30 °C to 40 ºC.

The other mills are assumed to have no drying hood and, therefore, the waste heat from their drying section cannot be reused, as most of the heat leaves the machine room through ventilation, at 25 °C to 40 ºC.

2.1.2 Material input/output

Depending on the required quality and characteristics of the end product, each paper and board type uses a different set of material inputs (see Table 8). Graphic paper uses virgin pulp (chemical pulp) to obtain the required brightness. Graphic paper also uses a large amount of filler material ($CaCO_3$) to enhance printability and opacity of the paper (Laurijssen, 2013). Folding boxboard also uses virgin fibre, but it uses mechanical pulp instead of chemical pulp. The other paper and board products are produced almost completely from recovered paper. Many mills also apply a coating to provide their product with strength, writability, or water resistance qualities. Especially maize or potato starch is utilised for coating.

[13] The actual current use of waste heat is difficult to determine and can vary greatly per mill. As indication of the amount of waste heat that can be used internally, (Marina, Smeding, Zondag, & Wemmers, A bottom-up approach for determining the European heat pump potential, 2017) provides a breakdown of the heat consumption per process for a packaging paper company, indicating a heat demand of 1.1 GJ/t for process water heating, 0.7 GJ/t for circulation water heating, 0.6 GJ/t for dryer ventilation heating, and 1.4 for machine room ventilation (note that a drying hood may significantly change the need for machine room ventilation).

Table 9: Overview of material consumption per paper type, in 2015

Paper machine; Main output	Recovered paper [t/t product]	Cellulose [t/t product]	Fillers and chemicals [t/t product]	Total input [t/t product]
Corrugated board	1.0	0.0	0.0	1.0
Folding boxboard	0.5	1.0	0.1	1.6[14]
Graphic paper	0.0	0.6	0.4	1.0
Graphic paper from recovered paper	0.9	0.0	0.1	1.1
Sanitary paper	1.1	0.0	0.0	1.1
Solid board	1.0	0.0	0.0	1.0
Moulded fibre	1.0	0.0	0.0	1.0
Specialty paper	0.8	0.2	0.0	1.0

Source: adapted VNP data.

2.1.3 Investment and operational cost

Paper and board production is highly capital-intensive (Ghosal and Nair-Reicher, 2007) and the required investments for a paper machine are in the hundreds of millions. The refurbishment cycle and technical lifetime of a paper machine are difficult to estimate, as it consists of many different parts that are continuously replaced, whereas the main body of the machine can last for many decades.

Table 10: Costs for multi-cylinder15 drying paper machine in the Netherlands (source: estimation from VNP)

Parameter	Capacity [t/yr]	Investment [euro]	Investment cost [euro/t/yr]
New paper machine	80,000	250,000,000	3,125
New paper machine	400,000	500,000,000	1,250
New paper machine	500,000	600,000,000	1,200
Stock preparation	400,000	3,000,000	8
Stock preparation	500,000	4,000,000	8

Operation and maintenance (O&M) costs[16] are an important part of the operational costs in paper and board production. Estimates for the operation and maintenance costs (see Table 11) were provided by the Knowledge Centre for Paper and Cardboard (KCPK), using a report of the Technopolis Group (Technopolis group, 2016). The O&M costs are relatively high for sanitary paper and relatively low for corrugated board.

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14 It is unclear what causes the larger required material input for folding boxboard.

15 Multi-cylinder drying is used in graphic paper, corrugated board, solid board, and folding box board production. The investment cost for sanitary paper (Yankee dryer) and moulded fibre (tunnel dryer) are unknown.

16 The costs for energy and raw materials are not included in the O&M costs.

Table 11: OPEX (source: estimation from KCPK)

[EUR_{2014} per tonne of product]	Operating and maintenance costs (O&M)
Corrugated board	64
Graphic paper	84
Sanitary paper	132
Solid board	94
Folding boxboard	94
Graphic paper made from recovered paper	83
Moulded fibre	94[17]
Specialty paper	84[18]

2.2 Steam supply

The main energy input for the paper machine is steam. In the mills, steam is produced using either a CHP or a boiler. The energy input used are natural gas, biogas, and solid biomass[19].

2.2.1 Energy use and efficiency

The steam supply system of the Dutch paper and board industry consists of boilers and CHP installations. The energy use (natural gas, biomass) of the boilers and efficiency of the CHP installations varies per mill.

Natural gas boilers are assumed to have an efficiency of 90% (LHV). A biomass boiler also, according to (ECN, 2016), has an efficiency of 90% (LHV)

Based on VNP data, the total efficiency of the CHP installations of the Dutch paper industry varies between 73% and 93%, with electrical efficiency varying from 15% to 33%.

