VIABILITY OF SELF-GENERATED ENERGY IN PAPER AND BOARD MILLS: STUDY ON MANUFACTURING COSTS

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Environmental Technology, Master's Thesis

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ABSTRACT

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111 pages, 35 figures, 8 tables and 5 appendices

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Keywords: paper industry, cartonboard, energy production, energy costs, the EU emissions trading system, the EU ETS, renewable energy, fossil fuels

This thesis investigated the feasibility of electricity generation at European paper and paperboard mills. The study was conducted considering manufacturing expenses. The aim was to research factors affecting the feasibility of electricity generation and the impact of the EU emissions trading system on the manufacturing costs. The experimental part was conducted on the AFRY cost competitiveness modelling tool. A hypothetical mill was modelled in four different energy production concepts. Included fuels cover residue-derived fuel, outsourced biomass, natural gas, and internal fuels from chemical pulp production.

The results showed that producing surplus electricity is unprofitable in various scenarios using a natural gas-based energy production concept. In the other concepts, electricity generation was feasible, also in different energy price variations. Currently, the impact of CO2 costs on manufacturing costs is minor. However, the results support the significance to increase by 2030 and cause changes in the feasibility of different concepts.

Based on the results, low-emission options emerged as the more profitable energy production concepts compared to fossil fuel utilization. This applied to the present time and increasingly to the upcoming years. Thus, the adversity fossil fuel-fuelled mills experienced in 2022 continued in the beginning of 2023, whereas sustainable fuels were more feasible options for energy production. The findings also indicate the position of renewable and low emission fuels as the beneficiary potentially persevering in the coming years.

TIIVISTELMÄ

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Paperi- ja kartonkitehtaiden sähköntuotannon kannattavuus: tuotantokustannusten tarkastelu

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Tässä diplomityössä tutkittiin sähköntuotannon kannattavuutta eurooppalaisilla paperi- ja kartonkitehtailla. Tutkimus toteutettiin tuotantokustannusten näkökulmasta. Tavoitteena oli selvittää tehtaan sähköntuotannon kannattavuuteen liittyviä tekijöitä ja tutkia EU:n päästökaupan vaikutusta kustannuksiin. Kokeellinen osuus toteutettiin käyttäen AFRYn kustannuskykymallinnusta. Hypoteettisen tehtaan mallinnus suoritettiin neljällä eri energiantuotantokonseptilla. Konsepteissa olevat polttoaineet kattoivat jätepolttoaineen, ostetun biomassan, maakaasun ja kemiallisen selluntuotannon tuottamat sivupolttoaineet.

Työn tuloksista selvisi, että sähköntuotanto yli tehtaan omavaraisuuden ei kannattanut käyttäen maakaasuperusteista tuotantomenetelmää. Muissa konsepteissa sähkötuotanto oli kannattavaa, myös energianhintojen eri vaihteluissa. Päästökaupan vaikutusten tarkkailun tulosten perusteella CO2-kustannusten merkitys tuotantokuluissa oli vuoden 2023 alussa vähäinen. Merkitys tuli kuitenkin kasvamaan vuoteen 2030 mennessä ja aiheuttamaan muutoksia sähköntuotannon kannattavuuteen.

Tulosten pohjalta voitiin tulkita, että vähäpäästöiset energiantuotantomuodot ovat kannattavampia sähköntuotantoon paperitehtaassa kuin fossiilisten polttoaineet. Vuonna 2022 todettu fossiilisen energiantuotannon kasvaneet kustannukset näyttivät jatkuvan vuonna 2023, kestävät polttoaineet sen sijaan olivat kannattava valinta. Useiden tekijöiden ennustetaan edistävän kestävien polttoaineiden käytön kasvua paperiteollisuudessa.

SYMBOLS AND ABBREVIATIONS

Roman characters

A	area	[m2]
BM	benchmark	[EUA/unit of product]
CLEF	carbon leakage exposure factor	-
E	energy	[J, Wh]
F	free allocation	[EUAs]
HAL	historical activity level	[unit of product]
m	mass	[g, kg, t]
P	power	[W]
t	time	[a]

Superscripts

1	biomass CO2 emissions not included
2	biomass CO2 emissions included

Abbreviations

a	year
Adt	air dried tonne
BFB	bubbling fluidized bed
BHKP	bleached hardwood kraft pulp
BM	benchmark
bp	backpressure

BSKP	bleached softwood kraft pulp
CBAM	Carbon Border Adjustment Mechanism
CCGT	combined cycle gas turbine
Cepi	Confederation of European Paper Industries
CFB	circulating fluidized bed
CHP	combined heat and power
CL	carbon leakage
CLEF	carbon leakage exposure factor
CO2	carbon dioxide
CSCF	cross-sectoral correction factor
CTMP	chemi-thermomechanical pulp
DIP	deinked pulp
EFTA	European Free Trade Association
eq	equivalent
EU	European Union
EU ETS	EU emissions trading system
EU27	27 European Union member states in 2020
EUA	EU allowance
EUR	euro
FBB	folding boxboard
FiT	feed-in tariff
GBP	pound sterling
GDP	gross domestic product
GHG	greenhouse gas

GWP	global warming potential
HW	hardwood
IR	infrared
LNG	liquified natural gas
NAP	national allocation plan
PP	pulp and paper
PPI	pulp and paper industry
PV	photovoltaic
q	quarter
RCF	recovered fibre
RCP	recovered paper
RDF	refuse-derived fuel
RED	renewable energy directive
RES	renewable energy sources
SEC	specific energy consumption
SW	softwood
WLC	white lined chipboard

Table of contents

Appendices

1. Introduction

The pulp and paper industry (PPI) is one of the most energy-intensive industries and among the largest energy consumers in the industrial sector, in the top five globally. The annual energy demand of the PPI was over 8.5 thousand PJ in 2021 (EIA 2016; IEA 2022b). It has been estimated that energy costs conventionally cover around 20-30 % of total manufacturing costs in pulp and paper production (European Commission 2017; Li et al. 2012; Reese 2021). However, in 2022, energy and electricity prices across Europe were highly volatile, creating uncertainties in the market and affecting consumers on both household and industrial levels. According to statistics published by Eurostat (2022), electricity prices increased in 22 European Union (EU) member countries in the first half of 2022 compared to the previous year, and natural gas prices reached record highs due to decreased supply from Russia. Furthermore, it is improbable that the prices will see stabilisation moving forward, while natural gas shortages in the European market have also become a possibility due to unbalanced supply demand. (Eurostat 2022; IEA 2022a.)

The recent developments in the energy markets have increased the prices of energy costs for the pulp and paper industry as fossil fuels are the next most common fuel used after biomass-based fuels. In Europe, paper and board mills either produce their energy at the site or source needed energy from the market. Electricity can be generated at the mill site or purchased from the market, while heat is produced at the mill. Therefore, increasing and unstable energy costs considerably affect the total operating costs of paper and board mills. (AFRY Smart 2023; Cepi 2023.) Additionally, European Commission (2022) estimate that fossil fuel subsidies will likely decrease in upcoming years and shift towards renewable sources and energy efficiency to support the clean-energy transition. EU has also decided to annually decrease the cap on emissions implemented by the Emission trading system (ETS), and simultaneously the price of carbon credits is predicted to increase. Thus, support mechanisms for fossil fuel usage are projected to dwindle while carbon dioxide (CO2) emission costs rise. (European Commission n.db.) The significance of the cost changes is influenced by the energy production concept of a mill. The energy concepts vary depending on the self-sufficiency rate, fuel mix and power generation technologies.

With the developments in energy markets, CO_2 prices and the EU ETS, the importance of considering and researching the extent of these developments' effects on the European paper and paperboard industry has increased. However, many of the changes have occurred in a short period, thus there are many uncertainties around the subject. Confederation of European Paper Industries (Cepi) (2023) report that the high energy prices have considerably affected the paper industry and have escalated to temporary shutdowns in 2022. Studies researching energy efficiency improvements and novel energy production technologies in the industry have been conducted by Moya & Pavel (2018), Lipiäinen et al. (2022) and Johansson et al. (2021), among others. However, few studies have yet been concluded on the status of conventional energy concepts amidst the current market setting and their attractiveness moving forward. Additionally, the development of the EU ETS is increasing the role of the scheme in the PPI. Stenqvist & Åhman (2016) studied the effect of the EU ETS allocation mechanism on the PPI during the third trading period (2013-2020). Corresponding research on the effect on the current fourth trading period (2021-2030) is unavailable.

The aim of this thesis is to research factors affecting the economic feasibility of electricity generation at paperboard mill sites in Europe from the aspect of manufacturing costs and the significance of these factors using AFRY cost competitiveness modelling tool. The key focus is on examining the effects of different power plant concepts and fuel mixes typical in European mills and the impact of CO_2 emission allowances. The target is to examine the behaviour of these components in the current energy market situation and in alternative price scenarios. Lastly, the thesis presents generally favourable energy concepts for flexible adjustment of power generation volume depending on the market prices. The results of the study are aimed to be used in the development work of the company's cost competitiveness tool.

The key research questions of this thesis are:

- How do different energy concepts affect the paper/paperboard manufacturing costs and the viability of electricity production at the mill site?

- How do specific cost components from the mill's electricity production affect the attractiveness of excess electricity sales?
- What is the impact of CO_2 emission costs and allocation of emission allowances, currently and until 2030?

The scope of the thesis is limited to a case study of a hypothetical European paperboard mill created for this study. The study is conducted from the view of manufacturing costs; thus, capital expenditures are excluded from the scope. The modelling is carried out using unit prices of 2023 first quarter (q1) available in the cost competitiveness tool. The analysis of the impacts of EU ETS and CO_2 costs until 2030 is limited to a study of the effects in various carbon credit price and allowance allocation scenarios as it is conducted separately from the electricity production viability analysis. Thus, the CO_2 costs analysis excludes the potential changes in other cost component pricing outside the CO_2 costs. Additionally, the impact of national energy subsidies is excluded from the experimental section; however, the implications are discussed in the theory and conclusions.

The thesis comprises a theory section and an experimental part. The theory section covers an overview of energy consumption in paper production, typical energy concepts at European paper and board mills, and a look into European energy subsidies and the EU ETS. The purpose of the theory part is to support the experimental section of the thesis. The experimental section includes modelling a hypothetical cartonboard mill using the AFRY cost modelling tool. The mill is modelled in four different energy concepts, which have varying fuel mixes, power plant models and, thus, CO_2 emissions and costs. The modelling is conducted in two base scenarios, of which the first presents a mill self-sufficient in power generation, and the second presents a mill generating excess electricity for sale in addition to the power requirements of the mill. The results are used to analyse how the different components affect the viability of electricity self-generation and excess electricity sales in different energy price and CO_2 cost scenarios. The results provide insight into the relative positions of various power plant concepts used in the paper industry in the current energy market and the impact of EU ETS on these standings. Lastly, limitations and conclusions of the study are presented.

2. Energy consumption in paper and board production

A paper manufacturing process consists, in order, of stock preparation, wet end processes, dry end processes and finishing (figure 2). The primary raw material for paper production is pulp. The pulp can be produced from wood fibre (virgin pulp) or recycled fibre. A paper mill can purchase virgin pulp or manufacture the virgin pulp from the raw material, wood, at the site. If the paper is produced from recycled fibre, the mill processes the material into pulp on-site. Paper mills that produce pulp at the mill site are called integrated mills. (Cepi 2021b.)

Paper and pulp manufacturing processes are energy intensive with high heat and power consumption. The global energy consumption in the industry is over 8.59 thousand PJ annually (IEA 2022b).) Specific energy consumption (SEC) of paper and board mills is affected by multiple factors, including the geographic location of the site, the technical age of machinery and the general plant site, the power plant concept and the mill's production capacity. For example, older machinery is usually less energy efficient than modern applications, increasing energy consumption. However, there are also differences in SEC between paper and board grades, used raw materials and process technologies. The grammages and properties of the end product, raw material mixes, integration status and required raw material processing affect the energy consumption of the production process. For example, coating increases energy consumption in the production process, while heat recovery deployed in the paper drying process improves energy efficiency. (Suhr et al. 2015; Vakkilainen & Kivistö 2014, 87.)

Figure 1 presents the average SEC for selected paper and pulp grades from two studies. However, multiple sources cite that the comparison of energy consumption between plants has many challenges, for example, due to differing documenting methods and principles, as well as the varying quality of data collection and results (Laurijssen et al. 2013; Suhr et al. 2015; Vakkilainen & Kivistö 2014, 87). For example, according to Laurijssen et al. (2013), an average SEC varied between 7.5 and 15 TJ/kt of product for different grades, based on data from Dutch mills. In contrast, Cepi (2022) reported that the average specific primary energy consumption in paper and pulp production was 13.21 TJ/kt of product in 2020. However, Koreneff et al. (2019) report that the average SEC is just below 10 TJ/kt for pulp and paper grades. Therefore, the SEC can vary considerably depending on the source and included data.

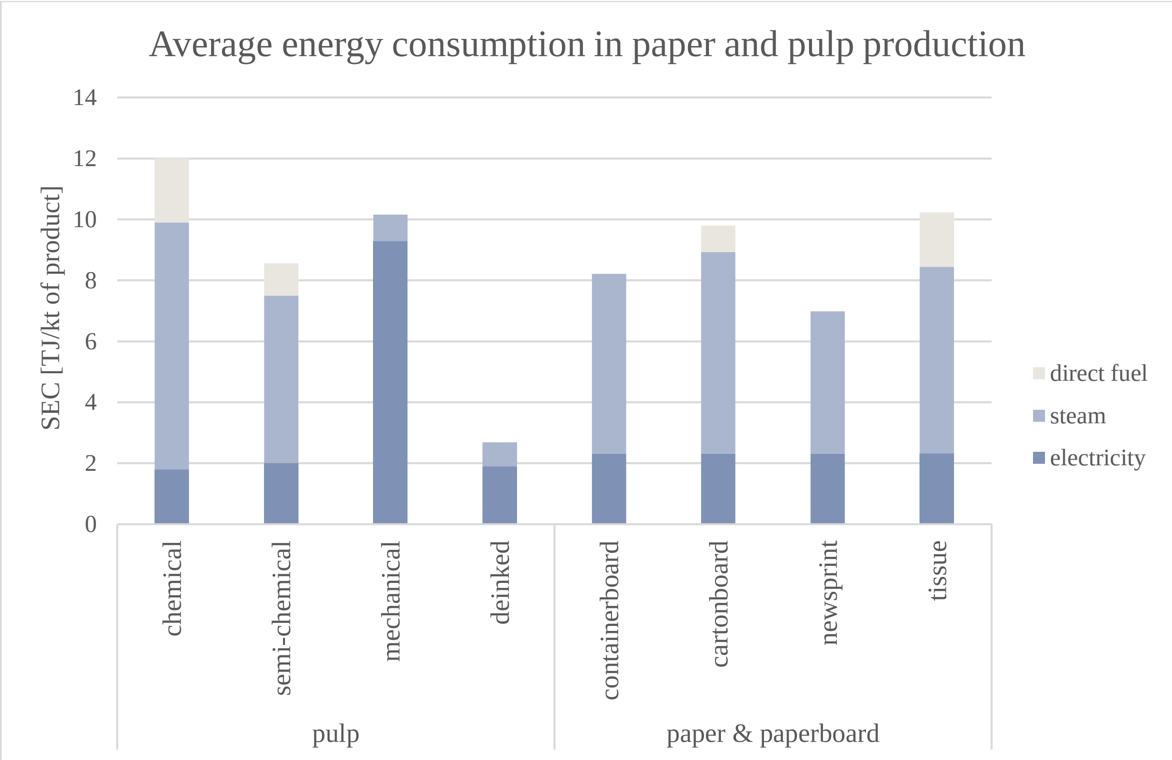


Figure 1. Average energy consumption by energy form in the manufacturing process of selected paper, paperboard, and pulp grades (Jacobs 2006; Koreneff et al. 2019).

Generally, energy is mainly consumed at the mill site in the paper and pulp manufacturing processes, at the power plant and in other functions, such as auxiliary purposes and water treatment. Energy consumption of paper and virgin pulp manufacturing processes are around the same level, both covering around 30 % of an integrated site's total energy consumption. Hence, virgin pulp integrated paper mills consume more energy than non-integrated sites, doubling the energy consumption of the manufacturing process. However, of virgin fibre-based pulps, chemical pulp mills also produce significant amounts of steam on the side in the recovery boiler, which is then used to generate electricity. Recycled fibre-based pulp (e.g., deinked pulp (DIP)) mills do not have energy production in the process. Power plant operations consume a little over 30 % of energy, while other functions cover less than 10 %. The power plant energy consumption figure includes losses from the production process. (Jacobs 2006; Suhr et al. 2015; Vakkilainen & Kivistö 2014, 99-103.)

In integrated pulp and paper mills, the energy consumption of the pulping varies depending on the pulp grade (figure 1). For example, chemical pulp production has the highest steam demand among pulp grades, often requiring direct fuel usage in the lime kiln. However, electricity consumption is low in the chemical pulping process. Overall, on average chemical pulp production process consumes the most energy, 12 TJ/kt of pulp. Mechanical pulping, on the other hand, consumes high amounts of electricity, over 9 TJ/kt of pulp; however, heat demand in the pulping process is low, below 1 TJ/kt of pulp, and no fuel is directly consumed. Recovered fibre-based pulp grades consume less energy than virgin fibre-based pulp grades, below 3 TJ/kt of pulp. (Cairnes 2020; Jacobs 2006; Suhr et al. 2015; Vakkilainen & Kivistö 2014, 99-103.)

Typical paper and board production processes are similar. Energy, including both steam and power, is needed in the production process. Some processes require heat, while electricity is needed to power most machines, such as motors. The motors run compressors, pumps, fans, conveyors, and vacuums, among other things. Additionally, energy is needed for auxiliary purposes at the plant. These include, among other things, power plant and waste-water treatment operations, transportation, lighting, air conditioning and heating of the facilities. Heat, on the other hand, is utilized in four main functions: heating of water, air, materials and chemicals, evaporating, heat loss replacement and conversion of heat energy into electricity at the power plant. For example, steam turbines require hot steam to generate electricity. Simultaneously, the power plant consumes part of the electricity generated. Overall, electricity covers around 25 % of the total energy consumption, while heat covers the rest if no fuel is directly consumed (figure 1). The direct fuel consumption depends on the grade. For example, for cartonboards, the direct fuel consumption is, on average, below 10 % of total energy consumption. (Suhr et al. 2015; Vakkilainen & Kivistö 2014, 114-119.)

Steam and power requirements of different stages in a generalized paper production process are presented in figure 2. Electricity is needed for all processes at the paper machine, excluding drying. These processes include slushing, screening, and refining in the stock preparation, forming and draining in wet end processes, pressing, drying, and calendering in dry end processes and coating. On the other hand, heat is required as steam in screening, drying, calendering, and coating. Fuel, such as natural gas, can be directly needed in the drying of coated paper and board. (Suhr et al. 2015; Vakkilainen & Kivistö 2014, 114.)

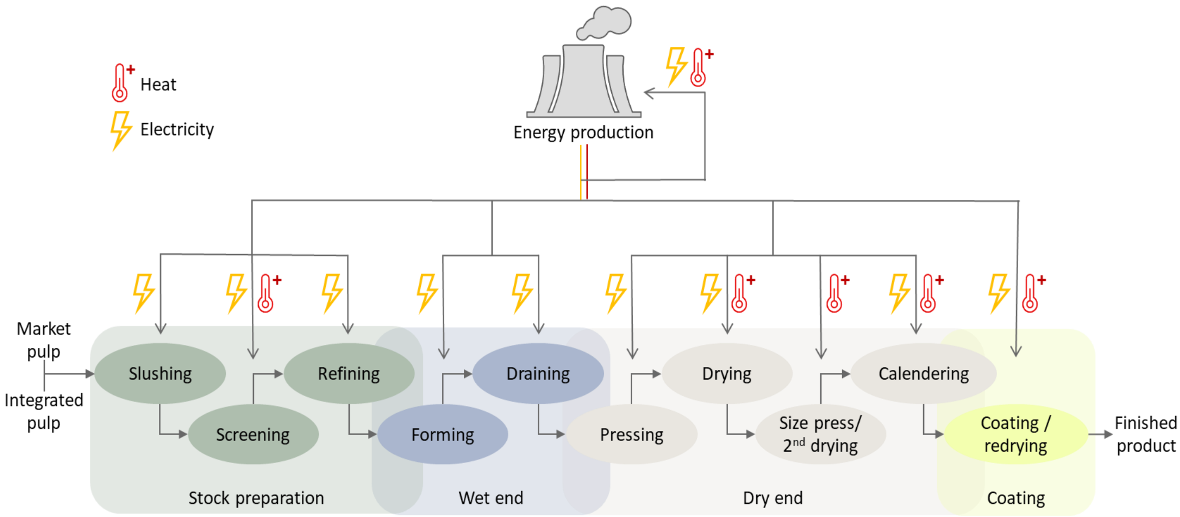


Figure 2. Power and heat energy requirements of the paper production process.