2.2.2 Capacity

Based on VNP data, an overview of estimated installed MW for the boilers and CHP installations was created (see Table 12). Please note that the installed capacity is not directly correlated to the energy consumption, as some of the installed capacity may not be used (for example: a boiler that is no longer used due to the heat provided by a newly installed CHP).

[17] There is no cost data for moulded fibre but are assumed to be the same as for solid board.
[18] There is no cost data for specialty paper but are assumed to be the same as for graphic paper.
[19] Note that other fuels such as diesel and LPG are also used, but in negligible quantities (less than 1%).

Table 12: CHP and Boiler MW installed

Paper machine; Main output	Electrical capacity CHP [MWe]	Thermal capacity CHP [MW_{th}]	Boiler capacity [MW_{th}]
Graphic paper	93	213	258
Corrugated board	84	131	154
Solid board	24	115	192
Folding boxboard	13	22	42
Sanitary paper	4	15	27
Graphic paper from recovered paper	0	0	125
Moulded fibre	0	0	0
Specialty paper	0	0	50
Total	217	496	849

Source: adapted VNP data

2.2.3 Investment and operational cost

The cost for CHP installations varies depending on the size of the installation (see Table 13). A major overhaul is required after 60,000 operational hours, requiring around 25% of the original investment (Energy Matters - Consultans for energy solutions, 2015).

Table 13: CHP cost data

CHP	Investment cost [EUR/kWe]	Cycle cost[20] [EUR/MW]	Variable operational cost [EUR/MWh]	Source
Small CHP (6 MWel)[21]	650	30	8	(Energy Matters - Consultans for energy solutions, 2015)
Medium CHP (22 MWel)[22]	550	75	7	(Energy Matters - Consultans for energy solutions, 2015)
Large CHP (42 MWel)[23]	500	100	5.5	(Energy Matters - Consultans for energy solutions, 2015)

The paper mills generally use natural gas boilers to produce steam, except for one graphic paper mill (Parenco) that uses a biomass boiler. The costs related to these two types of boilers are presented in Table 14).

The corrugated board mill Smurfit Kappa uses the biogas from their wastewater treatment plant for their combustion boiler. A natural gas combustion boiler has a technical lifetime of 25–40 years (IEA, 2010).

[20] Maintenance cost related to start/stop of the installation (Energy Matters - Consultans for energy solutions, 2015)
[21] Refers to a 6 MWel CHP with a 31.5% electrical efficiency and 42.5% thermal efficiency.
[22] Refers to a 22 MWel CHP with a 33.5% electrical efficiency and 41.5% thermal efficiency.
[23] Refers to a 42 MWel CHP with a 32.5% electrical efficiency and 42.5% thermal efficiency.

Table 14: Boiler cost data

Boiler	Investment cost [EUR/kW$_{th}$]	Fixed operational cost [EUR/kW$_{th}$ /yr]	Variable operational cost [EUR/kWh]	Source
Natural gas boiler	45–50	1		Energy Matters - Consultans for energy solutions (2015)
Biomass boiler	850	52	0.0043	ECN (2017)

3 Paper and board products and application

3.1 Paper and board end products

The paper and board products characteristics and end-uses can be described as follows:

- Graphic paper (from virgin or recovered paper) covers a wide range of products such as magazine paper, leaflets, and specialty papers. Graphic paper starts with a grammage of 12 g/m^2 and 18 g/m^2 for silk paper and cigarette paper, respectively (Papier en Karton, 2018). Aquarelle paper can reach up to 150 g/m^2 (Papier en Karton, 2018). Graphic paper can be bleached and non-bleached, ironed and non-ironed, wood containing and wood free, depending on customer demands (Papier en Karton, 2018);
- Corrugated board is board of 115-300 g/m^2 (Testvalleypkg, 2018). This paper type is mainly used as case material and it can be bleached or mottled (Cepi, 2018). The production can be done in several ways to achieve different strengths. There are different flute types that make the corrugated board appear thicker (Testvalleypkg, 2018);
- Solid board, also referred to as grey board is board in the range of 250 – 550 g/m2 (VPK paper, 2018). The thickness is than 0,4 – 0,87 mm (VPK paper, 2018). Solid board finds it application in food and industrial packaging, and cores or rolls (VPK paper, 2018);
- Folding boxboard is board in the range of 200 – 350 g/m^2 (Iggesund, 2018). It can be produced in single and multiple layers. Folding boxboards are used for food packaging, such that coating can be needed (Cepi, 2018). Yet, it is also available uncoated;
- Sanitary paper is a light paper product of 13 - 57 g/m^2 (Greensesal, 2018). Typical products are toilet paper, hand towels, kitchen towels and tissues (Cepi, 2018).
- Moulded fibre is used in handling and packaging of products, providing protection and convenience. Moulded fibre is used for both food and non-food applications. Examples include food containers, food trays and packaging for electronics[24].