The highest heat-consuming process in paper production is drying, which can comprise up to 90 % of heat consumption in non-integrated paper mills, excluding heat consumption of energy production. Due to the high heat demand, additional drying of paper with pressing before the dryer has a significant impact on heat consumption and has the possibility of bringing considerable energy savings. After drying, pressing has the highest energy consumption due to high electricity demand. However, pressing is not a significant energy consumer for some grades, such as tissue. Overall, electricity consumption is evenly spread among the production processes. Coated grades have increased energy demand due to direct fuel usage, commonly natural gas, in the coating process. (Suhr et al. 2015; Vakkilainen & Kivistö 2014, 80-81, 115.)

3. Paper and board mill energy concepts

This chapter provides an overview of standard steam and power production technologies used in paper and board mills. Emphasis is on power generation applications, as it is the focus of the practical section of the thesis. In addition to energy production methods, this chapter presents common fuels used in energy production and dominating the sector in different regions around Europe. In the end, the share of energy-related costs in total manufacturing costs is studied.

According to Cepi (2022), Europe’s total paper and board production capacity exceeded 100 million tonnes in 2021. Of paper mills, slightly over 20 % are integrated into some level of pulp production, including both virgin- and recycled fibre-based pulps, while the rest are non-integrated mills. Most integrated mills are located in Germany, Russia, Sweden, Finland and France. Germany’s integrated mills are focused on deinked pulp (DIP) production, while in Sweden, Finland, and Russia, integrated mills have the highest chemical pulp production in Europe. However, a large majority of paper and board are produced in non-integrated mills. (AFRY Smart 2023; FAO 2023.)

The energy concept of a mill consists of used energy sources and fuels, whether energy is produced on-site or sourced from the market and of heat and power generation technologies applied in on-site production. In Europe, paper and board mills have highly varying energy concepts that depend on the mill’s integration status, geographical location and scale, and available fuels and technologies. Mills either produce the required power demand on-site or purchase energy from the market. Mill’s energy production can cover the demand partly or in full. On-site energy generation can provide security of energy supply to the mills and the local municipality and generate profits from surplus energy sales. Thus, several mills opt to produce part or all of the energy demand on-site. Occasionally, a power plant is located by the mill, but another company owns it. An overview of power plant flows on-site of the paper mill is presented in figure 3. (Johansson et al. 2021; Paper Advance 2018)

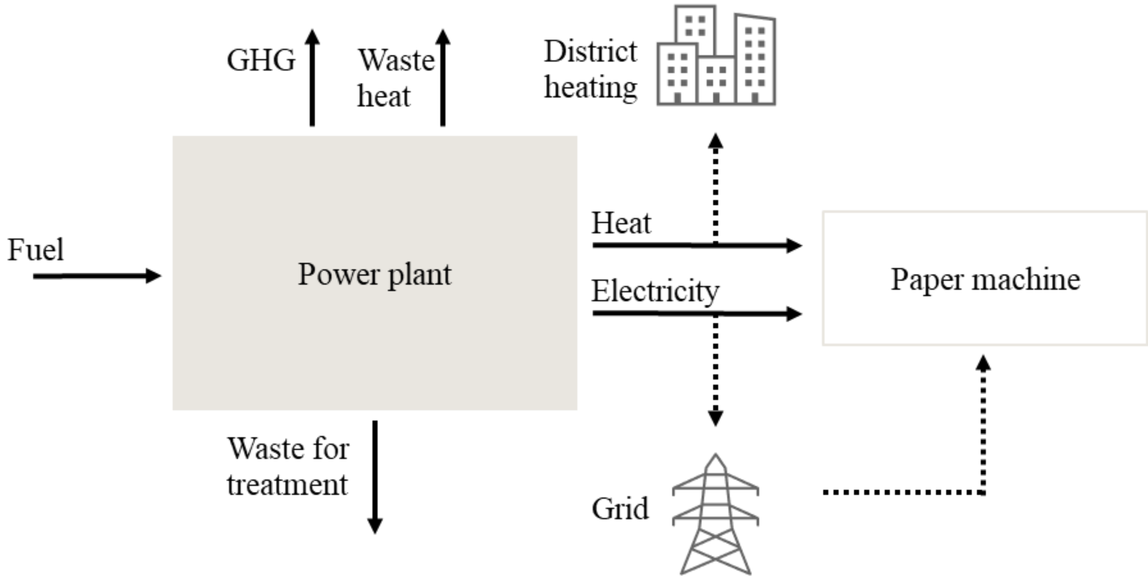


Figure 3. Generalised overview of a power plant in and outflows operating at a paper mill site. Paper mill integrated into chemical pulp production includes an additional heat source due to a recovery boiler.

Mills producing a high surplus of heat and power are notable energy providers in their regions. For example, in 2023, Holmen's integrated mills Iggesund and Hallsta in Sweden provided up to 26 GWh of heat for district heating of the local community, while the company's mill in Workington, the United Kingdom, provided almost 100 GWh of electricity to the grid (Holmen 2023). Another instance would be UPM's integrated paper plant Kaukas in Lappeenranta, Finland, which provides over 80 % of the city's district heating demand through the site's power plant (Pohjolan Voima 2022).

3.1. Heat production

At mill site, steam is produced with boilers or, as in gas turbine applications, with heat recovery methods. There are various boiler types and applications, and the boiler selection depends, among other things, on the mill's location, steam demand, possible electricity generation method, available fuels, investment funds and required environmental permits (Vakkilainen 2017, 55). This section presents the most common heat production applications used in paper and board mills, including integrated ones. These include fluidized bed, grate and recovery boilers and heat recovery steam generator applications. Other, more uncommon applications used in paper mills include, among other things, electric boilers, gasifiers, diesel engines and other heat recovery applications. (AFRY Smart 2023.)

3.1.1. Recovery boiler

Modern chemical pulp mills are self-sufficient and produce surplus energy, most of which is produced in recovery boilers, while the rest of the energy is produced in power boilers using bark, sludge, and other wood residues as fuel (Vakkilainen & Kivistö 2014, 119). Recovery boilers are deployed in chemical pulp mills (figure 4). Black liquor formed during the pulp production process is burned in recovery boilers. The aim of recovery boilers is to produce energy and recover cooking chemicals while also reducing odorous gases. This is executed by separating the inorganic chemicals during combustion. (Huhtinen et al. 2000 164, Vakkilainen & Kivistö 2014, 65-66.) Black liquor's organic substance burns in the boiler, while the inorganic chemicals are recovered for further treatment, producing green liquor. Heat energy is produced from the combustion of organic matter. The heat is then used to heat water and produce hot, high-pressure steam, which can be used in electricity production. The electricity is generated using steam turbines. Afterwards, the exhaust steam can be used as process heat for the mill. (KnowPulp 2023.)

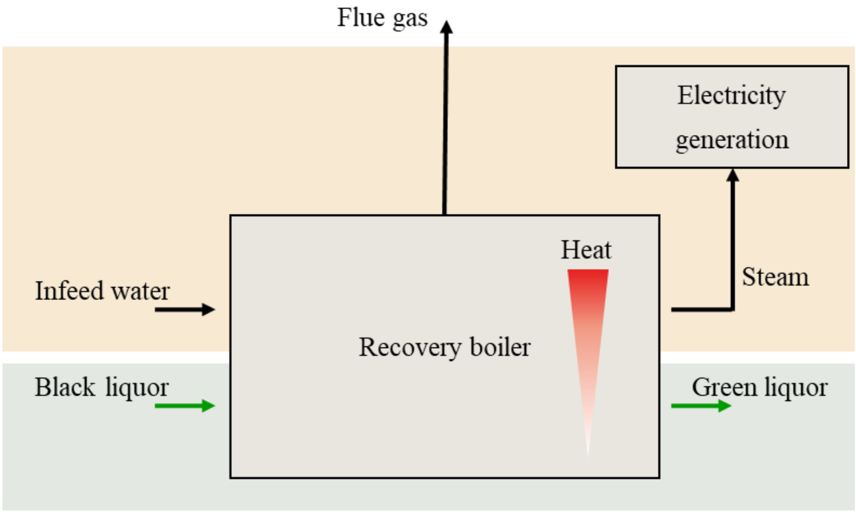


Figure 4. A schematic view of recovery boiler functions, steam generation (yellow area) and chemical recovery (green area), and main flows.

Recovery boilers have complex structures due to having multiple main functions instead of exclusively burning fuel to produce heat energy. Therefore, operating a recovery boiler is more challenging than conventional boilers. (KnowPulp 2023.) Black liquor has high water content, usually 15-25 %, as the liquor enters the boiler. Additionally, part of the dry matter consists of cooking chemicals that do not participate in the combustion. The heating value of black liquor is around 11.5 MJ/kg, which is poor compared to other fuels, such as residue-derived fuel (18 MJ/kg), wood pellets (17 MJ/kg) and coal (25 MJ/kg). However, as black liquor is a secondary product in pulp production, the mill has high availability of black liquor for fuel. (Tilastokeskus 2023; Vakkilainen 2017, 240.)

3.1.2. Grate boiler

Grate combustion is an old combustion method that has been in use for over two centuries. Nowadays, grate boilers are less popular for large-scale applications with more efficient technologies, such as fluidized bed combustion, dominating the market. However, grate combustion is still ordinary for smaller-scale applications. In the paper industry, the capacity of the boiler is typically below 20 MW. In grate boilers, fuel is injected into the furnace near the bottom of the boiler (figure 5). The fuel forms a layer on the grate bed. Grate boilers can use all forms of solid fuels, such as peat, coal, bark, and refuse-derived fuels (RDF), with little pre-treatment. The air is injected into the furnace from the bottom, with secondary air added later in the combustion process. (AFRY Smart 2023; Oakey 2015, 178; Vakkilainen 2017, 204-205.)

Two types of mechanical grate boilers commonly used in industrial applications are reciprocating and travelling grates. Reciprocating grates are inclined at a fixed angle, and the fuel is transported from the top of the grate to the lowest part with mechanical movement. Travelling grates utilise belts in automated fuel movement, and, in comparison to the reciprocating grates, the movement is horizontal. (Vakkilainen 2017, 205-207.)

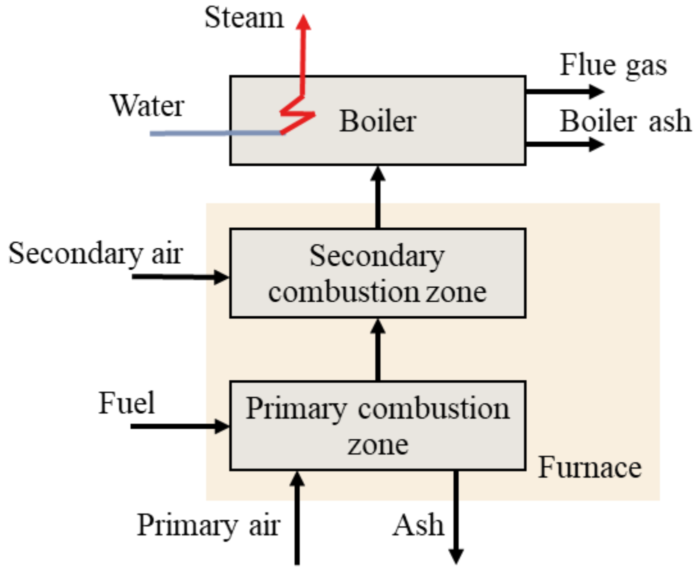


Figure 5. Grate boiler combustion process without flue gas and ash processing.

Grate boiler has low investment and operation costs, making it a cheap combustion option for solid fuels. However, grate boilers suffer from incomplete burning with moderate amounts of unburnt fuel at the end of combustion and cause high emissions. Additionally, grate boilers require a large grate area due to low fuel burning rate and fuel with relatively constant properties, including particle size and moisture content, to increase burning efficiency, making it less efficient for the simultaneous combustion of multiple fuels. (Oakey 2015, 180; Vakkilainen 2017, 204-205.)

3.1.3. Fluidized bed boiler

Fluidized bed combustion is a common method for solid fuel combustion. In fluidized bed boilers, it is possible to burn multiple fuels with different properties simultaneously, as the boiler efficiency is not primarily affected by fuel quality fluctuations. (Huhtinen et al. 2000, 153; Oakey 2015, 181.) Therefore, it is possible to burn low-grade fuels in fluidized bed boilers. Unlike grate boilers, fluidized bed boilers have low combustion temperatures and high combustion efficiency. In addition, CO2 emission costs have led to fluidized bed boilers gaining traction due to the possibility of biomass co-firing alongside fossil fuels. On average, fluidized bed boilers are utilised in larger applications. (Huhtinen et al. 2000, 153; Vakkilainen 2017, 211-212.) However, fluidised combustion’s investment and operation costs are high (Oakey 2015, 181, 198).

A fluidized bed consists of fine sand ash, which is suspended by air blown to the furnace through the bed, fluidizing it. The fuel is then injected into the furnace and mixed with the hot bed, leading to combustion due to ongoing contact with the hot sand particles. There are two common types of fluidized bed boilers in use: bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) boilers (figure 6). In CFB boilers, the hot particles are circulated back to the furnace, while in BFB boilers, the sand particles are supplied to the bottom of the furnace continuously. (Huhtinen 2000, 153-154; Oakey 2015, 183, 213; Vakkilainen 2017; 212, 218.)

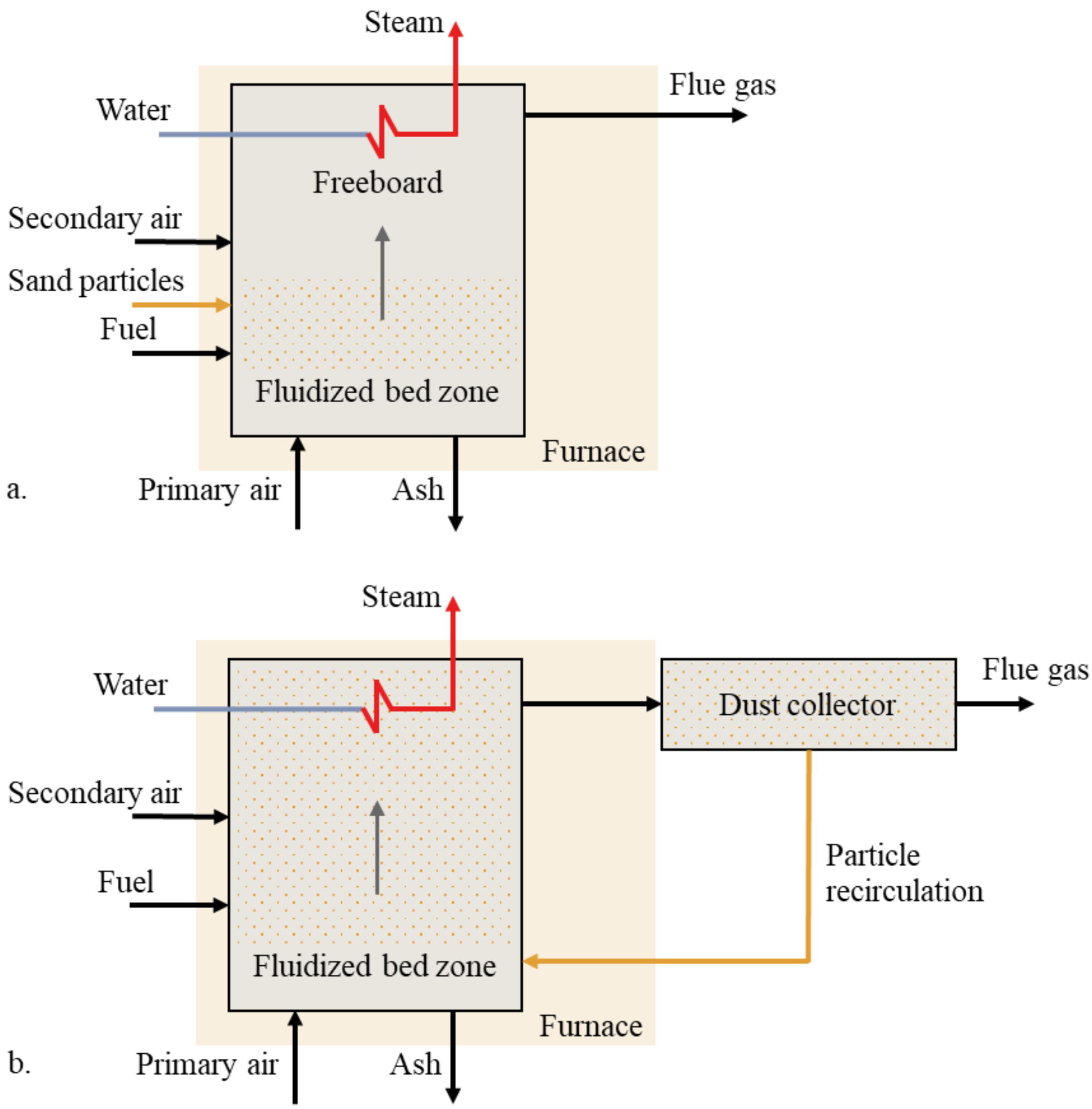


Figure 6. Bubbling fluidized bed boiler (a.) and circulating fluidized bed boiler (b.) systems, not including flue gas or ash processing.

BFB boilers are more advantageous for fuels with low heating values and high variabilities, such as wood residues and chips. On the other hand, CFB boilers are able to burn up to 100% fuel mix of coal or biomass, making it a more flexible option as BFB boilers can only utilise up to 20% coal in the fuel mix. Furthermore, CFB boilers are better suited to burning fuels with lower moisture content compared to BFB boilers. (Oakey 2015, 183, 213; Vakkilainen 2017; 212.)

3.1.4. Heat recovery steam generator

The most common type of heat recovery boiler is a heat recovery steam generator (HRSG), which is a watertube heat recovery boiler. HRSGs are utilised in joint with gas turbines, and they can be applied in cogeneration plants and combined cycle power (CCGT) plants (chapter 3.2.1). They are used to recover heat from a gas turbine's exhaust gas and, consequently, to generate steam for power generation or heating purposes at a mill. An overview of the HRSG process is presented in figure 7. Preheated feedwater is injected from the lower heat end of the HRSG; the water is first heated and then evaporated before exiting the generator as superheated steam. (Eriksen 2017, 4.) Operating an HRSG increases the electricity production efficiency of the gas turbine cycle as the recovered exhaust heat can be utilised in a steam turbine cycle. Hence, the electricity production efficiency can reach up to 60 %. Additionally, the overall efficiency of the CCGT plant producing energy for heating applications is increased to 75 %, including both electricity and heat production. (Huhtinen et al. 2013, 207-209.)

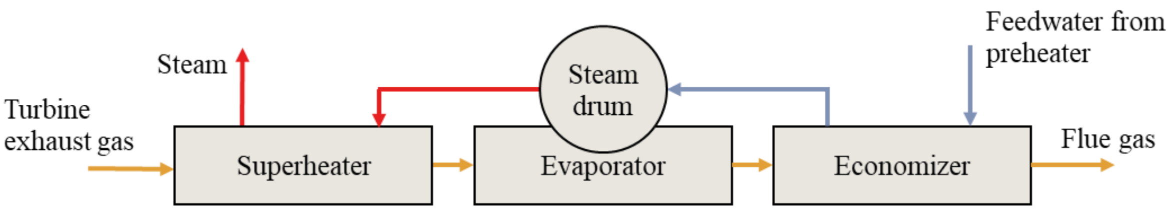


Figure 7. A simple heat recovery steam generator configuration. The circulation can be carried out in both high and low pressure in one HRSG.

HRSGs can be constructed as vertical or horizontal systems. Vertical operation benefits from lesser required space and stable flow, which also applies during start-up and partial load operation. On the other hand, the horizontal application requires smaller investment and operating costs than a vertical model; however, their operation is less stable during partial load operation. Horizontal models are more common for large units. (Huhtinen et al. 2000, 171; Vakkilainen 2017, 15.)

3.2. Electricity generation

A paper or board mill can produce the electricity required in the mill on site, partly or entirely, or purchase the electricity from the market. Turbine units mainly carry out power generation in paper and board mills. The highest annual power generation capacities of mills reach multiple hundred MWs. The applied turbine types vary, the most common types of turbines in Europe being backpressure, condensing and gas turbines. Other less commonly utilised power production methods include, for example, water turbines, wind turbines and solar photovoltaics (PV). Water turbines are most common in Austria; otherwise, they are rarely used in mill power generation, and the turbine capacities are usually low. (AFRY Smart 2023; Cepi 2021a.) According to a report by Cepi (2021), currently, power production using wind or solar power can only cover around 5 % of the mill's demand. This section does not cover these less common applications due to their present rarity and small scale. However, investments in renewable energy production with wind, solar and hydro energy are predicted to increase in the upcoming years (AFRY 2022; Johansson et al. 2021).