3.2 Commodity data

The market prices for paper and board input materials and end products for 2015 are provided in Table 15.

[24] https://www.imfa.org/molded-fiber/

Table 15: Relevant 2015 commodity prices[25] for the paper and board industry (2017 data)

Material	Market price range [EUR_{2015}/t]
Old paper (mixed)	120–140
Pulp; Cellulose NBSK	710–870
Pulp; Cellulose BEKP	750–920
Graphic paper	570–690
Newsprint	390–470
Uncoated mechanical	500–610
Coated mechanical	560–680
Uncoated woodfree	730–890
Coated woodfree	660–800
Corrugated board	570–690
Containerboard Virgin fibre	630–770
Containerboard Recycled Paper	500–610
Sanitary paper (France)	830–1010
Solid board	340–410
Folding box board	800–980
Cartonboard coated duplex	960–1170
Cartonboard white-lined chipboard	650–790
Specialty paper	800–1000
Wood pellets	130–150
Wood chips	100–120

Source: VNP/RISI

[25] Uncoated, coated and specialty paper are all graphic paper products. Note that newsprint is a separate product type which is no longer produced in the Netherlands (formerly produced by Parenco).

4 Options for decarbonisation

This chapter provides examples of decarbonisation options for the paper and board production derived from literature. This list of options is not exhaustive and provides only a limited view of the total potential of future developments of production processes and technologies in the paper and board industry.

4.1 Energy efficiency improvement

4.1.1 Heat pumps

Heat pumps move thermal energy in the opposite direction of spontaneous heat transfer, by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses a small amount of external power to accomplish the work of transferring energy from the heat source to the heat sink.

Paper and board production uses steam with temperatures between 150 ºC and 180 ºC (VNP, 2018). High temperature (HT) heat pumps that provide heat well above 130 °C for industrial application are currently not available and most systems above 90 °C do not have an acceptable CAPEX (Marina, Smeding, Zondag and Wemmers, 2017). Furthermore, a large temperature lift, coupled with Carnot heat pump limitations results in a lower efficiency (Marina, Smeding, Zondag and Wemmers, 2017). Further research is needed to achieve temperature levels of around 200ºC with efficient heat pump systems, which will enable heat pumps to be used by the paper and board industry using their current steam pressures.

Heat pumps up to 90 ºC are commercially available (TRL 9), although there has not been a substantial roll-out (ECN, 2018).

TRL levels for different types of skid-mounted heat pumps of around 2 MW_{th} output (ECN, 2018):

- Compression heat pumps using synthetic refrigerant up to 120 ºC – TRL 8;
- Compression heat pumps using natural refrigerant up to 120 ºC – TRL 6;
- Compression heat pumps using synthetic or natural refrigerant up to 160 ºC – TRL 5;
- Compression heat pumps above 160 ºC – TRL 4-5;
- Thermo-acoustic heat pumps for heat supply of 120–200 ºC – TRL 4-5.

HT heat pumps have gained a significant amount of attention. Although a MW size HT heat pumps is not commercially available yet, it can be expected that this will be achieved within the next couple of years (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017). A pilot scale HT heat pump installation (200 kW) was installed at the Dutch paper mill Smurfit Kappa Roermond by ECN (ECN, 2013).

Note that electrification of the drying process will have an impact on the required grid connection. Literature does not provide a clear overview of the expected additional connection cost when using a heat pump, but to illustrate the potential cost, according to Tennet[26] a 110 kV and 150 kV connection costs approx. EUR 1.5 million, and a 220 kV and 380 kV costs approx. EUR 3 million.

Table 16: Heat pumps, economic data

Parameter	Value	Source
Output	Steam	
Fuel	Electricity, waste heat	
Emissions	No on-site emissions	
Capacity	0.25–40 MW_{th}	Thermax (2018); ECN (2017)
Efficiency	3.5–4 COP	ECN (2017)
Lifetime	10–15 years	Lux Research (2018); Berenschot, Energy Matters, CE Delft, Industrial Energy Experts (2017)
Investment cost[27]	300–900 EUR/kW_{th}	Lux Research (2018; Berenschot, Energy Matters, CE Delft, Industrial Energy Experts (2017); ECN (2017)
O&M	3% of CAPEX	ECN (2017)

Heat pumps have strong potential in the paper and board industry due to the steam demand (5–15 bar steam) and available waste heat at varying temperatures (dew point per machine varies from 25 °C to 74 °C). The disadvantages are the low TRL for high temperature (up to 200 °C) heat pumps, and the relatively high impact of the technology on the production process (when compared to e.g. electric boilers).

4.1.2 *Compression refining*

The refining step is highly energy intensive, responsible for a significant amount of the electricity consumption in paper production. Recent research has shown that the current method of refining produces a high amount of fines (small particles that are splits of the main fibre). Production of these fines is partly responsible for the higher water retention and diminishes the recycling capability of the pulp material (Marsidi, 2008).

An alternative technology currently under development is Compression Refining. This technology applies beating forces, which reduces the amount of produced fines. The energy required for refining can be decreased by approximately 20% because of the higher efficiency compared to the normal disc refiner (respectively 95% to 25%). The paper production energy is also reduced (20%), thanks to less energy requirements in the drying step, and faster dewatering on the strings (Marsidi, 2008)**.**

Compression Refining is a technology under development. A 2.5 t/h continuous production model will be tested in 2019 (Clumpkens M. , 2018)**.**

[26] https://www.tennet.eu/nl/elektriciteitsmarkt/aansluiten-op-het-nederlandse-hoogspanningsnet/kosten-van-een-netaansluiting/

[27] For a reverse-Rankine cycle type heat pump.

Table 17: Compression Refining, economic data

Parameter	Value	Source
Output	Refined pulp	
Fuel	Electricity	
Emissions	No on-site emissions	
Capacity	2.5 t/h[28]	Clumpkens (2018)
Efficiency	50% less electricity consumption; 5% to 10% less drying energy consumption[29]	Estimation based on Clumpkens (2018)
Lifetime	Unknown	
Investment cost	Unknown	
O&M	Unknown	

4.2 Decarbonisation of steam supply

4.2.1 Biogas boiler

CO_2 reduction can be achieved by using biogas instead of natural gas to fire the boilers. This can be done without any impact when mixing only a low amount of biogas with the natural gas used for combustion (Cerna, Kopelentova and Zeeman, 2014). For higher biogas ratios, however, higher maintenance costs are to be expected as unwanted elements can cause the boilers and chimneys to clog. In addition, some biogas elements can cause corrosion of the ceramic coating of natural gas burners due to chemical reactions (Cerna, Kopelentova and Zeeman, 2014).

Several paper and board mills already use the biogas produced by their on-site, or nearby, wastewater treatment plant to replace part of their natural gas consumption. In addition, Smurfit Kappa Roermond Papier B.V.is looking for additional suppliers of biogas to be able to make full use of its biogas boiler capacity (VNP, 2016).

Table 18: Biogas boiler, economic data

Characteristics	Value	Source
Fuel	Biogas	
Emissions	CO_2 (short cycle)	
Capacity	50–300 MW_{th}[30]	IEA (2010)
Efficiency	87%–90% (LHV)	Estimation
Lifetime	<25	IEA (2010)
Investment cost	50 EUR_{2015}/KW_{th}[31]	Energy Matters (2015)
Maintenance cost	1.5–2.5 $EUR/kW_{th}/yr$	Estimation

28 Current model is a batch machine of 700 kg/hr, but in 2019 a continuous machine of 2.5 t/hr will be tested.
29 Due to assumed improved dewatering resulting in expected increased dmc after the press section of at least 1% (Marsidi, 2018)
30 It is not specified in the available literature what the typical size is for a hydrogen boiler. It is assumed that any steam boiler of any size can be converted into a hydrogen boiler by retrofitting the burner. Therefore, the size of industrial H_2 boilers is assumed to range from 50 to 300 MW_{th}.
31 Assume same as gas-fired boiler

4.2.2 Electric boilers

There are two types of industrial electric boiler systems:

- Using an electric heating element that acts as a resistance (electric boiler);
- Using the conductive and resistive properties of the water itself to carry electric current (electrode boiler).

Electric boilers and electrode boilers mainly apply to utility-related processes (steam production). The implementation threshold is perceived as relatively low as it does not require a complete redesign of primary processes (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017). The electric/electrode boilers can also be used as flex option to be used during periods of low electricity prices (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017)[32].

Saturated steam with temperatures of up to 350°C and 70 bar can be produced with commercially available electrode boilers (capacities of up to 70 MWe). Advantages of this technology is (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017), (Berenschot, CE Delft and ISPT, 2015):

- An efficiency of up to 99.9%;
- Robust;
- Low CAPEX;
- Can be used as flexible capacity.

Electric boilers can be provided with low voltage (400V) up to high voltage (690V). These boilers are already on the market (danstoker, 2018).