3.2.1. Gas turbine

Gas turbines utilise the chemical energy of fuel by transforming it through combustion into mechanical energy that powers a generator. In the combustion, air and heat are mixed with the fuel to produce hot exhaust gas. (Jansohn 2013, 4-5.) The turbine comprises three main components: the compressor, combustion chamber and turbine, shown in figure 2. Air is pressurised in the compressor to high pressure before reaching the combustion chamber. The compressor's power consumption is the highest of the components. Fuel gas is injected into the combustion chamber and heated with high-pressure air. The high-pressure hot gas is then guided to the turbine, which transforms the chemical energy contained in the high pressure and temperature of the gas into mechanical energy, which is then used in power generation. (Jansohn 2013, 89-188; Kauppinen 2018, 220-222.)

Gas turbines can be utilised in simple cycle applications with no other units, in cogeneration plants (CHP) or combined cycle plants. Combined cycle power plants recover heat from the turbine's hot exhaust gas with a heat recovery steam generator (HRSG) (chapter 3.1.4). HRSG produces steam for a secondary steam turbine cycle or the papermaking process. The steam turbine is used for additional electricity production, which significantly increases the electricity production efficiency of the plant. A combined cycle power plant is a system commonly utilised in paper production. (Jansohn 2013, 4-5; Kauppinen 2018, 42.) The electricity production efficiency of a gas turbine is around 30-45 % for simple cycle, while the efficiency can reach over 60 % for combined cycle systems (Jansohn 2013; 12, Kauppinen 2018, 219; Shiozaki et al. 2021). Combined cycle power plants are also known as combined cycle gas turbine (CCGT) plants. Figure 8 presents a CCGT plant's operating principles.

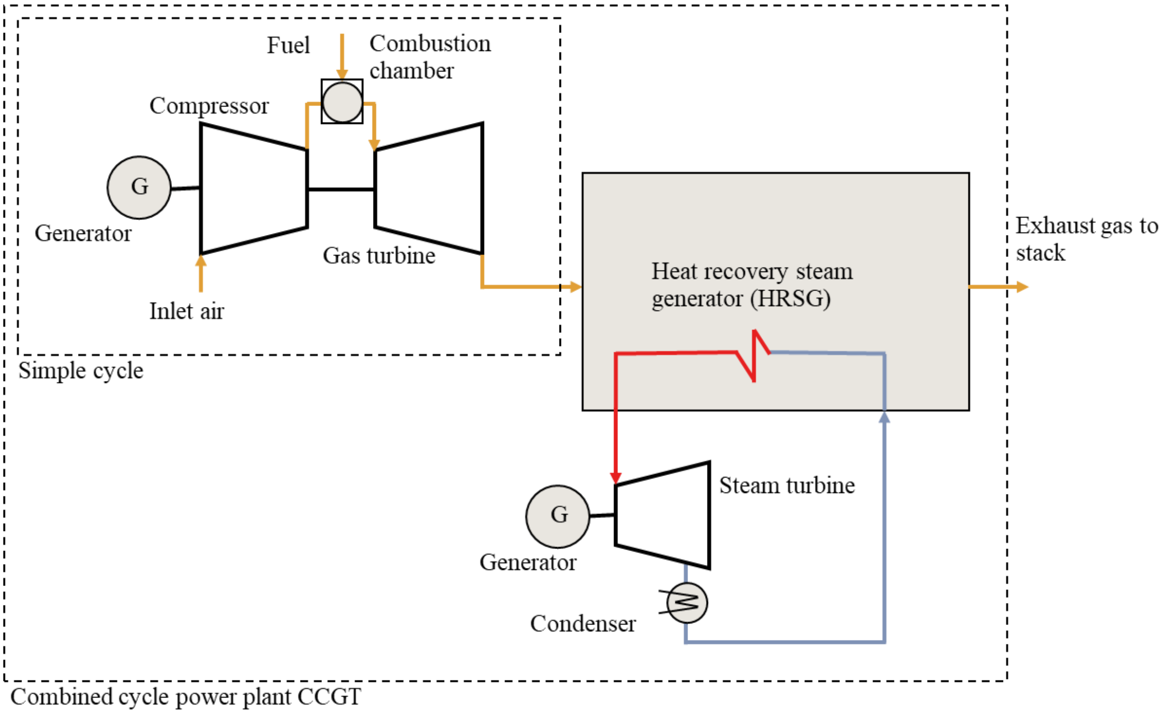


Figure 8. Combined cycle gas turbine (CCGT) system with heat recovery steam generator (HRSG) and a secondary steam turbine cycle.

Gas turbines benefit from the capability to utilise various fuels in operation. The turbines can operate on both gaseous and liquid fuels; however, the use of liquid fuels is on a downward trend, and, for example, oil is used mainly as a backup fuel (Jansohn 2013, 17-18; Kauppinen 2018, 42). On the other hand, natural gas is the most commonly utilised fuel as it provides various benefits to the turbine's operation, such as prolonging its components' lifetimes. Other alternative fuels, in addition to natural gas and fuel oil, include biogas, methane, liquified natural gas (LNG), diesel and biodiesel. (Jansohn 2013, 17-18.) However, fuels cannot be freely changed during operation, and the used fuels should have similar heating values to ensure sufficient burning without excessive emissions (Kauppinen 2018; 219-222).

Gas turbines are a common form of power generation for mills in Europe, especially in Italy, Germany, The Netherlands and Spain. In addition, gas turbines are the most used power generation units for paper and board mills in Italy, Spain and The Netherlands. For paper industry applications in Europe, gas turbine sizes typically range from below 1 MW up to 100 MW. Power generation from one or multiple gas turbines or gas turbines in a CCGT plant can cover all the electricity requirements of a paper or board mill. (AFRY Smart 2023.)

Investment costs of gas turbines and CCGT plants are low compared to steam turbine power plants; however, the fuel and maintenance costs of gas turbines are notably higher (Kauppinen 2018, 219). Fuel costs cover most of the combined cycle gas turbine's total costs (Jansohn 2013, 12). CCGT plants are moderately sized and, thus, do not take up much space (Eriksen 2017, 2).

3.2.2. Steam turbine

Steam turbines utilise steam to generate mechanical energy for power production. Water is heated in a boiler to produce the required steam, which can be powered by various fuels depending on the boiler type. These boilers can operate on fossil and renewable fuels. For example, coal, oil, gas, peat and bio-based fuels, including biomass and biogas, are possible fuels. Thus, in contrast to gas turbines, the fuel is not directly injected into the turbine but used in the boiler to generate steam. The high-temperature steam is then directed to the turbine at high pressure. In the turbine, the steam's heat energy is transformed into mechanical energy for electricity production. Exhaust steam from the turbine has decreased pressure and temperature. The use of the exhaust steam varies depending on the steam turbine type. Additionally, steam turbines can utilise steam extraction from the turbine to increase production efficiency. (Kauppinen 2018, 43-44.)

Steam turbines can be categorised into backpressure (bp) and condensing turbines (Kauppinen 2018, 46). Backpressure turbines are typical in the paper industry due to combined heat and power production (CHP), and, in Europe, bp-turbines are the most used form of power generation in the paper and board industry. Compared to gas turbines, which are more concentrated in specific regions, units of bp-turbines have been installed in paper and board mills all around Europe. (AFRY Smart 2023.) In bp-turbines, the electricity produced is directly proportional to heat demand. The turbine exhaust steam can be used in district heating or as process heat in processes requiring low or medium-pressure steam, such as paper drying. Figure 9 displays a bp-turbine system that utilises exhaust heat as process steam. Bp-turbine systems can be adjusted to output steam with the needed pressure for the process, with exhaust steam pressure between 1 to 3 bar. (Kauppinen 2018 37, 45; Tanuma 2022, 23-25.) The sizes of bp-turbines used in the paper and board industry range from below 1 MW to over 120 MW (AFRY Smart 2023).

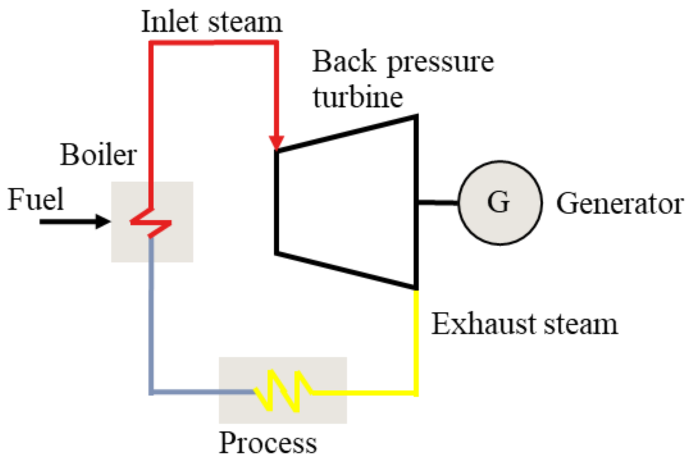


Figure 9. Backpressure turbine cycle with process heat application.

Extraction bp-turbines include an additional steam extraction from the turbine through an extraction opening to produce surplus process heat. It can be utilised in the paper industry if there is a need for process heat with different properties, including pressure and temperature, in two manufacturing stages (Mitsubishi Power n.d.; Turtle Turbines 2022). Alternatively, the extraction bp-turbine can extract steam from the turbine cycle for preheating inlet steam, while the final turbine output steam is utilised as process heat (Kauppinen 2018, 37).

The electricity production efficiency of bp-turbines is around 30 %; however, when combined with heat production, the total production efficiency can reach up to 90 %. Furthermore, additional steam extractions increase turbine efficiency. Therefore, bp-turbines systems are more energy- and resource-efficient than condensing turbine systems. (Kauppinen 2018, 37; Tanuma 2022, 37.) The structure of a bp-turbine is simpler compared to condensing turbine, and the system requires little to no cooling water; thus, no condensing process is required. Hence, the manufacturing cost of a bp-turbine is lower than that of a condensing turbine. However, bp-turbines can only respond to occurring imbalances between electricity and heat demand by utilising condensing end system (extraction condensing turbine) as heat demand determines electricity output amount (Tanuma 2022, 25.)

In condensing turbines, the steam flow is fully allocated for electricity production, and there is no combined heat production (figure 10). After the turbine, the exhaust steam is directed to a condenser in which the steam fully condenses to liquid form. The water is then cycled back to the boiler for heating. The steam extracted from the condenser has lower pressure than bp-turbine pressure, below atmospheric pressure (Amidpour 2021). Heat losses in the cycle are significant due to cooling and condensation of the exhaust steam, which is not utilised. Additionally, the construction of the condenser requires considerable investment and maintenance costs. However, the electricity production efficiency of condensing turbines can reach up to 46 %, which is considerably higher than in bp-turbines. (Kauppinen 2018, 37-39; Tanuma 2022, 23.

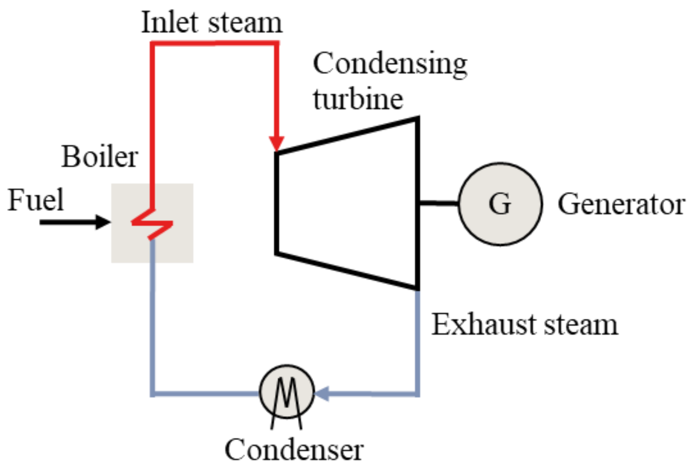


Figure 10. Condensing turbine cycle.

Compared to bp- and gas turbines, condensing turbines are less common in the paper industry, partly due to their incapability to utilise heat. However, on average, condensing turbines in paper mills have higher power capacity than bp- and gas turbines with a weighted average capacity of over 40 MW/unit, considering mill production capacity. In Europe, condensing turbines in paper mills range in size from below 1 MW up to 170 MW. Condensing turbines are, however, widespread in chemical pulp mills, which produce high amounts of excess steam on the recovery boiler, as the excess steam can be utilised in maximising profit from electricity sales. (AFRY Smart 2023; Kauppinen 2017, 37-39.)

Extraction condensing turbines combine bp- and condensing turbines' features. The turbine includes an additional steam extraction from the system with an extraction control valve that enables adjustment of process steam flow. Hence, the amount of steam extracted for process heat can be changed according to demand, while the main control valve determines the amount of input steam to the turbine. Therefore, the amount of electricity generated can vary. The turbine exhaust steam is delivered to the condenser. Therefore, extraction condensing turbines can supply process steam and electricity and are more flexible than bp-turbines. However, the steam supply is lower, making extraction condensing turbines less common in the paper industry. (Tanuma 2022, 25-26.)

3.2.3. Surplus electricity sales

According to statistics provided by Cepi (2022, 26), total electricity consumption at the paper and pulp mills was shy of 90 000 GWh in 2020 in Europe (Appendix 1, statistics exclude Hungary, Romania, and Slovenia). Of the total consumption, around 52 000 GWh of electricity was purchased, accounting for 58 %. Electricity production at the mills accounted for almost 50 000 GWh, of which around 12 500 GWh was sold to the market. Therefore, approximately 25 % of the electricity generated on-site was sold to the grid. Almost all the power generated on-site was produced with CHP. Specific electricity consumption was 0.92 MWh/kt of the final product. (Cepi 2022, 26-27.)

As per AFRY's database, over two-thirds of paper and board mills can be estimated to have power generation on-site, while the rest purchase their total electricity demand from the market. On average, mills with their own power supply produce more than half of their electricity demand on site. The estimated percentage of mills producing surplus electricity, more than their demand, is slightly over 10 %. Additionally, chemical pulp mills can be significant electricity producers. (AFRY Smart 2023.) These mills can sell their excess electricity to the grid, providing profit for the company. Additionally, mills can decrease their electricity consumption and instead sell electricity generated on-site to the grid to balance the electricity supply or at times of high electricity prices. Such operation possibility is, for example, presented by Sundman (2022). Furthermore, Johansson et al. (2021) state that companies have expressed interest in selling more electricity if the electricity is produced using renewable sources.

3.3. Fuel mixes

Fuels used for power and steam generation can be split into internal and outsourced fuels. Chemical pulp integrated mills commonly utilise internal fuels from pulp production, which include black liquor, bark, other wood residues and sludge. Paper and board mills, on the other hand, mostly purchase fuels used in on-site energy generation. These fuels include biomass-based fuels, for example, wood chips, pellets and energy crops, fossil fuels and refuse-derived fuels (RDF). Natural gas is the most common fossil fuel, followed by coal and fuel oil; however, lignite and peat are also utilised. In many cases, multiple fuels are utilised in one site. (Cepi 2022; Suhr et al. 2015.) The selection of fuels is often affected by geopolitical factors, such as fuel availability and price (Johansson et al. 2021).

The total estimated annual energy consumption by fuels for operation at full mill production capacity in European paper and board mills is presented in figure 11. The estimated annual fuel consumption is over 390 000 GWh (1 410 000 TJ). The consumption is dominated by two fuels, as over 50 % (almost 207 000 GWh) of the consumption comes from biomass-based fuels, including both internal and outsourced, and 37 % (144 000 GWh) from natural gas. Other fossil fuels comprise less than 10 % of the consumption, approximately 30 000 GWh, while waste-based fuels cover around 3 % with less than 13 000 GWh.

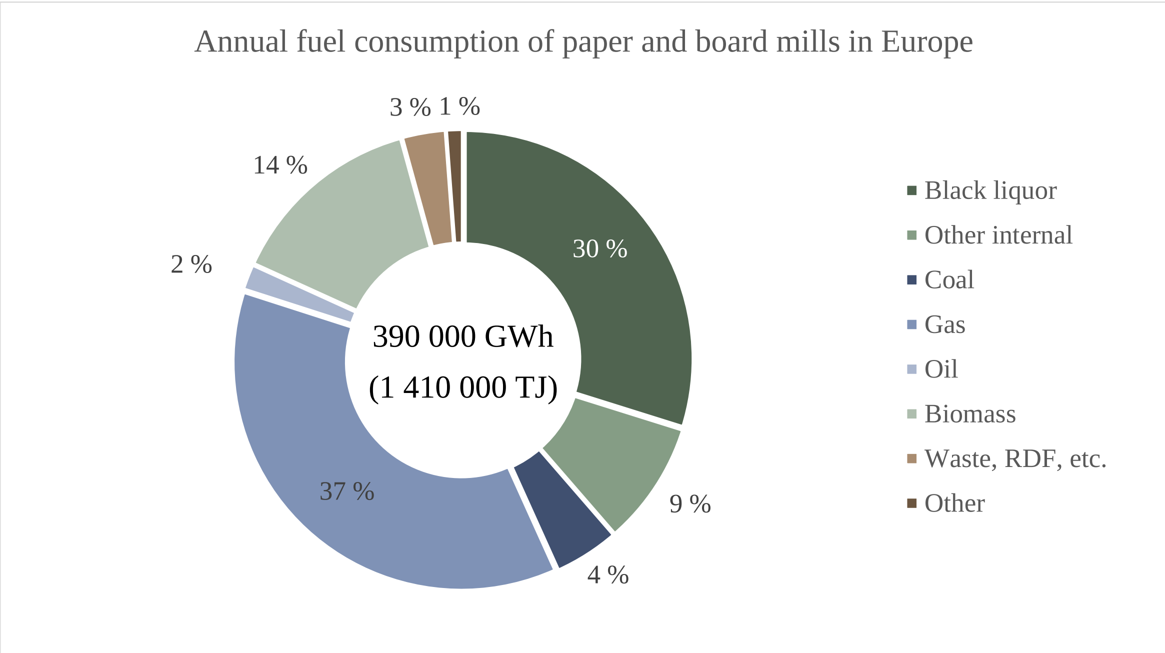


Figure 12. Total estimated annual fuel consumption (GWh) by fuel type in European paper and board mills in 2022. The total consumption is estimated to be over 390 000 GWh (1 410 000 TJ). Biomass refers to procured off-site sources. (AFRY Smart 2023.)

Country-level fuel mixes have high variation. Some countries depend on natural gas, most notably Italy, Germany, The Netherlands, Spain and The UK. Paper and board production in Belarus, Ukraine, Romania, Croatia and Serbia is also almost entirely dependent on natural gas; however, their paper and board production capacities are insignificant at Europe's level. Poland and Turkey use the most coal, with a combined consumption of over 7 900 GWh annually. Other countries with a significant share of coal usage include Hungary, Slovenia and Bosnia-Herzegovina. Biomass-based internal fuels, such as black liquor, bark and sludge, are the most common fuel type in most countries in Northern Europe, where sourced biomass is a common energy source as well. (AFRY Smart 2023.) Sweden, Finland and Russia have the most pulp production in Europe and have many chemical pulp integrated mills, which explains the large share of internal fuels in energy production (FAO 2023).

3.4. Energy costs

Energy costs consist of fuel costs, electricity costs, and profit from electricity and heat sales. CO2 emission costs can also be included in energy costs. Historically, fuel costs have varied highly depending on the fuel type and the country. For example, in 2018, natural gas prices reached 26 EUR/MWh in Germany for industrial consumers, excluding taxes and levies, while in Estonia, the price exceeded 34 EUR/MWh. Similarly, electricity costs have had a wide variety across Europe. For example, in late 2019, the retail electricity price for industrial consumers excluding taxes and levies, was 185 EUR/MWh in Italy, while in Sweden, the corresponding price was 59 EUR/MWh. (European Commission n.da.) Fuel and electricity prices can also fluctuate considerably over short periods. For example, in 2022, natural gas prices in Europe reached a record high price of 338 EUR/MWh in August, while at the beginning of June, the price was still 85 EUR/MWh (appendix 2) (Trading Economics 2023b). Carbon costs are determined according to the EU ETS by various factors, including the amount of CO2 emissions emitted (chapter 5); thus, the CO2 costs depend on the fuels used (Appunn & Wettengel 2023). The additional profit will be offset from the total energy costs if a mill sells surplus electricity and heat.

There is some variety in estimates about energy costs' share of total costs in the pulp and paper industry. Values presented by multiple research studies and other sources are visible in figure 13. It should be noted that these studies were mainly conducted before 2021 and, thus, do not consider the recent increase in energy prices (appendix 2), which has potentially affected the share of energy costs in total manufacturing costs.

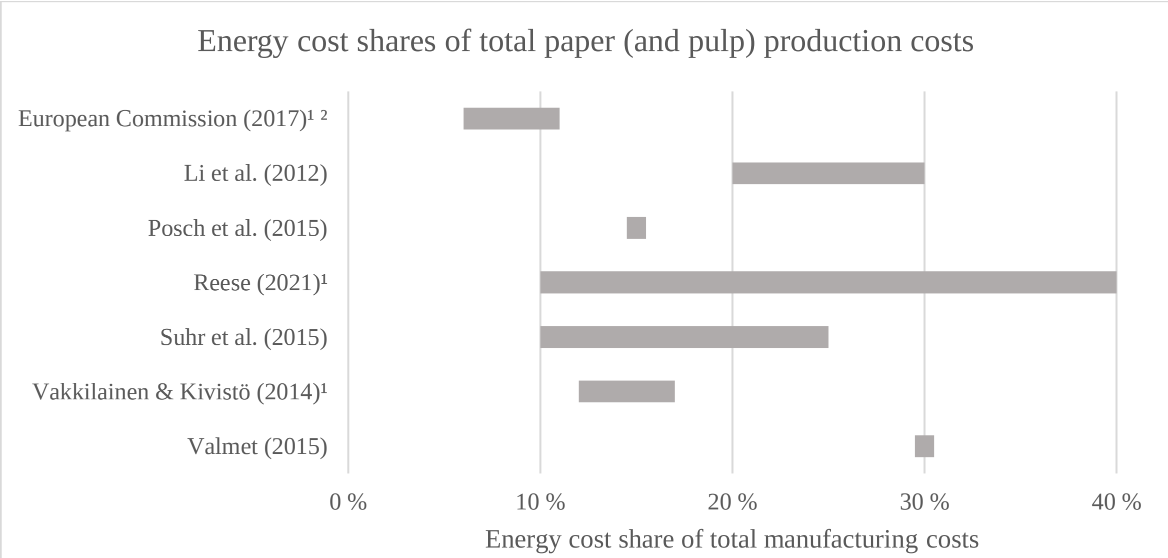


Figure 13. Range of energy costs shares in the total production costs of paper (and pulp) according to multiple sources. [1]Share calculated for both pulp and paper manufacturing processes. [2]Values present the EU27 average during 2010-2017.

The shares vary between six and 40 %. The smallest energy cost shares of around 10 % are presented by European Commission (2017). On the other hand, Valmet (2015) and Li et al. (2012) estimate the costs to account for up to 30 % of total costs. Multiple sources, such as Reese (2021) and Suhr et al. (2015), present notable ranges with no specific values. According to European Commission (2017), the highest shares of energy costs were in Lithuania and Estonia during 2010-2017. The lowest energy cost shares were reported in Ireland, Poland and the Czech Republic during the same period. Most countries had a visible decrease in the share of energy costs during the period, on average of -4.5 %. (European Commission 2017.) Overall, the share of energy costs alternate depending on the location of the mill, as well as fuel mix, used technology and size of the mill.

4. Energy subsidies in the European Union

This chapter covers, on a general level, the different energy subsidies in use in the EU. The chapter includes an overview of which kinds of support mechanisms are in place, such as tax credits and income support, and which are popular among EU Member States. The share of subsidies distributed for different energy sources is also expanded upon in addition to the number of subsidies aimed at the manufacturing industry. Additionally, the chapter includes a section on recent developments in the subsidies amidst the energy crisis through example cases and a look into the subsidies aimed towards renewable energy source biomass, which is also studied through example cases. Other renewable energy subsidies are less relevant from the view of this study due to sparse utilization in the paper industry (chapter 3.3).

4.1. Overview

In the European Union (EU), energy subsidies are distributed nationally by the Member States to support energy production, markets and consumers economically. This is implemented, for example, by preventing consumer prices from increasing above market level or by giving benefits to consumers and producers with the aim of reducing expenses. (Badouard 2022, 14-15; European Commission 2022b, 3-4.) In Finland, for example, the Ministry of Economic Affairs and Employment grants subsidies for projects exceeding 5 million EUR, while funding organization Business Finland handles more minor cases (Ministry of Economic Affairs and Employment of Finland n.d). European Commission categorizes energy subsidies into four groups:

> "(i) government measures involving the direct transfer of funds; (ii) government revenue that is otherwise foregone (not collected); (iii) governments providing goods and services or purchasing goods; and (iv) price and income supports" (European Commission 2022b, 3).

Thus, energy subsidies are provided by direct transfers, tax expenditures, income and price support, and support for research and development (R&D). The subsidies can be targeted towards energy efficiency, production, demand, and infrastructure and industry restructuring. All energy sources, including fossil fuels, nuclear, renewable energy sources (RES) and electricity, are part of energy subsidies (figure 14). Additionally, some subsidies are not specific to one energy source group and hold the name "all energies". (European Commission 2022b, 3-6.)

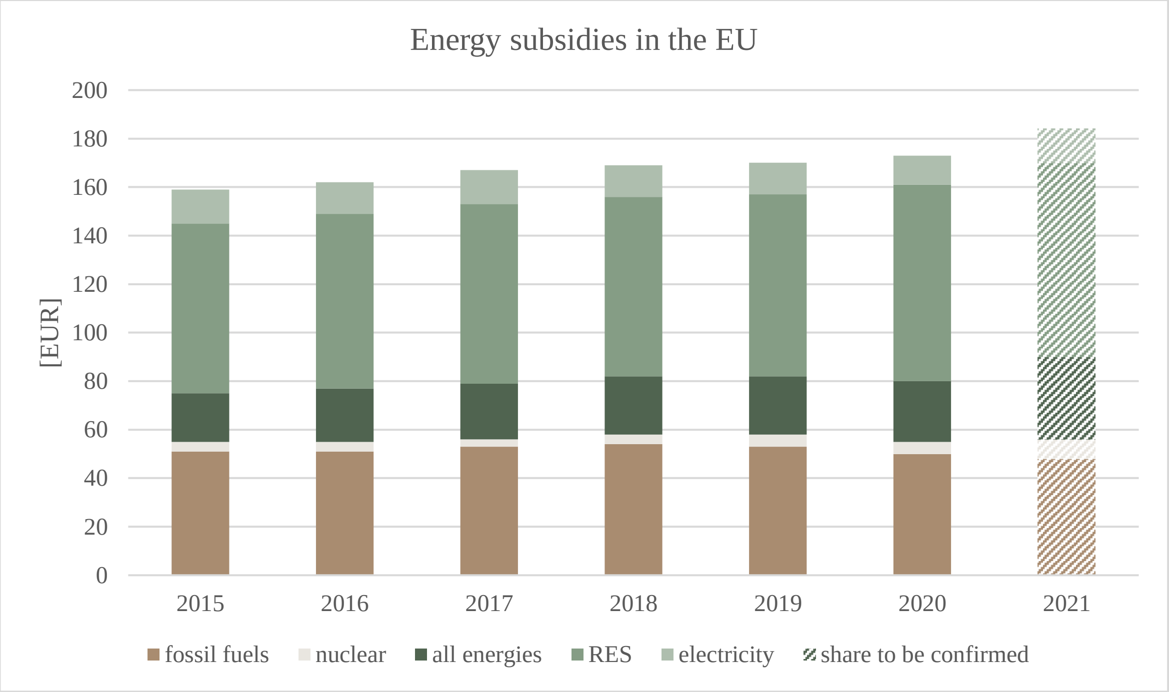


Figure 14. Energy subsidies in the EU by fuel categories. All energies are referred to as "subsidies not directly attributable to energy carriers or fuels" (European Commissions 2022b, 6).

The total value of energy subsidies was 184 billion euros in 2021 in the EU (figure 14). The amount increased by 6 % compared to 2020 when the total value reached 173 billion euros. Overall, during 2015-2021 the total value of energy subsidies increased steadily. In 2020, the share of energy subsidies of the EU's gross domestic product (GDP) was 1.2 % on average, while at the Member State level, the share varied from 0.3 % (Luxembourg) to 2.9 % (Latvia). There is a high variety among the EU Member States on the main target of the subsidy, with some countries providing the most support for fossil fuels while others focus on energy-efficiency measures or renewables. (European Commission 2022b 4-5.)

Overall, Renewables received the most subsidies, 47 %, with fossil fuels just shy of 30 %, followed by all energies, 15 %, and electricity and nuclear, 7 and 3 %. The most significant form of subsidy for renewable energy sources, with four-fifths, is income and price support, such as feed-in tariffs (FiTs) and premium schemes. Tax credits are the most common subsidy for fossil fuels, all energies and electricity. Altogether, subsidies comprise almost 50 % of income and price supports and 36 % of tax expenditures (figure 15). Direct transfers and R&D support are less common overall, covering only a minor fraction of total subsidies. (European Commission 2022b, 7-9.)

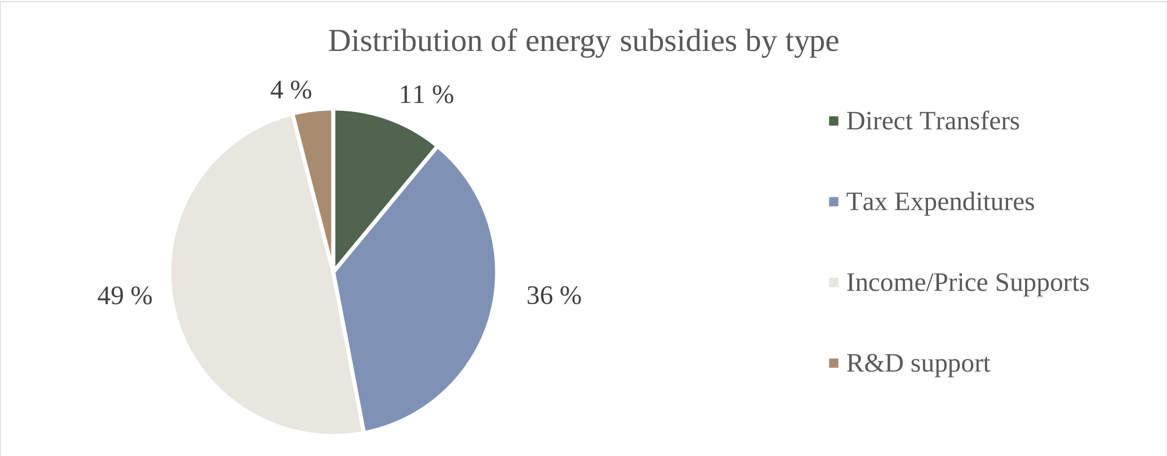


Figure 15. Distribution of energy subsidies in the EU by type of subsidy (European Commission 2022b; 9).

On the EU level, the value of energy subsidies received by the whole industrial sector has remained relatively stable, around 22 billion euros annually during 2015-2021. In 2021, the manufacturing industry’s share of total energy subsidies was around 10 %. Fossil fuel subsidies for the industry decreased overall during 2015-2020; however, gas and oil subsidies increased during this period, the growth being 0.5 and 1.1 billion euros, respectively. This is mainly explained by a sharper downturn of subsidies on coal, with a total of 1.4. billion euro decrease. (European Commission 2022b, 7-11.)

4.2. Recent developments

The steep increase in energy prices forced European governments to adopt additional energy subsidies throughout 2022 and at the start of 2023. Subsequently, this caused an increase in support for fossil fuels. Among others, in July, Germany introduced a 5 billion EUR programme to support energy-intensive industries, such as the paper industry, against high gas and electricity prices. Companies in the most affected sector are eligible to apply for the highest grant, a category in which the paper and paperboard industry is included. The highest amount includes up to 50 million euro grant and 70 % of energy price difference compared to 2021 average prices. (European Commission 2022b, 7-11; Federal Ministry for Economic Affairs and Climate Action 2022.)

However, in November 2022, Germany approved an additional, more extensive support package of which 99 billion EUR is allocated to reducing electricity, gas and district heating prices. The support scheme will come into effect at the beginning of March 2023, retroactively covering January and February of that year and last until April 2024. The scheme introduces price caps for electricity and natural gas. For industrial companies, the cap is 13 cents/kWh for electricity and 7 cents/kWh for gas, not including taxes or levies. The price cap will cover up to 70 % of the companies' electricity and gas consumption levels compared to September 2021. Consumption over that level will be subject to market prices. With these two support programmes, Germany has allocated the highest financial figures to protect the local industry against high price volatility. (Kurmayer 2022; Wehrmann 2022.)

Nevertheless, Germany has been one of many European countries to introduce aid schemes targeted towards industrial companies' heat and electricity prices. France has announced support with an around 10 billion EUR package, including reduced electricity taxes and direct monetary support to companies (Conesa 2022; Rose & Russel 2022). The Swedish government has introduced an electricity aid package, which helps support electricity costs of over 1.5 higher than the average 2021 prices of the companies. Like Germany's support scheme, the limit is up to 70 % of consumption in 2021. (Ministry of Climate and Enterprise

2023). Some countries have, however, provided less aid for companies amidst high electricity and energy costs. For example, in March 2023, Finland was still developing support schemes for companies, aiming to introduce easement to terms of payment and electricity bill loans later in 2023 (Ikävalko 2023).

4.3. Examples of renewable electricity subsidies: biomass

Renewable electricity subsidies include wind, solar, geothermal, hydro and biomass subsidies, with biomass being the most common RES in the pulp and paper industry. Various countries in Europe provide or have until recently provided price support for biomass-based electricity production, for example, through tax reductions, green certificates, feed-in tariffs or premium schemes with tenders. While previously the most used subsidy scheme, the use of FiTs has decreased in Europe, with the most common form of subsidy currently being auction-based premium schemes. (European Commission 2022b, 9; Motiva 2022; Zabala & Diallo 2022, 19.) Tendering is more cost-effective for the government than fixed support schemes, such as feed-in tariffs and tax reductions, as the costs vary according to the current production costs and market situation. Various European countries, including Germany, France and Denmark, have opted to provide auction-based support for biomass energy instead of FiTs. (Zabala & Diallo 2022, 34, 105-106.) According to OECD (2020) statistics, in Europe, a typical length of a support agreement is 12 to 20 years, providing biomass electricity producers a stabler market position for the duration of the agreement. However, subsidies for biomass electricity sales can generate a backwards situation in the PPI. Pulp and paper producers can be attracted by the subsidies to sell their own biomass electricity production and to purchase required electricity from the grid, creating profit from the sold renewable electricity.

In Finland, biomass-related FiTs have recently been closed for applications since the first quarter of 2021 for wood chips and since the beginning of 2019 for biogas and other biomass-based power plants. For other biomass-based fuels, new small boilers with thermal power up to 8 MW could apply for the support, whereas for biogas and wood chips, there was no power limit for singular units. The FiT system was operated with constant price and few restrictive factors for biogas and -mass, while the wood chip tariff varies depending on multiple factors. The support period for a power plant can last up to 12 years in Finland. Therefore, the tariff system still affects the current renewable electricity sales market and will also do so in the upcoming years. Hence, even discontinued biomass support can have a long-lasting impact on pulp and paper producers' strategies. (Energiavirasto 2021.)

An example of currently operating tariffs for biomass electricity is Portugal. Pulp and paper producers utilizing biomass and residual forest biomass in CHP and electricity production gain additional revenue from electricity sale tariffs. (DGEG 2011; Trinomics 2019, 43.) As a result, some Portuguese pulp producers have invested in electricity-only power plants that use residual forest biomass as fuel. An example is in Celbi pulp mill of company Altri, where the plant has invested in an electricity-only biomass boiler to generate renewable electricity subject to the tariff system (Greenvolt 2019; Technoedif n.d). However, it has been noted by Nunes et al. (2022) and Trinomics (2019, 43) that there is a lack of residual forest biomass to support a larger supply for electricity production, thus possibly limiting the implementation of current and upcoming projects in Portugal.

5. The EU emissions trading system

This chapter provides an overview of the European Union's emissions trading system, including its mechanisms and allowance system. A section covering the carbon credit price development is included. Additionally, the chapter presents an outlook on the development of the trading system up to 2030, a section on the position of the pulp and paper industry in the system and the effects of the trading system on the industry.

5.1. Overview

The European Union's emissions trading system (EU ETS) is the world's largest carbon market. The system covers all EU Member States and European Free Trade Association (EFTA) States, which includes Iceland, Liechtenstein, and Norway. The system is designed to cost-effectively limit emissions caused by the industry sector, including power and energy-intensive manufacturing sectors, and commercial aviation. The manufacturing industries covered are "oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cartonboard, acids and bulk organic chemicals" (European Commission n.dc). In the energy sector, both heat and electricity production are included.

The included sectors cover 40 % of greenhouse gas (GHG) emissions caused in the EU. The system covers various GHGs, which include CO2, nitrous oxide (N2O) and perfluorocarbons (PFCs). CO2 emissions have been included in the scope since phase 1, while N2O and PFC emissions were introduced in phases 2 and 3, respectively. CO2 emissions are measured for all sectors included in the scope, while N2O emissions are calculated only for specific acids and glyoxal and PFCs measured only in aluminium production. The EU ETS has proven to be effective in limiting industrial emissions as, in 2019, the ETS had led to emission reductions of around 35 % in the included sectors during the system's operation. (European Commission n.dc; IETA n.d.) The effectiveness is also supported by research authored by

Bayer & Aklin (2020), who argue that the savings reached over 1 billion t CO2 emissions during 2006-2018.

The EU ETS was established in 2005, making it the first global emission trading scheme. The system is currently in its fourth phase, which will last until 2030, the first three trading periods having taken place 2005-2007 (phase 1), 2008-2012 (phase 2) and 2013-2020 (phase 3). For phases 1 and 2, each EU Member State was required to prepare a national allocation plan (NAP), which stated the allowance cap and allocations to each installation. This practice was discontinued from phase 3 onwards, and an EU-wide emission cap was introduced. During phases 1 to 3, the carbon market increased from over 300 million credits in 2005 to almost 8 billion in 2012.

5.2. Cap and trade mechanism

The EU ETS works on a “cap and trade” mechanism, which utilises a principle of “polluter pays”. Cap represents the maximum limit of GHG emissions that can be emitted annually, with the limit decreasing over time. The cap decreases yearly for fixed installations and aviation, with a linear rate of 2.2 % for 2021-2030. The cap drives the emission allowance market. One emission allowance equals 1 t CO2-equivalent of GHG emissions. Therefore, for example, if a company holds one allowance, it has the right to emit 1 t CO2-eq in a year. Emission allowances are also known as emission permits or carbon credits. (European Commission n.dc.)

EU determines the Union-wide emission cap, which decreases linearly annually. In 2021 the total cap for stationary installations was over 1,570 billion allowances, which decreased by 2.2 % in 2022. After the EU has distributed the allowances for each state, the governments set the cap on business-level emissions for each company included in the scope. Then the governments distribute the allowances to companies either free of charge as free allowances or through an auction. (European Commission n.dc.)

5.2.1. Free allocation and auctions

Some companies receive a portion or all the carbon credits without cost through basic allocation. At the start of phase 1, up to 95 % of allowances were distributed for free. However, the share of free allocation has decreased in each phase, with phase 3 introducing auctioning as the default method. Currently, in phase 4, 43 % of allowances are distributed free of charge, while the rest is auctioned. Basic allocation is calculated by multiplying four factors, which are product benchmarks (BM), historical activity level (production data) (HAL), carbon leakage exposure factor (CLEF) and cross-sectoral correction factor (CSCF). If emissions produced by an installation exceed the number of allowances calculated for the installation in basic allocation, the company must purchase allowances to cover all emissions. (European Commission n.dc.)

Free allowances are distributed to sectors at high carbon leakage (CL) risk to prevent company operations from transferring to regions with less strict carbon regulations. Higher the risk, the more significant level of basic free allocation. The sectors with the highest risk receive full allocation of the benchmark levels without costs (Carbon leakage indicator CLI ≥ 0.2). For sectors outside of leakage risk (CLI ≤ 0.2), free allocation will be phased out by 2030, starting at a maximum of 30 % of benchmark levels in 2026. (European Commission n.dc.) Additionally, in December 2022, the European Commission decided on phasing out free allocation during 2026-2034 for sectors covered in the new Carbon Border Adjustment Mechanism (CBAM), which include cement, iron and steel, aluminium, fertiliser and electricity (European Commission 2022a). Currently, the manufacturing industry receives up to 30 % of carbon credits with free allocation, with the share decreasing yearly (European Commission n.dc).

Over half of all emission permits are auctioned. The auctioning of allowances was started in 2013 to reduce the share of free allocation. As the number of free allocation credits decreases, the number of allowances companies need to purchase increases. However, a share of allowances is withheld in a market stability reserve (MSR) to respond to possible market imbalances. These allowances in the reserve may be released to the market if needed, and more allowances can be transferred to the reserve from the carbon market in case of a surplus of credits. (European Commission n.dc.)