Note that to be considered a decarbonisation option, the electricity supply must come from a renewable source.

Table 19: Electric boiler, economic data

Characteristics	Value	Source
Fuel	Electricity	
Emissions	0	
Capacity	0.4–70 MWe	Berenschot, Energy Matters, CE Delft, Industrial Energy Experts (2017)
Electrical efficiency	95%–99%	Thermona (2010)
Lifetime	10–15 years	Berenschot, CE Delft, ISPT, (2015); VNP (2018)
Investment costs/CAPEX	150–190 EUR/kWe_{2017} (incl. installation)[33]	Berenschot, CE Delft, ISPT, (2015)
Maintenance costs/OPEX	1.1 EUR/kW/yr FOM and 0.5 EUR/MWh VOM	Berenschot, Energy Matters, CE Delft, Industrial Energy Experts (2017)

Although electric boilers are commercially available, there are some challenges regarding the electricity infrastructure and additional costs for connection. For example, Smurfit Kappa

[32] The potential for steam boilers with an integrated gas-fired and electric element is currently ongoing (TNO, 2018).

[33] Note, however, that the electricity connection costs are site specific and can therefore vary significantly

Roermond Papier B.V. researched the option of implementing an electrode boiler for 9.5 or 30 MWe of flexible power to make use of low electricity prices, but came to the conclusion that the investment cost could not be recuperated unless the connection cost (150 kV cable) and annual grid cost could be shared with the grid operator (Berenschot, Delft, and ISPT, 2015).

4.2.3 Hydrogen boiler

Hydrogen can be used as an alternative for natural gas to produce steam in combustion boilers. To be considered a renewable option, the hydrogen (H_2) has be produced from electrolysis using renewable electricity (green hydrogen) or from natural gas in combination with CCS to mitigate CO_2 emissions (blue hydrogen).

The use of hydrogen in generic industrial boilers appears to be feasible and would only require a retrofit of the burner to accommodate hydrogen gas properties (E4tech, 2014). For 100% use of hydrogen, oxyfuel burners could be used to combust the hydrogen using pure oxygen instead of air to avoid nitrous oxide (NO_x) formation. This would also increase the combustion efficiency by 15% compared to conventional natural gas boilers (E4tech, 2015).

The availability of affordable hydrogen produced from renewable electricity (green hydrogen) or hydrogen produced from natural gas in combination with CCS (blue hydrogen), is currently a limiting factor. This may change as there are currently over a hundred of hydrogen project initiatives in industry, transportation, built environment and energy sector (Gigler and Weeda, 2018), although the initial application of hydrogen might be prioritised towards higher temperature processes or feedstock, because of the loss of exergy when hydrogen would be applied to produce low temperature heat.

Table 20: Hydrogen boiler, economic data

Characteristics	Value	Source
Fuel	Hydrogen	Johansson (2005)
Emissions	Water vapour NO_x	Johansson (2005)
Capacity	50–300 MW_{th}	
Efficiency	85% (HHV)	VNP (2018)
Lifetime	15–25 years	VNP (2018); E4tech (2015)
Investment cost	110 EUR_{2015}/kW_{th}	E4tech (2015)
Maintenance cost	3.5 $EUR/kW_{th}/yr$	E4tech (2015)

4.2.4 Ultra-deep geothermal energy

Ultra-deep geothermal technology is not yet being applied, in the Netherlands. The main characteristic of ultra-deep geothermal technology is the depth of the well from which one extracts hot water: >4,000 metres, hence the name ultra-deep geothermal energy (UDG). A typical project consists of two wells, a production and injection well, also called doublet. The wells are either fully vertically drilled or vertically with a curvature deep below. The bottom of each well is situated in a water-holding limestone layer, around 4,000 metres below ground level. Salty hot water (brine) under pressure is pumped up through the production well, cooled in a heat exchanger and injected into the injection well. In principle, there is no loss of water, but some degassing may be needed as natural gas or oil needs to be separated from the brine. The estimated production temperature varies between 120 and 140 °C and makes this technology suited for low temperature steam supply for industry. The installation further consists of a production pump, and oil and/or gas separator, an above ground heat exchanger and an injection pump.

The Smurfit Kappa Parenco paper mill is part of a green deal to develop ultra-deep geothermal energy. The proposed energy project will focus on supplying 180 °C steam to Smurfit Kappa Parenco for the paper production processes and using the residual heat to feed a regional heat net in Renkum, Wageningen and Ede[34].