5.2.2. Trade and carbon credit price

Emission allowances work as the currency in the carbon trade market. If a company emits more GHGs than has been allocated to them by the government, either as free allowances or through the auction, they have three options in general. The company can reduce their emissions to match the set cap or purchase more allowances from other participating companies through trade. The last option is not to follow the regulation, thus leading to a baseline penalty of 100 EUR/t CO2-eq not covered by the allowances, which annually increases according to the EU Consumer Price Index, on top of the requirement to acquire the allowances. Alternatively, if a company has extra credits, in other words, they have emitted fewer emissions than have been allocated to them, the company can sell their surplus credits at the carbon trading market. This way, companies can create profit from low-emission operations. (European Commission n.dc.)

The development of carbon credit price is presented in figure 16.

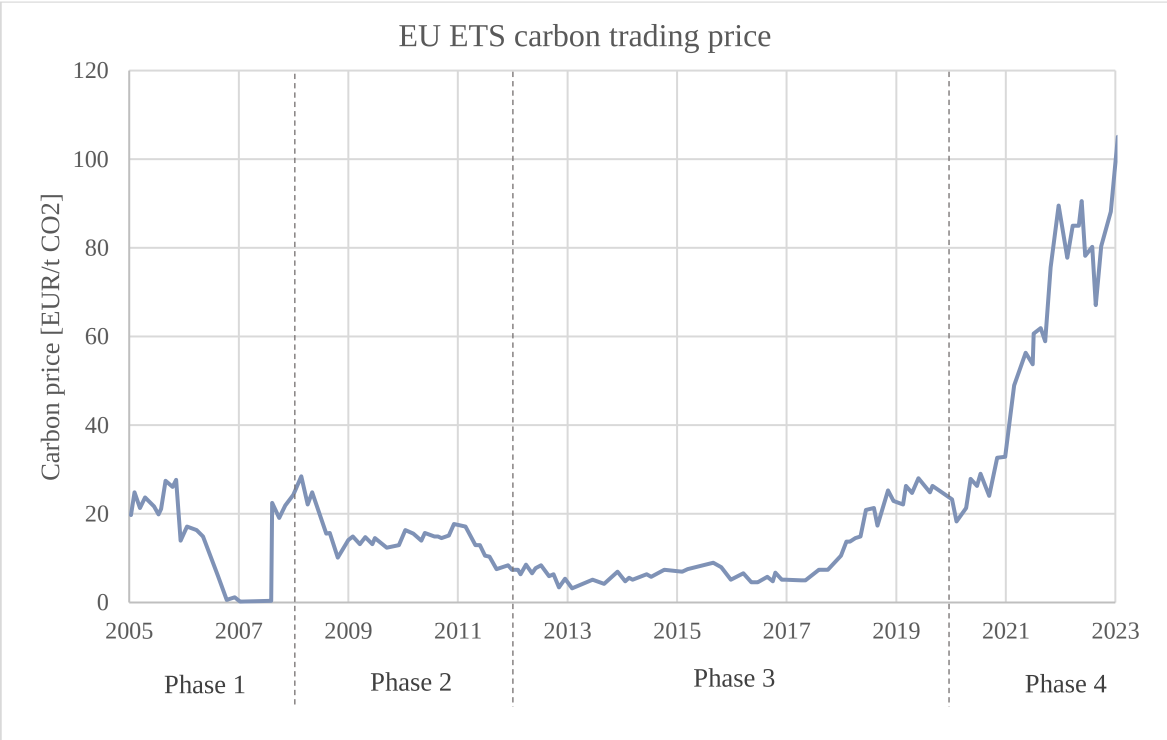


Figure 16. The EU ETS carbon price development 2005-2023 (Trading Economics 2023a).

One major issue in phases 1 and 2 was the over-allocation of emission allowances leading to an excess supply of credits and, thus, allowance prices dropping to zero at the end of phase 1 in 2007. This was escalated due to the allowances of the first trading period not being transferrable to phase 2. The emission cap was decreased for phase 2 to avoid this phenomenon; however, the reduction had little effect on the surplus allowances as an economic crisis occurred during the period. Thus, the allowance prices stayed at a low level, although highly volatile, throughout phases 1 and 2. (European Commission n.dc.)

Nevertheless, overall, the price of emission allowances has increased since the start of the system. However, between 2013 and 2017, the prices dropped below previous levels for the first time since 2008. The prices have since increased, reaching over 100 EUR /t CO2-eq at the beginning of 2023 and exceeding the 100 EUR/t CO2-eq mark multiple times by March. In 2022, the prices varied between 60 and 100 EU/t CO2-eq with an approximate average price of 80 EUR/t CO2-eq. (Trading Economics 2023a.) In general, high prices are seen as an indication of the EU ETS's effectiveness. Consequently, the trading market incentivises companies with high emissions to cut emissions to either reduce the cost of purchasing extra credits or gain profit from excess credit sales. (Bayer & Aklin 2020; European Commission n.dc.)

5.3. Outlook

Phase 4 (IV) started in 2021 and will last until 2030. A series of actions were taken to increase the effectiveness of the EU ETS within its role in helping reach the EU target of climate neutrality by 2050. An overview of actions and changes in phase 4 is presented in figure 17. The role of the market stability reserve started in 2019 was strengthened with increased reserve capacity and limitation to the credit validity period. The annual emission cap reduction rate was increased to 2.2 % compared to 1.74 % in phase 3. In December 2022, European Commission decided to further increase the linear cap reduction rate to 4.3 % for 2024-2027 and 4.4 % for 2028-2030. The carbon leakage rules were also improved to better target the companies at the highest risk while reducing the free allocation of companies in lower-risk sectors and sectors included in the new CBAM. In phase 4, the allocation is split into two periods, 2021-2025 and 2026-2030. The basic allocation is calculated homogenously for 2021-2025. For 2026-2030, the benchmarks will be adjusted, leading to decreased baseline and, thus, less free allocation. In addition, the number of free allowances will be reserved for new businesses yet to be installed. The EU ETS also included two new funds, the Innovation and the Modernisation Funds, since phase 4. (European Commission n.dc; European Commission 2019b; ICAP 2022.)

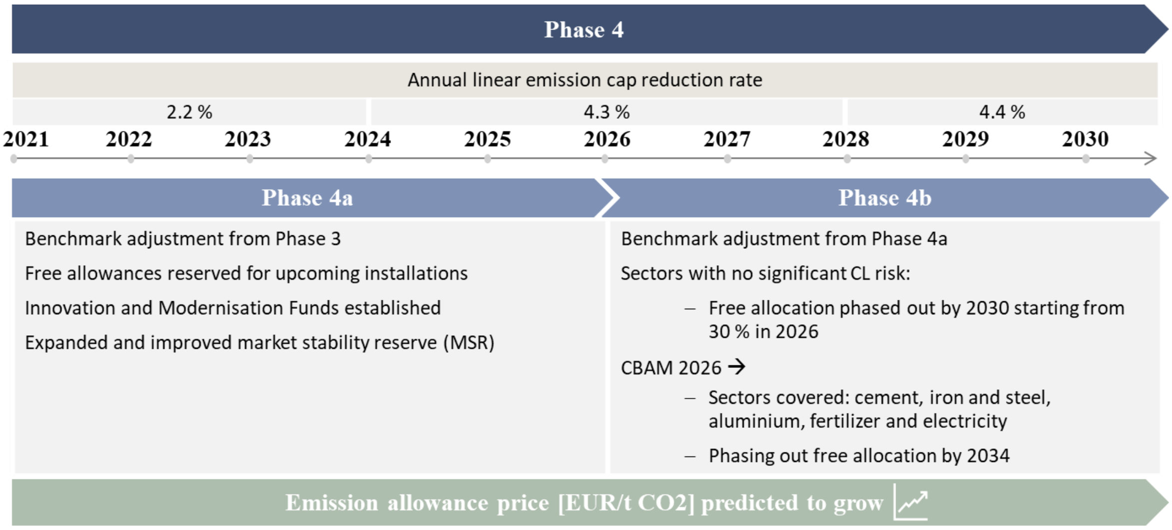


Figure 17. Overview of changes implemented in phase 4 of EU ETS and largest upcoming updates to the system by 2030.

Carbon permit prices are affected by the market situation. In 2022 various power plants switched fuel to coal from gas amidst the record high gas prices, leading to soaring carbon permit prices due to high emission levels of coal combustion. The reduction of free allocation is predicted to impact credit prices with increased demand. In addition, the EU carbon neutrality target might project onto prices as an upward trend. However, the carbon price is predicted to be negatively impacted by decarbonisation projects and energy efficiency improvements leading to decreased demand. Overall, predicting the emission allowance prices includes many challenges, such as probable reformations in EU ETS policies before the start of phase 5 in 2031, new EU-level schemes and changes in geopolitical status. (Bayer & Aklin 2020; Ecologic Institute 2022; Engin et al. 2022; Neiron 2022; Twidale 2023.)

The carbon market price is foreseen to continue in the upward trend seen since 2021. A range of predictions for 2025 and 2030 is visible in figure 18.

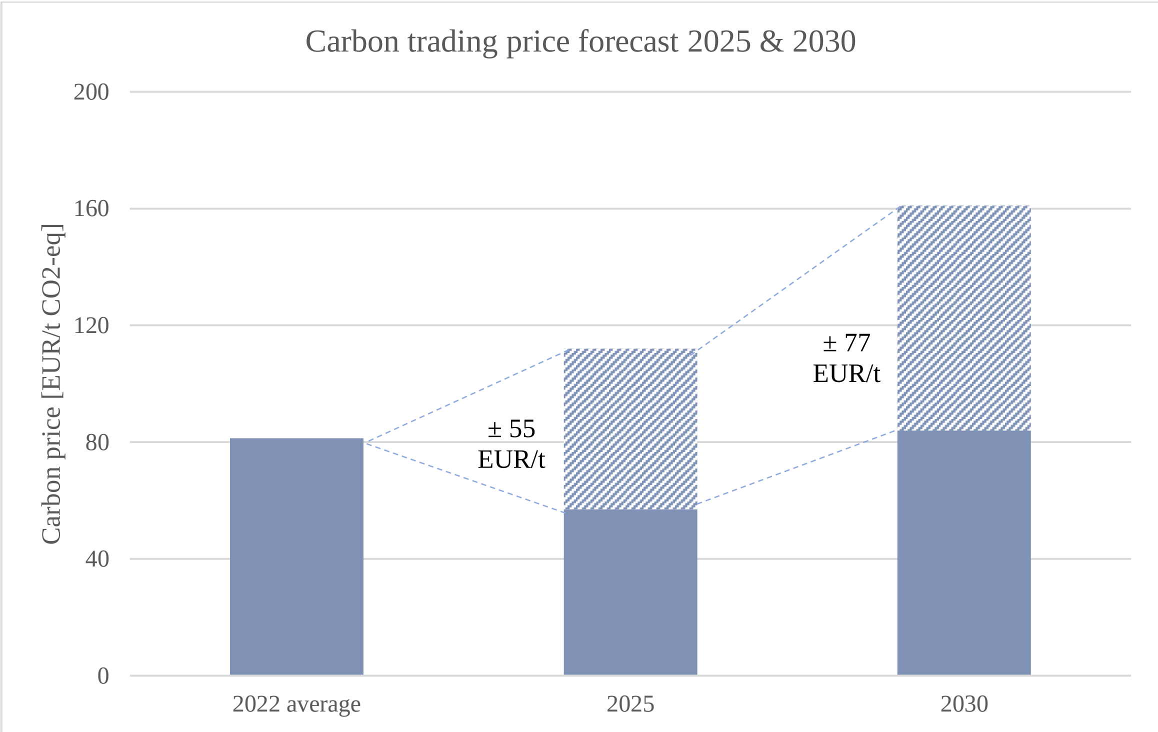


Figure 18. Average EU ETS carbon credit price in 2022 and forecasts for 2025 and 2030. The dashed areas show the range of predictions from different sources. (Climate Trade 2022; Ecologic Institute 2022; Engin et al. 2022; Statista 2023a; Twidale 2023.)

While there are notable differences in forecasts for 2025, ranging from 57 EUR/t CO2-eq to 110 EUR/t CO2-eq, the annual average prices have been forecasted by more analyses to increase compared to analyses predicting a price decrease. The predicted prices often reach or exceed 100 EUR/t CO2-eq in 2025. (Ecologic Institute 2022; Engin et al. 2022; Neiron 2022; Statista 2023a; Twidale 2023.)

For longer-term forecasts, the prices have higher volatility, with the lowest predictions being around 84 EUR/t CO2-eq and the highest over 160 EUR/t CO2-eq. For example, Statista (2023a) predict the average price to be around 100 EUR/t CO2-eq during 2026-2030, while S&P Global projects that the prices will surpass 100 EUR/t CO2-eq from 2025 onwards and reach over 120 EUR/t CO2-eq by 2030 (Engin et al. 2022). The forecast from S&P Global for 2030 has comparable results to Refinitiv’s long-term forecast, which is on the same level for 2030. The highest values are by Bloomberg, Enerdata, PIK and CAKE that forecast the price for 2030 to exceed 140 EUR/t CO2-eq. However, contrary to all other forecasts, predictions by ICIS show that credit prices will remain at around the current level until 2030. (Ecologic Institute 2022.) There seems to have been a lack of studies or analyses regarding price forecasts beyond 2030 due to little information on the EU ETS phase 5.

5.4. Pulp and paper industry

The pulp and paper industry is obligated to participate in the EU ETS, with the sector being included in the manufacturing industries category. CO2 emissions are the only GHG included in the scope for the PPI. (European Commission n.dc.) On average, during 2005-2021, the CO2 emissions of the PPI accounted for around 1.7 % of total annual emissions covered by the EU ETS (EUTL 2022). The pulp and paper sector has been included in the highest risk of carbon leakage group since the start of the EU ETS, and it will be included in the group during phase 4 (2021-2030) (European Commission 2019a). Thus, the sector has historically received all baseline emission permits in free allocation. The comparison of verified emissions of the PPI in the EU27 following the EU ETS scope and free allocated allowances is presented in figure 19.

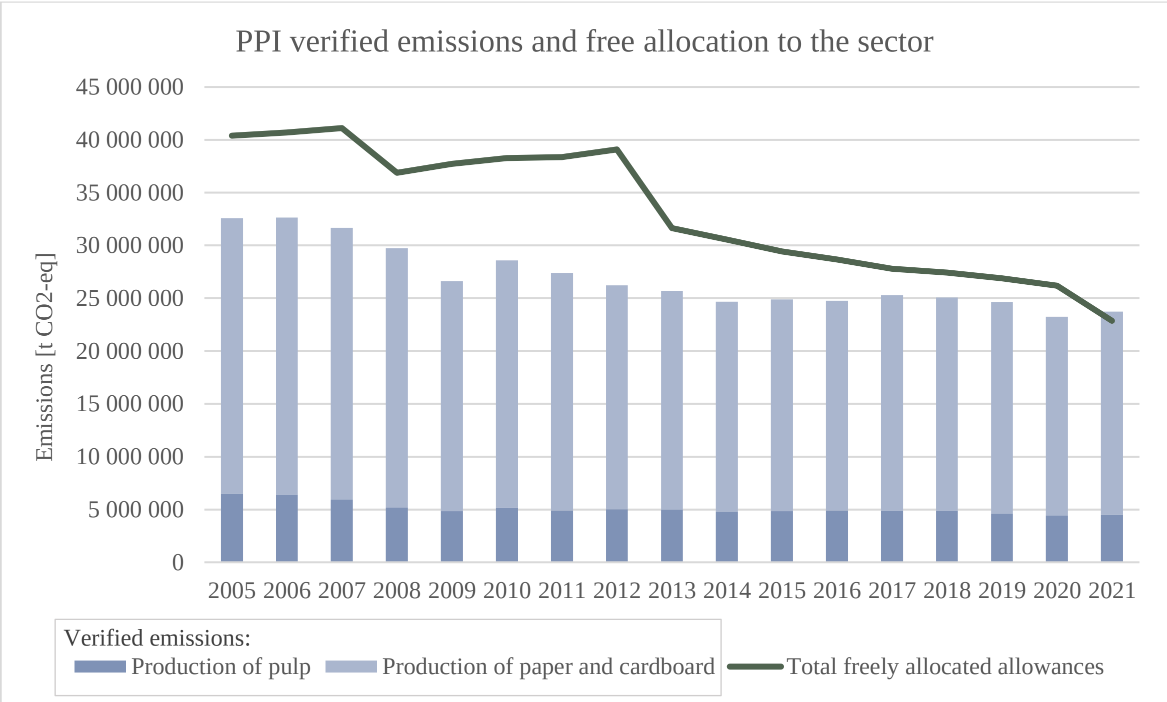


Figure 19. Verified pulp and paper production emissions compared to allowances freely allocated to the sector. Data coverage EU27. (EUTL 2022.)

Overall, the total emissions of the PPI have decreased since 2005, although the emission levels remained stable during 2014-2019 at around 25 million t CO2-eq. However, the total number of freely allocated allowances has fluctuated more, especially during phases 1 and 2. Since the start of phase 3 in 2013, the trend in free allocation has been a decline. With the cap on total free allocation being reduced in phase 4 and adjustments made to the baseline allocation, the number of freely allocated allowances dropped between 2020 and 2021, with the drop accounting for over 3 million t CO2-eq (European Commission n.dc). The number of free allowances slightly dropped again in 2022, with the total amount accounting for 22.85 million t CO2-eq (EUTL 2022). It should be noted that according to the EU ETS directive (2003/87/EY), biomass is considered emission-free with an emission factor of zero. However, since the start of phase 4, the biomass used must be sustainably sourced and fulfil the GHG savings criteria as stated in Renewable energy directive (RED II) ((EU) 2018/2001) article 29.

Historically, the free allocation of allowances has continuously exceeded the total emissions of the pulp and paper sector. However, 2021 was the first year during which the total free allocation did not cover the CO2-eq emissions caused by the sector, with a total of 23.7 million t CO2-eq emissions and freely allocated allowances up to 22.9 million t of CO2-eq emissions. As the number of allowances in free allocation is foreseen to fall, the emissions will probably continue to exceed the total free allowances if no significant emission reductions occur in the sector. Even though the total PPI CO2 emissions have decreased since the start of the trading system, specific CO2 emissions have not decreased by 2016. However, some countries, such as Sweden and France, have improved specific CO2 emissions. (EUTL 2022; European Commission n.dc; Stenqvist & Åhman 2016.)

The system boundaries determined by the EU ETS specify which emissions are considered in the trading system. The boundaries for pulp and paper production include all production processes, such as paper and board machines, energy production units and pulp mills. Pulp and paper products have been categorised into 11 product benchmarks, which include four pulp categories and seven paper/board grades (Appendix 3). Each product benchmark has a defined benchmark value in unit allowances/t of product for the first allocation period of phase four, 2021-2025. According to the current regulation, the benchmarks will be adjusted to the second allocation period, which indicates a lower base allocation for paper and pulp installations in 2026-2030. (European Commission 2018.)

The pulp and paper industry will continue to receive full basic allocation (chapter 5.1.1) as per current regulation as the industry has received historically. However, in 2021 the European Commission conducted an impact assessment to review possible measures for extending the EU ETS. The assessment included a section about better targeting of carbon leakage rules and tightening the criteria for free allocation from 2026 onwards. Instead of the current carbon leakage risk group, the tiered option presented would have ranked the sectors in carbon leakage using a carbon leakage indicator (CLI) of emission and trade intensity. Using the indicator, the sectors would have been categorised into no, medium, or high-risk groups. The no-risk group would have followed the set regulation of phasing out the free allocation by 2030, starting at 30 % in 2026. The high-risk group would have received full free basic allocation while the medium-risk group would have received 60 %. The pulp and paper industry would have been set in the medium risk group, thus decreasing the basic allocation from the current 100% to 60% of the baseline. The presented option has yet to be further developed; however, it brings forth the opportunity for something similar to be implemented in the upcoming years. (European Commission 2019a; European Commission 2021a.)