Table 21: Ultra-deep geothermal energy, economic data

Parameter	Value	Source
Output	Steam	
Fuel	Electricity, heat	
Emissions	Assuming well not drilled on-site, no on-site emissions	
Capacity	17 MW[35]	PBL (2018)
Efficiency		
Lifetime	15[36] years	
Investment cost	2,509 EUR/kW_{th}	PBL (2018)
Fixed O&M	107 EUR/kW_{th}/yr	PBL (2018)
Variable O&M	0.0076 EUR/kWh_{th} output	PBL (2018)

4.3 Alternative processes

4.3.1 Microwave drying

The application of microwave technology for drying in the paper industry is at a low TRL but shows promise. Instead of heating the paper web thermally with a temperature gradient, microwave drying affects the dipolar water molecules equally. Microwave drying is often used in the food industry, to bake or dry products, but is also used for wood finishing treatments.

Researchers have shown in 2003 on four different grammages of paper that microwave drying on paper is possible and efficient. Furthermore, the technology has advantages not only regarding energy efficiency but also regarding paper characteristics like tensile strength and bending strength, which can be enhanced using microwave drying, leading to a better product. A challenge of the technology are safety aspects and managing the web temperature in case of a paper break.

The efficiency and economic cost of an industrial size microwave dryer for the paper and board industry cannot be provided, due to the low TRL of this application of the technology. A feasibility study conducted by ISPT, however, showed that microwave drying can increase

34 http://www.thinkgeoenergy.com/paper-producer-planning-utilisation-of-geothermal-at-renkum-netherlands/
35 The expected size of a typical UDG project is assumed to be 17 MWth (SDE+ 2019). An annual full load production time of 7000 hours is assumed, supposed to be representative for low temperature steam demand in industry (baseload).
36 Lifetime is expected to be 15 years, but thus far no project has been running more than a few years.

paper machine speeds by 30% and reduce energy consumption for drying by 20% (Bajpai, 2016).

4.3.2 Air-laid technology

The most energy intensive part of paper production is the removal of water. A more drastic solution to reduce energy consumption is to make paper without the use of water. Dry formation, also known as air-laid technology, produces paper webs without the use of water (FINDEST, 2018). The technology is already applied in nonwoven textile production and could potentially be used in the papermaking industry (FINDEST, 2018). Currently, the achieved paper strength is rather low making it less suitable for board with packaging purposes but could be used in the production of sanitary paper or graphic paper.

Reports have shown that the drying energy demand may be reduced by up to 50% (Bajpai, 2016). However, it has also been estimated that an additional 150–250 kWh electricity per ton paper would be needed (Bajpai, 2016). Wastewater treatment steps would be eliminated from the production process (FINDEST, 2018).

Air-laid technology uses different techniques to ensure the quality of the paper product. One technique uses latex as a binder (LBAL). Thermal bonding (TBAL) is also possible. When these two techniques are combined this is called multi-bonded air-laid technology (MBAL) (Jezzi, 2017). Hydrogen-bonded air-laid (HBAL) technology is also known (Jezzi, 2017). MBAL is expected to grow substantially, in the future (Jezzi, 2017). Currently, Dan Web, located in Denmark, produces MBAL installations and has so far sold over 60 installations worldwide (Dan-web, 2018). A major advantage in the further development of MABL is that thicker products can be produced, although this involves higher costs (Jezzi, 2017).

Figure 11 illustrates the multi-bond air-laid technology as supplied by Dan Web. The input in this process is fluff pulp, which is made from softwoods (Nanko, Button and Hillman, 2005). After the web is formed in the multi-head forming section, latex is sprayed on to the web to bond with the fibres (Jezzi, 2017). In the oven, the fibres are then also thermally bonded to ensure greater paper strength. Finally, the embosser refines the product by imprinting patterns.

Figure 11: Schematic representation of air-laid technology (Jezzi, 2017)