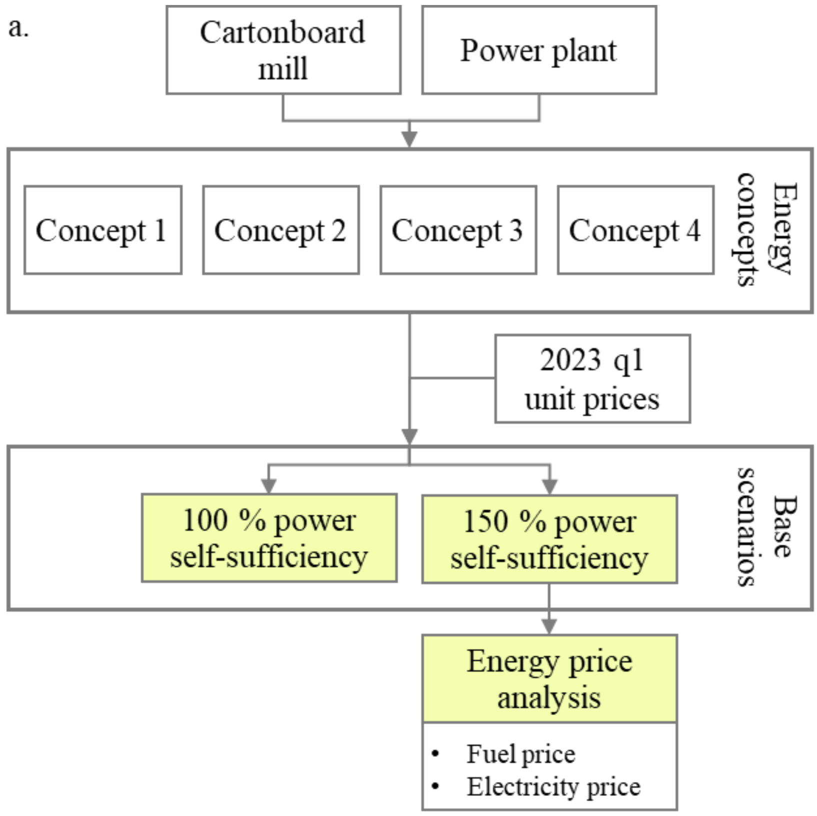
Research by Stenqvist & Åhman (2016) found that the free allocation system is beneficial for large producers, particularly for integrated producers in the PPI. The study results show that large integrated mills benefit from the free allocation most as the system is benchmarked on non-integrated paper mills. The benefits are due to many chemical pulp integrated mills delivering additional steam to district heating networks and often possessing a highly biomass-based fuel mix, which increases the number of free allowances received and reduces the emissions counted in the EU ETS produced by the company. However, integrated mills do not receive free allocation on pulp production when the pulp is consumed at the mill in question. The study notes that integrated paper mills in Sweden received, on average, four times more allowances than the mill's emitted emissions. On the other hand, some industry operators do not receive enough allowances to cover the mill emissions. (European Commission 2018; Stenqvist & Åhman 2016.)

Various large pulp and paper producers bring forth the effect of emission allowances on their operation, either as profitability or cost. Some companies currently do not need to purchase allowances as the free allocation covers the company's emissions or the company receives surplus free allowances. Examples of such companies operating integrated chemical pulp mills in Europe are UPM (2023), Stora Enso (2023) and Altri (2022). For instance, Altri reports that the company currently does not need to purchase allowances while stating that the situation might change with the reduction of baseline free allocation (Altri 2022). At the same time, Stora Enso reports receiving free allowances totalling up to 0.1 million tons of surplus emissions allowances after subtracting the group's emissions (Stora Enso 2023). On the other hand, some producers, especially ones producing paper products at non-integrated sites, must procure permits to cover the total emissions. For example, tissue manufacturer

Essity states that the company must purchase allowances to cover the emissions of the production plants, with the company having had a deficit of 0.3 tons of emissions in the EU in 2022 (Essity 2023). DS Smith, a company focusing on paperboard products with no significant integrated mills, also reports that the company had to purchase emission allowances with over 25 million GBP in 2022 and foresees the need to increase in the upcoming years (DS Smith 2023). However, some companies also use the carbon market to generate profit. For instance, Stora Enso reports on profiting from the company’s surplus allowances and purchasing additional credits from the market (Stora Enso 2023).

6. Mill concept modelling and calculation principles

This chapter presents the AFRY cost competitiveness tool and explains the selection of the modelled paperboard product and mill concept. An overview of the modelling structure and analyses presented in the chapter is shown below (figure 20).



b.

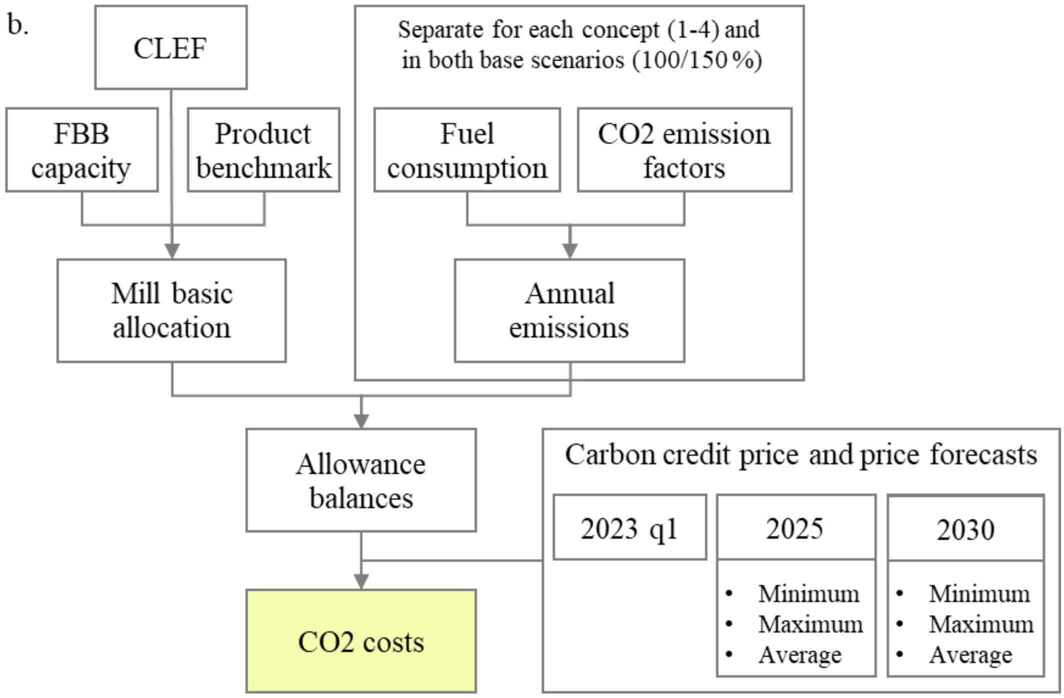


Figure 20. Scope and structure of base scenario modelling process and energy price analysis (a.) and CO2 emission and costs analysis structure (b.).

A cartonboard mill and adjacent power plant are modelled using AFRY cost competitiveness modelling tool. The chapter includes a detailed section on the four selected modelled energy concepts, which are introduced in chapter 6.4. The mill is modelled in each energy concept, and each concept is modelled in two base power self-sufficiency percentage scenarios, 100 % and 150 % power self-sufficiency. An energy price sensitivity analysis is conducted based on the 150 % self-sufficiency modelling results. Afterwards, a CO2 cost analysis is performed. The related CO2 emission and basic emission allowance allocation calculation principles and chosen price scenarios for the CO2 cost modelling are introduced in chapter 6.5.

6.1. Overview of AFRY cost competitiveness modelling

The cost competitiveness method is used to analyse the relative competitiveness of pulp and paper mills or, more specifically, production lines. The results can be used to assess asset quality and the cost level of target paper or pulp machines compared to competitors in specific grades or regions. The assessment can be carried out on the machine or cost component levels. The method aims to compare production lines' relative differences in costs. The primary users of the tool are employees of the company, and the results are utilised internally and in different client projects, such as pre-feasibility and investment studies. Additionally, one main use of the tool is in an online analysis portal provided by AFRY, AFRY Smart, which is in continuous use by clients and internally.

The AFRY cost competitiveness tool is based on AFRY's detailed data coverage of pulp and paper mills globally. The database includes mill-specific information regarding integration status, production lines, products, production capacities, technical details and process characteristics, raw materials, energy concepts and mill personnel. The data also contains start-up years as well as information on investments and rebuilds of the mill. In addition to the mill database, the data comprises extensive parameters on regional productivity, efficiency and cost levels, regional historical consumption, regional unit prices, exchange rates and transportation costs. Regional unit prices are updated to the tool four times a year, once each quarter.

The result of the cost competitiveness analysis is the total manufacturing costs for each paper machine (PM) included in the analysis, with the costs categorised into individual groups, cost elements. An example of the final cost breakdown categories of cost competitiveness modelling is presented in figure 21.

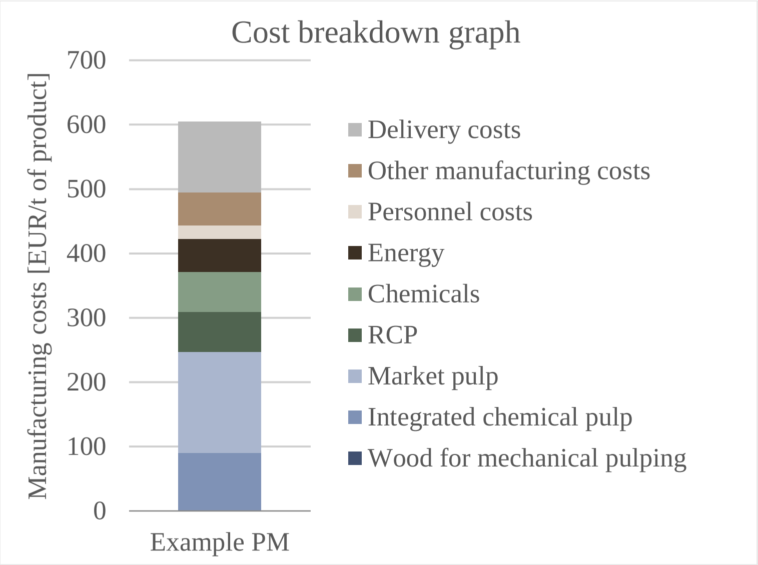


Figure 21. The total manufacturing and delivery costs and a breakdown of cost competitiveness modelling categories for an example PM.

The analysis is carried out using the pulp and paper mill cost model and the mill database. The cost model has specific power plant modelling, which models the energy consumption and production at the mill and allocates the energy to PMs. The energy modelling includes the most common energy production applications concepts of pulp and paper mills: recovery boilers, power boilers, such as grate and fluidised bed boilers, different kinds of gas turbine plants, steam turbines and hydropower. Wind, solar and hydrogen energy production methods, which are more novel in the pulp and paper industry, are currently in development for the modelling tool. The key inputs to energy modelling include boilers and power generation equipment characteristics, fuel mixes and process steam variables.

For this study, the energy category (figure 21) is divided into two more specific categories, power and fuel costs, to more accurately analyse the effect of different cost components. In addition, CO2 emission costs are added to study the effect of emission allowances on the total costs.

6.2. Selection of modelled product

In the last decade (2012-2022), total global paper and paperboard production volume has increased over six per cent from around 390 million tons to over 415 million tons, with packaging paper and board in the lead. Simultaneously, graphic paper production has decreased. Paperboard demand, with a focus on packaging applications, is estimated to continue growing in the upcoming years. Paperboard with the highest production volumes is containerboard, followed by cartonboard. (AFRY Smart 2023; Metsä Group 2022; Statista 2023b.)

Containerboard manufacturing concepts are highly dependent on the board grade. Testliner is produced from recycled material, and the production sites can have an integrated recycled fibre plant at the site. On the other hand, kraftliner is produced using virgin fibre and the mill is usually integrated into chemical pulp production. Thus, the board grades' significant differences in raw materials lead to variations in board composition and integrated mill concepts. (AFRY Smart 2023; Kirwan 2013, 327; Paulapuro 2000, 66-67.)

Of cartonboard grades, white lined chipboard (WLC) has the highest production capacity, followed by folding boxboard (FBB). WLC is partly manufactured from recycled fibre. Thus, WLC mills are often integrated into recycled fibre production. FBB, on the other hand, is produced from virgin fibre and can be either integrated or non-integrated to a chemical pulp production line, in addition to integration to mechanical pulp. (AFRY Smart 2023; Kirwan 2013, 24-25; Metsä Group 2022.) FBB is a common coated cartonboard grade used in multiple end-product applications in the consumer packaging sector, such as food, cosmetic, cigarette and pharmaceutical packaging. (Kirwan 2013, 24; Paulapuro 2000, 58). Of cartonboard grades, FBB has had the highest increase in production capacity since 2012. Additionally, the grade is predicted to have the highest demand growth rate. (AFRY Smart 2023; Jobe 2023; Metsä Group 2022.) Furthermore, a report by Future Market Insights (2022) estimates the FBB market to double its value by 2032.

Due to considerable differences between virgin and recycled-based containerboard production and cost components, it would be difficult to compare different containerboard energy concepts equally. Similarly, as a recycled material-based cartonboard, using WLC as the grade in the experimental section would introduce issues when conducting the chemical pulp integrated mill comparison. Additionally, the estimated average energy consumption in FBB production falls around the industry average, as seen in chapter 2. Accounting for these factors, suitability to model various energy concepts for one specific grade, developments in the market and increased demand, FBB is chosen as an eligible grade for the modelling.

6.3. Modelled cartonboard mill

The modelled mill is a cartonboard mill, which manufactures a three-layered folding boxboard. The board machine characteristics are chosen based on the European industry average values for FBB production according to AFRY Smart (2023), with a final basis weight of 240 g/m2 (industry average). Hence the capacity of the PM is 270 kt/a (~770 t/day), trim width 4 500 mm and design speed is 650 m/min. However, the machine is assumed to be brand new, with a start-up in the fourth quarter (q4) of 2022. The machine includes a headbox, multi-layer former, shoe press, dryer, rewinders and reeler. The mill includes a coater. Modelled infrared (IR) dryers use natural gas. For the location of the mill, Germany is chosen. Quarter one (q1) of 2023 prices of the tool are used to ensure the most up-to-date price scenarios in modelling. It is assumed that no rebuilds or expansion projects take place. The results are presented in manufacturing costs using unit EUR /t of FBB.

The mill has an integrated softwood chemi-thermomechanical pulp (SW CTMP) production line on the site, which uses woodchips as raw material. An integrated CTMP line is typical for FBB production in Europe; hence it is essential to include CTMP production in the modelled mill (AFRY Smart 2023). The CTMP forms the middle layer, while the outer chemical pulp layers, bleached softwood kraft pulp (BSKP) and bleached hardwood kraft pulp (BHKP), are market pulp. BSKP and BHKP are the usual raw materials for the outer layers of FBB (Paulapuro 2000, 58-59).

6.4. Modelled energy concepts

The result comparison uses four different energy concepts 1-4 for the mill. An overview of the concepts' 1-4 characteristics is presented in table 1. The energy concepts have different power plant concepts, including fuel mix and heat and power generation technologies. The fourth concept includes a fully integrated chemical pulp production facility at the mill site. The fully integrated concept creates changes in raw material sources and costs compared to concepts 1-3, in which these costs are identical. However, the fully integrated concept is necessary to construct a holistic overview of the European paper and paperboard market, as over one-fifth of mills are integrated to some degree (chapter 3). It also provides a comparison point between the positions of non-integrated and chemical pulp -integrated mills.

The modelling is conducted in two base scenarios. In the first base scenario, all concepts are modelled as 100 % electricity self-sufficient, covering the whole energy demand of the mill with no surplus production for sale profits. In the second base scenario, the mills are modelled as 150 % power self-sufficient with surplus electricity sales. The model requires adjustments to the input values to achieve these self-sufficiency percentages. Due to the operating model of the tool, the 100 % and 150 % self-sufficiencies cannot be modelled precisely without creating improbable turbine capacities; thus, the self-sufficiency percentages are modelled with a precision of one decimal. Some concepts include additional equipment or fuels in the 150 % self-sufficiency scenario to ensure sufficient energy production.

Concepts 1 and 2 are similar in power plant technologies. Both concepts include a fluidized bed boiler and backpressure and condensing turbines. The boiler produces steam for both bp- and condensing turbines. The turbines utilise the steam separately in different cycles to ensure the necessary supply of process steam and to optimise the electricity yields. In concept 1, the boiler is a bubbling fluidized bed (BFB) boiler, while in concept 2, the boiler is a circulating fluidized bed (CFB) boiler. The fuel mix for concept 1 consists entirely of RDF. For concept 2, the fuel mix is 100 % purchased biomass.

Concept 3 differs from concepts 1 and 2 in its power plant structure, consisting of a CCGT power plant, which operates 100 % on natural gas. In CCGT, an HRSG and bp-turbine are used in addition to the gas turbine. The power plant has one of each unit. After the heat of the gas has been recovered in HRSG, the steam is utilised in the bp-turbine in power and process heat production for the board manufacturing process. In the 150 % self-sufficiency base scenario, a condensing turbine is added to the power plant to ensure sufficient electricity production.

Concept 4 differs from concepts 1 to 3 due to its full integration into chemical pulp production in addition to the CTMP line. Therefore, the fuel mix consists entirely of internal fuels, including black liquor and bark. The chemical pulp mill includes a recovery boiler for black liquor recovery and steam production and a CFB boiler for bark combustion. The power plant includes one backpressure and one condensing turbine. The outer layer pulps, BSKP and BHKP, are produced in the chemical pulp mill; thus, no market pulp is purchased in this concept. BSKP and BHKP consumption is relatively small in FBB production, and creating a chemical pulp mill that only produces pulp to the integrated FBB mill with a capacity of 270 kt/a would be unrealistic and unprofitable. Thus, to create a plausible-sized integrated chemical pulp mill, the pulp mill produces excess pulp, which is sold outside the site as market pulp. The capacity of the chemical pulp line is 345 kt/a. (AFRY Smart 2023.) In the 150 % self-sufficiency base scenario, the mill outsources biomass to cover the fuel consumption in energy production.

The decision for each energy concept included in the study was made in alignment with the objectives outlined. The selection is based on the information and aspects presented in the theory section. These include common energy concepts in European mills with a specified focus on cartonboard plants, characteristics of each power and heat production applications and emerging trends in fuel options. For example, as outlined in chapter 3.3, internal fuels and natural gas are popular fuels in the European industry. Thus concepts 3 and 4 present examples of widely used fuel concepts, while RDF is continuously more utilised as a mill energy production option. The selection is also adjusted after AFRY’s expert opinions on concepts most beneficial for the thesis objectives. The energy concepts are simplified to identify the significant factors affecting each concept’s feasibility more effectively and due to the relative comparison aspect of the cost competitiveness modelling tool.

Table 1. Characteristics of modelled energy concepts 1-4. The specifications in brackets are only applicable in the second base scenario, 150 % power self-sufficiency.

	Concept 1	**Concept 2**	**Concept 3**	**Concept 4**
Fuel mix	RDF 100 %	Purchased biomass 100 %	Natural gas 100 %	Internal fuels 100 % (+ biomass)
Heat production technology	BFB boiler	CFB boiler	HRSG (CCGT)	Recovery and CFB boilers
Power generation technology	Bp- and condensing turbine	Bp- and condensing turbine	Gas and bp-turbine (+ condensing turbine)	Bp- and condensing turbine
Source of BSKP and BHKP	Market	Market	Market	Integrated chemical pulp

In all scenarios, heat recovery from the CTMP plant is circulated back to the CTMP production and utilised in the pulp production process, thus not affecting the energy modelling of the mill. The raw material scope of CTMP is woodchips instead of alternative roundwood because producing CTMP from roundwood generates bark as a side product. The bark could have been used as a secondary fuel in energy production. However, this is not plausible in concept 3 as the bark is unsuitable fuel for gas turbines, causing the CCGT concept to be less comparable to the other concepts. Defining the scope to woodchips also excludes the aspect of profiting from bark sales.

6.5. CO2 emissions and costs

Calculation principles for CO2 emissions, annual allocation of allowances, allowance balances and costs of CO2 for the mill in each concept are presented in this section. The annual allocation calculation is conducted for phase 4 of the EU ETS and split into two trading periods, phase 4a (2023-2025) and 4b (2026-2030). The CO2 cost calculations are done for three selected years, which are 2023, 2025 and 2030. The years are selected to cover the current situation and the near future and end of phase 4 estimations. The annual CO2 emissions are assumed to remain at the same level each target year, while the annual allocation changes from 2026 onwards. The results are calculated for both energy concept base scenarios, 100% and 150 % power self-sufficiencies. The analysis of the CO2 cost results is conducted separately from the energy price sensitivity analysis.

FBB is included in coated cartonboard product benchmark in the EU ETS. In EU ETS coated cartonboard benchmark includes emissions of processes contained in the system boundaries, which are defined as:

> "All processes which are part of the paper production process (in particular paper or board machine and connected energy conversion units (boiler/CHP) and direct process fuel use) … Emissions related to the production of the consumed electricity are excluded from the system boundaries" (European Commission 2019b).

Additionally, electricity exported from the installation is not eligible for free allocation. On the other hand, heat is eligible for allocation when the heat is produced or consumed at the installation site. (European Commission 2019b.) In the AFRY cost competitiveness tool, CO2 emissions are calculated based on the fuel consumption in the mill. These include fuel consumption in energy production, including internal fuels, and usage of fuels in production processes, including lime kiln and paper dryer fuels. The model does not consider other possible CO2 emission sources at the mill or supply chain, such as vehicle emissions from raw material transportation and mill facility heating and electricity. The CO2 emissions are calculated based on specific CO2 emissions factors for each fuel (kg CO2/GJ fuel). The CO2 emissions are presented in unit of kg CO2/t of product. As the EU ETS Directive (2003/87/EY) categorizes the emission factor for biomass as zero within the conditions presented in chapter 5.3, the emissions from sourced biomass usage are examined both as emission-free and as including emissions.