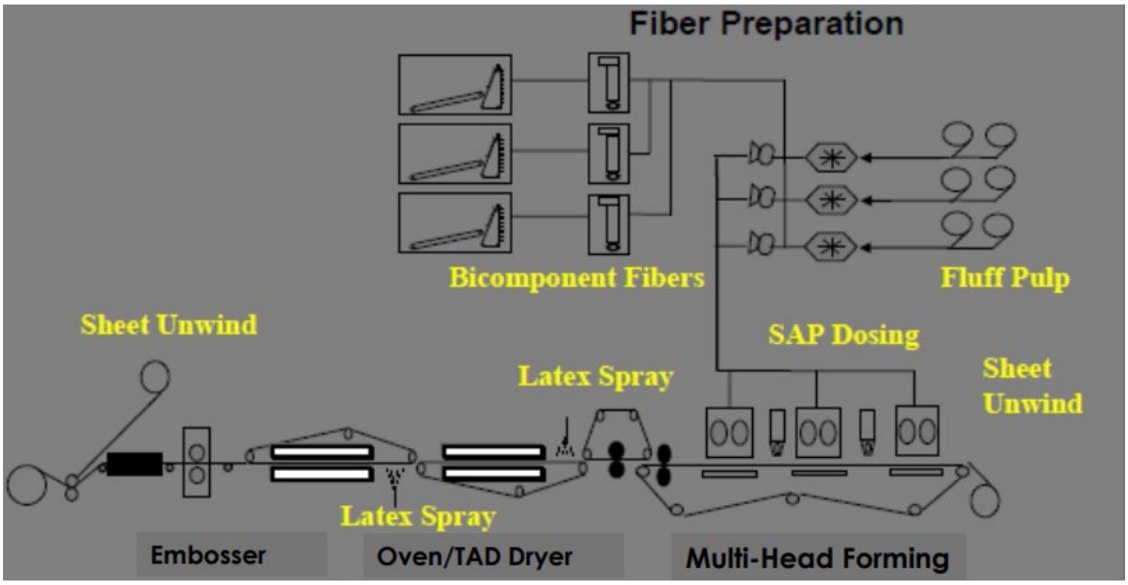

Table 22: Characteristics of air-laid technology from various sources

Property	Value	Source
Energy reduction potential drying energy	50%	FINDEST (2018)
Electricity consumption	150–250 kWh/t paper	Bajpai (2016)
Capacity	12,000–20,000 t/yr	Jezzi (2017)
CAPEX	Unknown	
OPEX	Unknown	
Speed limitation	400–500 miles/minute	Jezzi (2017)

4.4 Other technologies

The technologies mentioned in Section 4.3 are radically new technologies that might need 10 to 20 years of development before they can be implemented. Since the technologies introduced mainly depend on electricity, one could argue that using those technologies could result in plant emissions reaching zero for the drying section. However, improving the existing drying technology also remains relevant. Electric drying technologies might only be applicable for a specific paper type. Furthermore, the development of any technology is strongly related to the interest and cooperation of large machine building companies, such as Voith. Involvement of main manufacturers of machinery for the paper and pulp industry is crucial for accelerated development, scale-up and implementation.

Various other technologies within the paper sector are under development, as well as general heat recovery technologies that could be applied in many sectors. Below is a selection of these technologies.

4.4.1 CapWa – Capture of evaporated Water

CapWa technology (short for Capture of evaporated Water) is used to recycle process-related water.

Nowadays, when water evaporates it is lost to the atmosphere when it leaves the system. This water, thus, is then wasted instead of being recovered. However, with CapWa technology, gas separation membranes are installed in wet air outlets of manufacturers in the paper industry (Ludwin Daal, KEMA Nederland BV, 2013). Depending on the membrane, water can be separated in a purified form, after which it can be reused in the paper production process. The positive side effect is that it may be used to prepare the air containing steam from the drying section into a suitable 'air-free' stream to allow heat recovery via vapour recompression. This could potentially lead to CO_2 reductions.

This technology has already been tested laboratories and has found its first pilot in a coal fired station in Israel producing 100 kg of water per hour (Ludwin Daal, KEMA Nederland BV, 2013). Also, in a Dutch paper mill the method was tested and will find a follow up module in an upcoming project. Economically on European paper sector scale savings of EUR 1 billion are expected (Ludwin Daal, KEMA Nederland BV, 2013). However, this technology is still in its pilot phase but looks promising for scaling up in Dutch paper mills.

4.4.2 Mechanical vapour recompression

Another option to optimise paper production is the use of MVR in the exhaust air of the paper drying section. The evaporated water from the paper web present in the exhaust air is recompressed mechanically so that the right temperature and pressure are achieved to enable the steam to be integrated into the production process (GEA Process Engineering GmbH).

The compressor consists of a centrifugal fan, which is driven by electrical energy. The installation becomes more efficient with increasing size of the heat exchanger surface (GEA Process Engineering GmbH).

The thermal energy reduction may be up to 50%. There is an increase in electricity consumption of 160 kWh/t. This technology cannot completely eliminate CO_2 emissions, however, reusing heating energy may significantly decrease the energy input for the drying section, thus reducing CO_2 emissions from the steam production.

This technology is already on the market. Investment costs are high, but the return on investment (ROI) is estimated at around 1.5 years. A disadvantage is the presence of air in the exhaust fumes from the drying section. Combination with the CapWa technology could potentially solve this problem.