The CO_2 emissions factors used in the study are presented in table 2. RDF is assumed to have around 60 % biomass fraction; thus, the CO_2 factor is based on the remaining share of the waste (Tilastokeskus 2023). According to RED-II Directive ((EU) 2018/2001) article 29, only biomass fractions of waste fuels (RDF) are subject to GHG saving conditions. In this study, the emissions from the biomass fraction of RDF are not considered as the assessment for inclusion in the zero-emission category is less strict than biomass fuels.

Table 2. CO_2 emission factors for fuels (Tilastokeskus 2023).

CO2 factors for different fuels	**t (CO2)/TJ**
Biomass	0 / 112
Internal fuels (black liquor, bark)	0
Natural gas	55.37
Waste / RDF	31.8
Lime kiln (natural gas)	55.37

The total emissions are calculated by multiplying the CO_2 factors with the annual consumption of fuels, separately for each fuel type used in the same concepts, and then adding the emissions together.

Basic free allocation of emission allowances for coated cartonboard includes installations with a daily production capacity of over 20 tonnes, which the modelled mill exceeds (European Commission 2019b). The preliminary basic allocation for product benchmarking is calculated according to equation 1.

$$F_{prel} = BM * HAL * CLEF \tag{1}$$

where F_{prel} is the annual basic free allocation [EUAs], *BM* is the benchmark for coated cartonboard [EUAs / unit of product], *HAL* is the historical activity level [units of product] and *CLEF* is the carbon leakage exposure factor applicable for the product. (European

Commission 2019b). For coated cartonboard, the unit of production is air-dried tonnes (Adt). Product benchmark calculation for phase 4 is presented in appendix 4.

The final annual basic allocation is achieved by equation 2.

$$F_{final} = F * CSCF \tag{2}$$

where F_{final} is the final annual basic allocation [EUAs] and *CSCF* is the cross-sectoral correction factor. The annual allocation is calculated for two phase 4a (2023-2025) and phase 4b (2026-2030).

For concepts 1-3, the only benchmarked product of the mill is the coated carton board, while concept 4 also includes product benchmark for long fibre kraft pulp and short fibre kraft pulp, which comprises the market pulp share. The study is conducted for the cartonboard mill, with results being analysed in production expenses per tonne of paper. Additionally, the inclusion of another benchmark product complicates the comparison of allocation effects between the energy concepts. Therefore, the share of allocation from market pulp is not included in the study. (European Commission 2019b.)

Allowance balance is used to calculate emission costs for FBB production with carbon credit prices. Allowance balance depicts the number of allowances the installation is short of or has a surplus of after the final basic allocation has been deducted from the installation's annual emissions (equation 3).

$$Allowance\ balance = Annual\ emissions - F_{final} \tag{3}$$

where allowance balance is presented as EUAs, and annual emissions is the mill’s total annual emissions [t CO2/a].

To convert the allowance balance to CO2 costs, the EU ETS carbon credit price (EUR/t CO2-eq) is used. As only CO2 emissions are accounted for in the paper and pulp industry, the carbon credit price is presented in unit EUR/t CO2 henceforth. For 2023, the price used is an average in the first quarter (q1) of 2023, which is also used for other unit prices. The average CO2 price was 94.07 EUR/t CO2 in q1. (Trading Economics 2023a). For 2025 and 2030, the minimum, maximum and average price predictions presented in figure 18 (chapter 5.2) are used. The same values are presented in table 3 below.

Table 3. Carbon credit price in q1 of 2023 and price forecasts for 2025 and 2030 (Climate Trade 2022; Ecologic Institute 2022; Engin et al. 2022; Statista 2023a; Trading Economics 2023a; Twidale 2023).

Year	**Unit**	**Min**	**Max**	**Average**
2023 q1	EUR/t CO2			94.1
2025	EUR/t CO2	57	112	84.5
2030	EUR/t CO2	84	161	122.5

As seen in the table, the lowest price predictions, and the average of the estimates for 2025 are lower than the price in q1 of 2023. On the other hand, the forecasts for 2030 mainly predict the prices to increase with an average of 123 EUR/t CO2. Modelling the results with different price scenarios enables a wider analysation of the results.

7. Results and discussion

This chapter starts with presenting the base scenario modelling results, including the 100 % and 150 % self-sufficiency scenarios. After the modelling results are reviewed, energy price sensitivity analyses are presented. In addition, the annual emissions of each energy concept, annual allocation of emission allowance for the mill, allowance balances and final CO2 cost results in each price scenario are presented in chapter 7.3. Lastly, a discussion on the limitations of the study methods and the modelling results is conducted.

7.1. Base scenarios

Concepts 1-4 are modelled in two base scenarios. In the first scenario, the mill produces enough power for the FBB production to be self-sufficient; however, no excess power is produced for sale (100% self-sufficiency). In scenario two, on the other hand, the mill is entirely power self-sufficient and produces surplus electricity, which is sold to the grid. The amount of surplus power presents 50 % of the mill's electricity demand, making the mill's self-sufficiency percentage 150. The base scenario modelling uses prices from 2023 q1, as described in chapter 6.2.

7.1.1. 100 % power self-sufficiency

Table 4 presents the annual fuel consumption of concepts 1-4 in energy production and electricity output of power plants. Concept 4 has the highest fuel consumption, 2280 GWh, caused by the chemical pulp production for both integrated and market pulp demand. Concept 4 also produces a little surplus steam, which is not used in electricity production or directly at the mill. Other concepts have similar fuel consumption and electricity production numbers, varying between 768-789 GWh and 38-39 MW, respectively.

Table 4. Annual fuel consumption by fuel type in energy production and estimated electricity generation for 100% self-sufficiency. The Minus sign indicates sold steam.

	Concept 1	**Concept 2**	**Concept 3**	**Concept 4**
Natural gas			768 GWh/a	
RDF	789 GWh/a			
Biomass		785 GWh/a		- 8 GWh/a
Black liquor				1917 GWh/a
Other internal fuels (bark, sludge)				371 GWh/a
Total fuel consumption	789 GWh/a	785 GWh/a	768 GWh/a	2280 GWh
Electricity output	328 GWh/a (39 MW)	329 GWh/a (39 MW)	319 GWh/a (38 MW)	496 GWh/a (59 MW)

In addition to the fuels used in energy production, the paper machine requires natural gas in the IR dryers. Therefore, each concept has natural gas consumption originating from the paper machine. The consumption of natural gas is around 18 GWh annually. In addition, concept 4 requires natural gas in the chemical pulp production process' lime kiln. Natural gas consumption is 1.2 GJ/t of BSKP and 1.0 GJ/t of BHKP in the lime kiln.

Figure 22 presents the modelling results as cost breakdown data. Total manufacturing costs are 669, 684, 759 and 512 EUR/t of FBB for concepts 1-4, respectively.

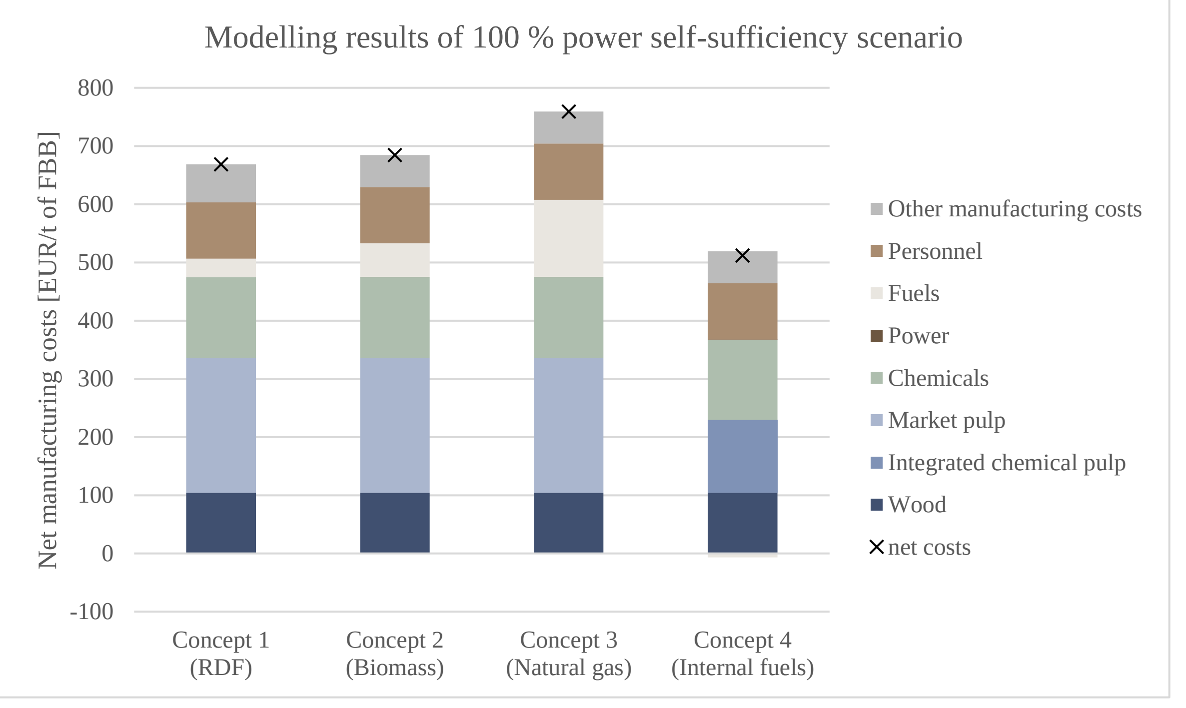


Figure 22. Cost breakdown of concepts 1-4 manufacturing costs when the mill has 100% power self-sufficiency. Thus, purchased electricity costs are zero or near zero.

Concept 3 has the highest total manufacturing costs due to high natural gas fuel costs. Through concepts 1-3, fuel costs vary between 32 EUR/t for concept 1 to 132 EUR/t for concept 3. Hence, in q1 2023, RDF had the lowest price among included purchased fuel types. However, RDF has the highest other variable costs, such as waste management costs, visible in the other manufacturing costs column of concept 1. Thus, the difference between concepts 1 and 2 caused mainly by the fuel price is diminished by the higher other costs of RDF. Concept 4 utilizes only internal fuels, black liquor, and bark, to produce steam and electricity; however, a small surplus of steam is produced with the available fuels. The steam sale shows as a negative in the chart; however, the number is insignificant to the net cost. Thus, it is excluded from further analyses. All concepts have similar wood, chemical and personnel costs. Overall, concept 4 also has the lowest total manufacturing costs due to cost benefits from the integrated chemical pulp as raw material in addition to the internal fuels. As previously mentioned, there are some variations between concepts 1-3 in the amounts of fuel required for energy production (table 4); however, the differences are minor and have little effect on the total cost figures.

Of all concepts, the CCGT plant has the highest fuel costs compared to the other manufacturing costs, with a share of 17 %. On the other hand, the chemical pulp integration benefits from internal fuel usage; thus, concept 4 has no significant fuel costs. The share of fuel costs for concepts 1 and 2 are similar, both RDF and biomass accounting for between five and ten per cent share, with RDF having a slightly smaller share. The shares of energy costs in this scenario are generally lower than the share presented by the literature (chapter 3.4). However, the studies cited in chapter 3.4 estimate the average share for the industry, while the modelling focuses on a few specific concepts. In addition, the modelled scenario presents the mill as power self-sufficient, which does not represent the industry average.

7.1.2. 150 % power self-sufficiency

In the 150% power self-sufficiency scenario, the mill sells the surplus electricity to the market, creating profit. The modelling results of this scenario are presented in figure 23.

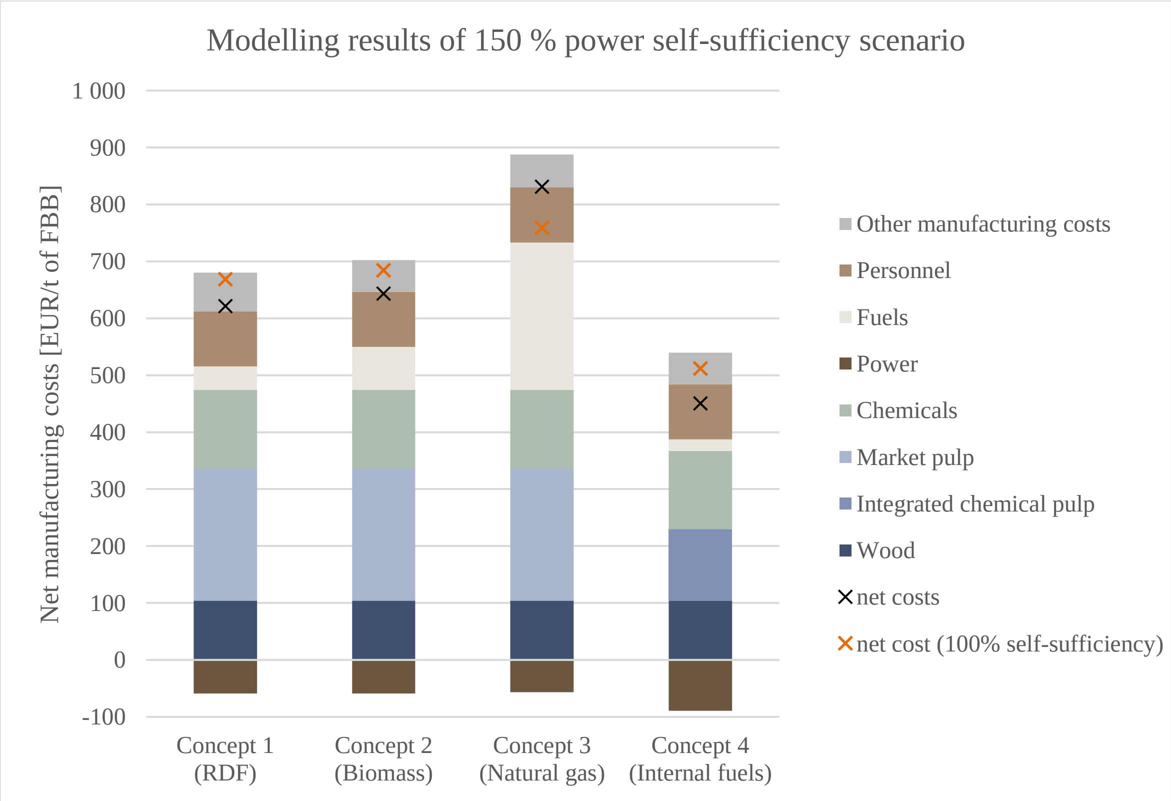


Figure 23. Cost breakdown of concepts 1-4 manufacturing costs when the mill has 150% power self-sufficiency. Thus, the mill is profiting from surplus electricity sales.

Total manufacturing costs are 621, 641, 831 and 450 EUR/t of FBB for concepts 1-4, respectively. The total net manufacturing costs decrease for all concepts, excluding concept 3 when the mill produces excess electricity for sale. The only costs affected by the surplus electricity production are fuel, power and other costs. The change in other costs is small, between 1-3 EUR/t, thus having little effect on the total variation. All concepts benefit from negative power columns due to profit from excess electricity sales. However, concept 4 benefits most from the electricity sales as 50 % surplus electricity is the highest in MWs for the concept. This is due to the high electricity consumption at the integrated facility. The pulp production does not yield enough raw material for fuel to cover the total electricity production. Thus, the mill must purchase some biomass to cover the total fuel consumption requirements. In concepts 1 and 2, RDF and biomass fuel costs are doubled compared to the 100 % scenario; however, the profit from electricity sales is higher than the added fuel costs. Concept 3 is the exception, as the net costs increase compared to the 100% scenario. The cost of natural gas to produce excess electricity is higher than the profit gained from the electricity sales.

7.2. Energy price analysis

The price of electricity and fuels, especially natural gas, has been much higher in 2022 and q1 2023 compared to the price levels of decade prior (Eurostat 2022; IEA 2022a; Trading Economics 2023b). Thus, the share of energy costs in total manufacturing costs has recently changed considerably. Sensitivity analysis is carried out to analyse the effect of fuel and electricity price changes on the modelling results. The analyses are only conducted at a theoretical level sensitising the energy prices. Possible subsidies and other support mechanisms for different energy production methods and fuels are not included. The effect of CO_2 emissions and the EU ETS on feasibility are analysed separately in the thesis. The effect of fuel and electricity price changes for concepts 1 and 3 is presented in figure 24 and for concepts 2 and 4 in figure 25. The analysis is conducted for the 150 % self-sufficiency scenario, as the electricity sales prices have little effect on the costs in the 100 % self-sufficiency scenario.

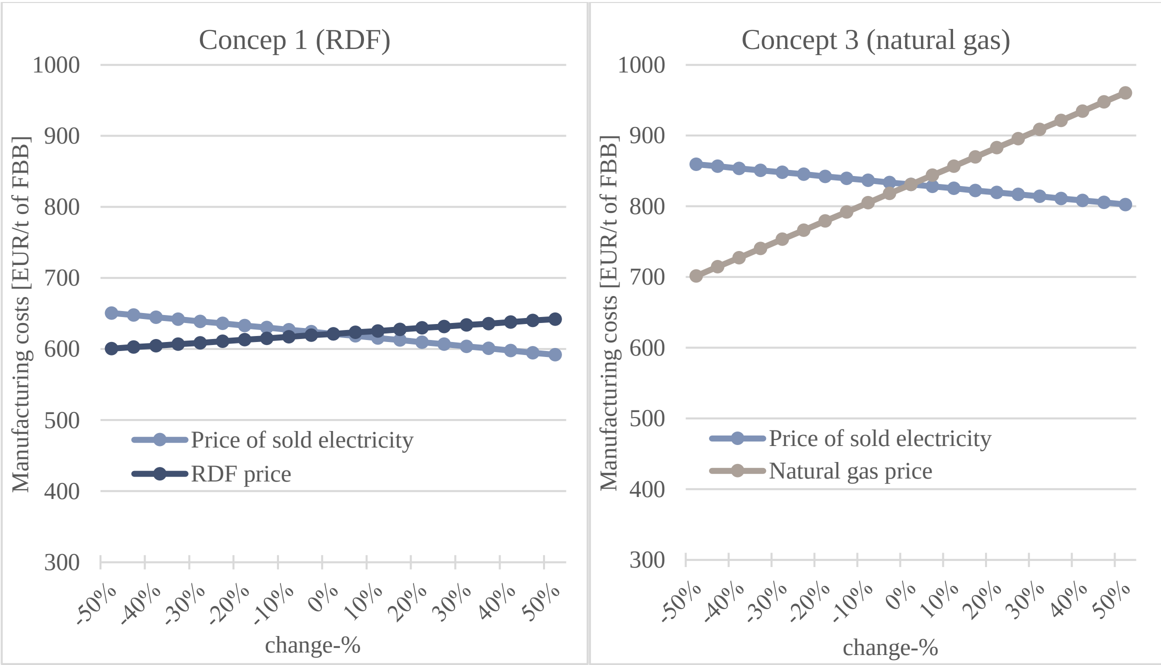


Figure 24. Sensitivity analysis comparing the effects of sold electricity and fuel price changes to the total manufacturing costs of concepts 1 (left) and 3 (right) in the 150% self-sufficiency scenario.

Electricity sale price changes similarly affect total costs for concepts 1 to 3. If the sales price increases, the mill profits more from the sale, and if the price decreases, sees the mill a loss in profit. A 50 % change in the price accounts for around 29 EUR/t, with the total range in figures adding up to around 60 EUR/t. In concept 4, the electricity sales price has a more significant effect on the manufacturing costs, as the chemical pulp integrated concept profits most from the electricity sales in the current q1 prices (-89 EUR/t). A 50 % change represents around 45 EUR/t difference from the q1 manufacturing costs.