4.4.3 Technologies under development

In addition to the technologies described above, there are many research and development projects currently underway to increase the efficiency of paper drying and to further reduce CO_2 emissions. Next to many other topics, superheated steam drying as well as impulse-assisted drying are of interest to the Dutch paper and board industry. When using superheated steam, it is easier to dry without the risk of condensation. Due to the research status, estimations on energy and emission reduction are not yet confirmed. Impulse-assisted drying is an extension of the common press section. In other sectors, this technique is already being used; however, no trials have yet been run in the paper sector.

5 Discussion

This chapter discusses the time frame for implementation of options and other current considerations.

5.1 Short-term options

Electric boilers are available and can be implemented without adjustments to the main production process. Steam production using electric boilers is generally expensive compared to steam production using natural gas boilers, due to the price of electricity compared to the price of natural gas. The flexibility of the electric boilers, however, allows them to be used only at times when the electricity prices are low.Electric boilers may require significant additional investments due to the required larger connection to the electricity grid, which, at current prices, hampers their application (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017).

Biogas is another short-term alternative to decarbonise part of the paper industry's CO_2 emissions. Five mills already use biogas (Smurfit Kappa Parenco, Smurfit Kappa Roermond B.V., Eska B.V., Huhtamaki Nederland B.V. and DS Smith paper De Hoop) as energy carrier, and Solidus Solutions Board B.V. is looking for partners to achieve economies of scale sufficiently large to create an attractive business case for their 300,000 m^3 of biogas[37]. As with an electric boiler, biogas boilers can be implemented with little impact on the production process. Their application is limited by the amount of available biomass suitable for digestion or the amount of available biogas/green gas from third parties.

The use of hydrogen to replace natural gas is another utility side solution. However, there is currently no infrastructure nor large scale production of green or blue hydrogen. Also, initial hydrogen production might be steered predominantly towards higher temperature processes or to be used as feedstock, instead of steam production.

5.2 Medium- to long-term options

Compression refining is currently in the pilot scale phase of development. Once the development is finalised, this option can significantly lower the CO_2 emissions from graphic paper mills, which are responsible for around one third of the total CO_2 emissions from the Dutch paper and board industry (a reduction of around 5%–10% in drying energy, in addition to reducing the electricity consumption for refining by half).

Heat pumps are an efficiency option that convert low temperature waste heat into high temperature heat. They are currently already available up to temperatures of 90 ^oC. High temperature heat pumps that provide the required steam pressure and temperature levels required for paper and board production are however still under development. Once developed, however, this option can reduce a substantial part of the direct CO_2 emissions from the paper and board industry. The impact on the production process of a heat pump, however, is considerable.

[37] https://vnp.nl/wp-content/uploads/2016/07/Naar-een-duurzame-energievoorziening.pdf

Air-laid technology has a rising market share and is promoted especially in new paper production sites. The technology has potential for large energy savings in the drying step. The input of fluff pulp makes this technology only suitable for products using virgin fibres rather than recovered paper. Note that increasing the use of virgin fibres is considered not desirable due to the lower energy efficiency within the total value chain, compared to products made from recovered fibres (Laurijssen, 2013).

Ultra-deep geothermal energy has potential for paper and board mills, depending on the location. Smurfit Kappa Parenco started research in 2012 into geothermal energy (IF Technology, 2012). According to a geological study, the region of Renkum has a source of geothermal energy suitable for the paper mill’s needs. The depth of the digging would be 5,000 m NAP where the temperature is estimated to be 185°C (IF Technology, 2012). The heat from this depth would be used to convert water to steam. The capacity of this installation would be 20 MW and would be able to make warm water and steam of 3,8 bar and 160°C available for the production process (IF Technology, 2012). In the end this could save 25% of the natural gas consumption (IF Technology, 2012). For the realisation of the drilling and installing the technique an investment of EUR 54 million is expected (IF Technology, 2012). However, EUR 12.5 million in annual savings, including CO_2 credits, is expected. In June 2017, a Green Deal was signed between Alliander, Smurfit Kappa Parenco and QNQ to start the project on ultra-deep geothermal energy (Alliander, 2018). From the studies executed so far it can be concluded that geothermal energy might be an interesting renewable energy source for the larger paper and board companies in the Netherlands. However, investment costs are high, making coalitions for such project almost mandatory. Geothermal energy is a locally dependent solution and might not be easily applied by other Dutch paper mills.

Microwave drying is a technology that has the potential to electrify the drying energy consumption of the paper and board production. The application of this technology in the paper and board industry, however, is at a low TRL.

Various other technological options are under development, both within the sector (e.g. enhanced dewatering) as well as general technologies that might be applicable in several sectors (e.g. vapor recompression).

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