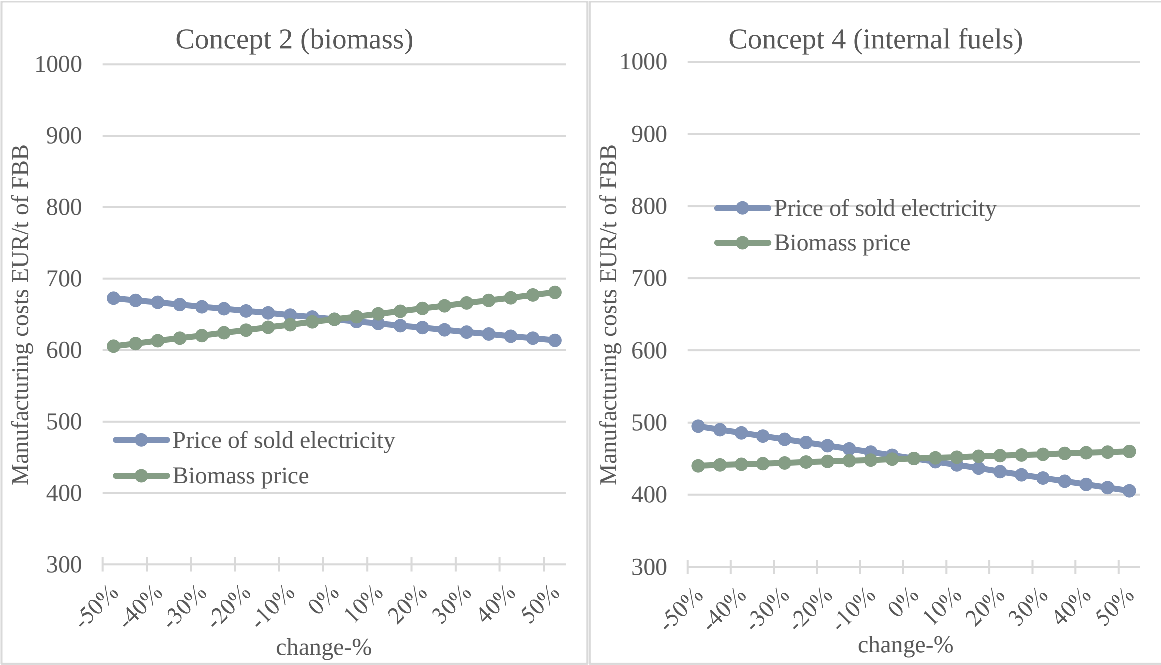


Figure 25. Sensitivity analysis comparing the effects of sold electricity and fuel price changes to the total manufacturing costs of concepts 2 (left) and 4 (right) in the 150% self-sufficiency scenario.

Of fuel prices, concept 3 is most affected by the changes in natural gas prices as the fuel price comprises the largest share of manufacturing costs among the concepts. A five per cent change in the price causes the total manufacturing cost to vary by 13 EUR/t. A 50 % change causes a variation of 129 EUR/t. Compared to concept 3, concepts 1, 2 and 4 see considerably more minor cost variations depending on the fuel price. For concept 4, the change is the slightest due to the low amount of purchased fuel required. In concept 1, RDF price has a lower effect than biomass-based concept 2 due to the concept’s smaller share of fuel costs. Overall, prices of electricity and fuels have a visible effect on the product’s total manufacturing costs; however, the effect is most significant for natural gas due to the high prices of fossil fuels.

Figures 26-29 include two variable sensitivity analyses, which are conducted using fuel and electricity prices as variables. The 100 % power self-sufficiency scenario’s manufacturing costs are included in the analysis to compare the feasibility of manufacturing costs of the 150 % self-sufficiency with different energy prices.

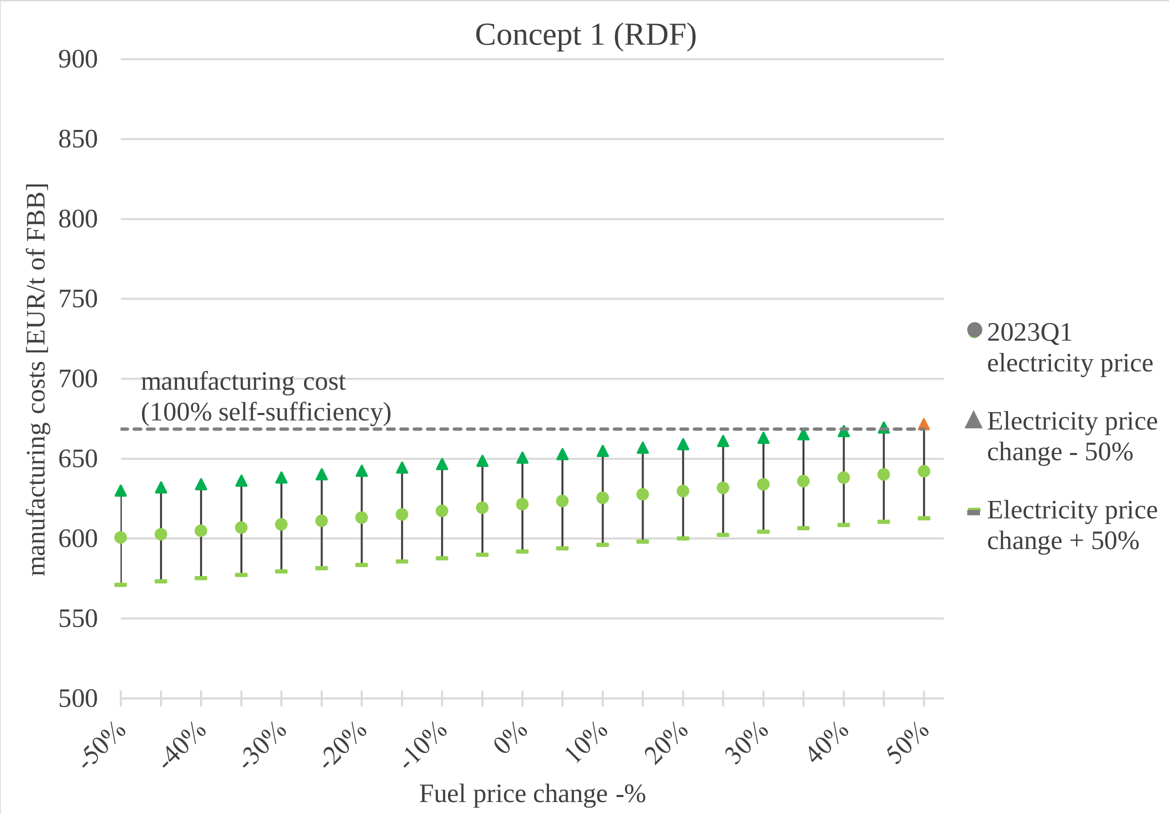


Figure 26. Two variable sensitivity analysis of concept 1 FBB manufacturing costs using electricity and RDF price.

In figure 26, it is visible that the excess electricity production is profitable when compared to no excess electricity sales, even in high price variations. In this analysis, only if the electricity sales price decreased by almost 50 % and the RDF price increased by 50 % would the costs be higher than in the 100% self-sufficiency scenario. Hence, according to this analysis, producing surplus electricity using RDF with a BFB boiler and bp- and condensing turbines is profitable for the mill.

Figure 27 shows that the biomass-based energy concept is flexible to the price changes of fuel and electricity and feasible in most price scenarios. If fuel prices decrease, the concept shows itself as more profitable. In the case of a fuel price increase, the net manufacturing costs remain under the net costs of the 100% self-sufficiency scenario up to a 50 % fuel price increase if the electricity price remains at the current level. However, if the electricity sale price decreases while the fuel price dramatically increases, the net costs will exceed the original costs. The differences in fuel prices mainly cause this difference between concepts 1 and 2. The biomass price in 2023 q1 is higher than the RDF price; thus, concept 2 is more vulnerable to fuel price variations.

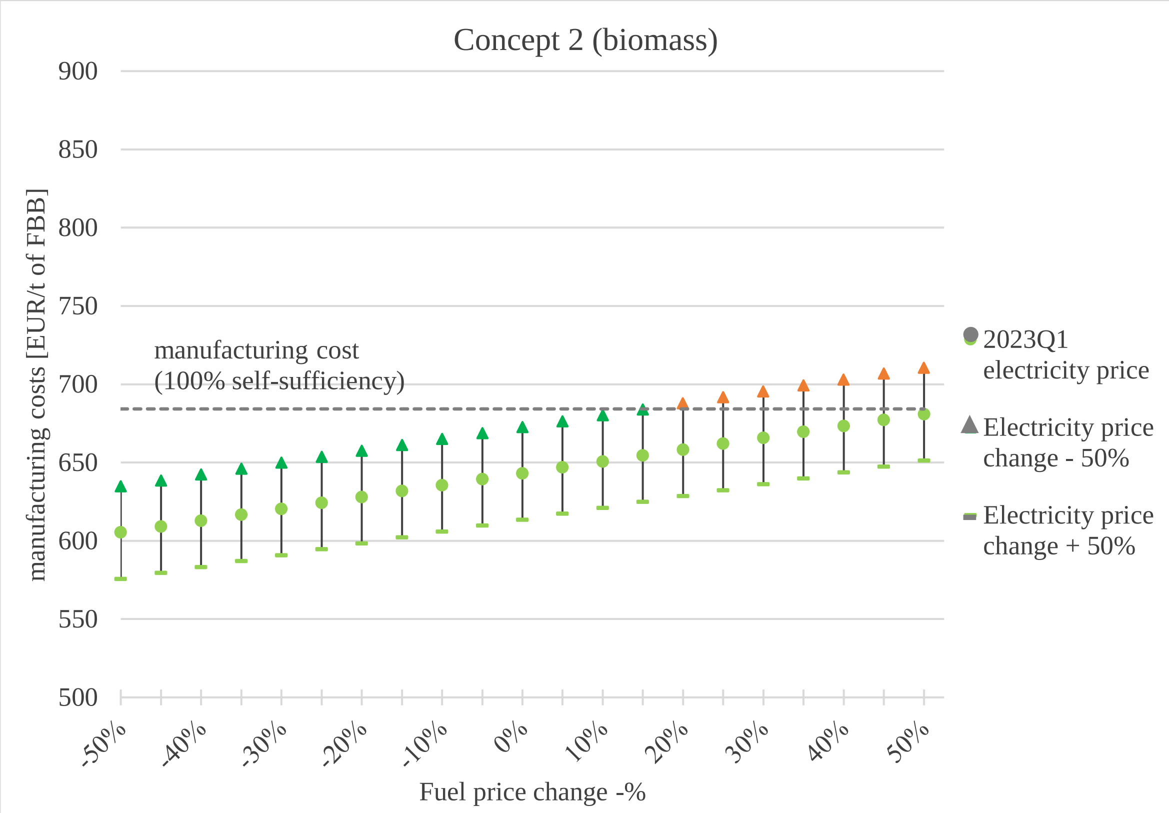


Figure 27. Two variable sensitivity analysis of concept 2 FBB manufacturing costs using electricity and biomass prices.

Contrary to concepts 1 and 2, as seen in figure 28, in concept 3, the current energy prices cause the excess electricity production to be unprofitable using a CCGT plant. The manufacturing costs fall below the base scenario of 100% self-sufficiency only when there are significant price changes in electricity and natural gas prices. The natural gas price should decrease a minimum of 20 % for the costs to reach the net cost level without excess electricity production. Additionally, in this scenario, the electricity sales price significantly increases. If fuel prices exceed that level, excess electricity production is unprofitable and causes more expenses than profit. Natural gas and electricity prices have a high correlation in many regions and countries, including Germany (eia 2022; Uribe et al. 2022). Therefore, if the natural gas price decreased, electricity price would decrease as well. Hence, for concept 3 to be profitable, natural gas and electricity prices should decrease by a minimum of 35 %.

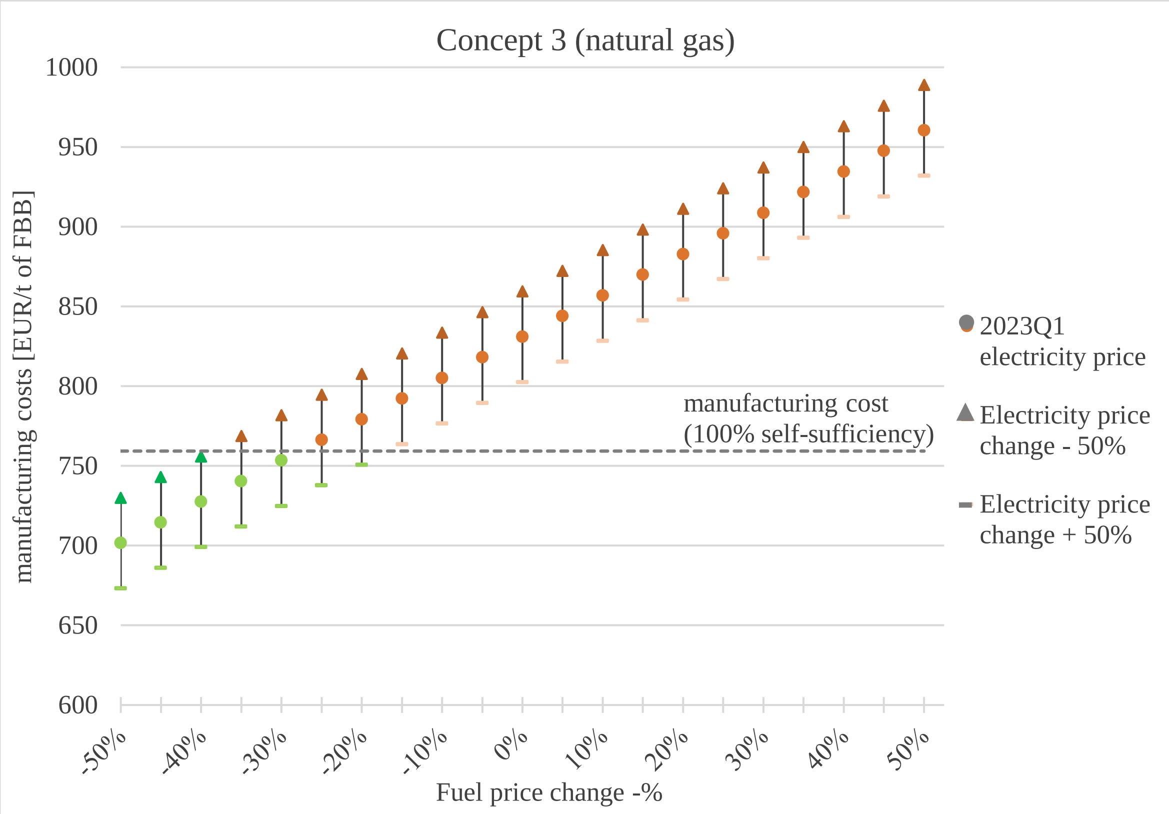


Figure 28. Two variable sensitivity analysis of concept 3 FBB manufacturing costs using electricity and natural gas price.

Concept 4 (figure 29) is similar to concept 1 in high flexibility to price changes. Even though the electricity price changes have the highest effect on concept 4 compared to concepts 1-3, the costs remain below the comparison level. Even at the extremities of the analysis, the excess electricity production is profitable in the chemical pulp integrated mill.

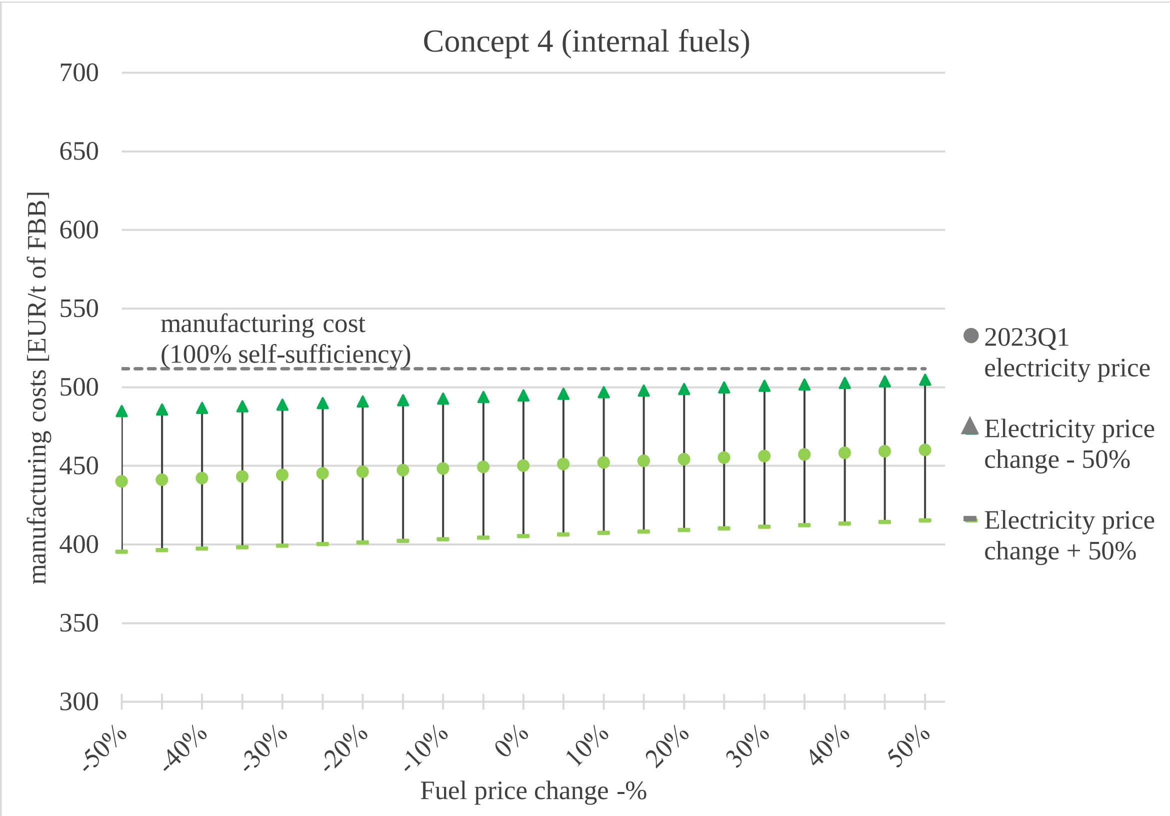


Figure 29. Two variable sensitivity analysis of concept 4 FBB manufacturing costs using electricity and biomass price.

Overall, the natural gas based CCGT power plant is the most unfeasible of the concepts due to the current high natural gas prices. Even with the 50 % change in fuel prices, concept 3 would remain most unprofitable. The RDF-fuelled power plant, on the other hand, would be more profitable in most price variation scenarios compared to the biomass-based concept 2 with a similar power plant structure. This can be attributed to the current higher price of biomass than the RDF price in the cost competitiveness tool, which causes more significant fluctuations of net costs during fuel price changes. Concept 4 remains the most cost-efficient energy production concept, as outsourced fuel prices do not highly influence the chemical pulp integrated mill due to the internal fuels available.

7.3. CO2 emissions and costs

This section includes CO2 emission calculation, annual allocation and allowance balance calculation results. In addition, the CO2 costs for the production of FBB in the modelled price scenarios of 2023 q1, 2025 and 2030 are presented and analysed. The CO2 calculations are analysed for 100 % and 150 % self-sufficiency base scenarios. The results are used to examine the effect of EU ETS on FBB manufacturing expenses in different energy concepts and carbon credit price scenarios up to 2030.

7.3.1. CO2 emissions

The results of annual CO2 emissions calculated for each concept are presented in table 6.

Table 5. Annual emissions for each concept. [1] biomass CO2 emissions not included. [2] biomass CO2 emissions included.

	Emissions t CO2/a	
	100% power self-sufficiency	*150% power self-sufficiency*
Concept 1	84 010	110 130
Concept 2[1]	3 610	3 610
Concept 2[2]	270 740	359 450
Concept 3	132 280	258 710
Concept 4[1]	8 180	8 180
Concept 4[2]	-	130 322

The annual emissions are higher in the 150 % self-sufficiency scenario compared to the 100 % self-sufficiency. If biomass is considered CO2 emission-free, concept 3 has the highest annual emissions in both scenarios, 132 280 and 258 710 t CO2/a, respectively, due to natural gas having a high CO2 emissions factor. Second is concept 1, with 84 010 t CO2/a emissions in the 100 % self-sufficiency scenario and 110 130 t CO2/a in the second scenario. The gap between concept 1 and 3 emissions is over 48 000 t CO2/a in the 100 % scenario and 148 00 t CO2/a in the 150 % scenario. However, in concept 2[2], the emissions from using biomass are double the emissions of concept 3. Additionally, in the 150 % self-sufficiency scenario, concept 4^2's annual emissions reach 130 000 t CO2.

All concepts' emissions include the direct usage of natural gas in drying. The emission account for 13.4 kg CO2/t of FBB or 3 610 t CO2/a. As explained above, concepts 1, 2^2, 3 and 4^2 have emissions outside these factors. However, in both base scenarios, direct fuel usage is the only source of accountable emissions for concept 2^1. In the case of concept 4, natural gas is also required in the lime kiln, which causes around 4 570 t CO2/a. Thus, the annual CO2 emissions for concept 4^1 is 8 180 t CO2.

7.3.2. Annual allocations for the mill

CLEF is defined as 1.0 for installations at significant risk of carbon leakage, which coated carton board is part of (European Commission 2019a). The exact value applies for 2021-2030. For coated carton board, the *BM* value is 0.207 EUA/t of product for 2021-2025 (Appendix 3). The calculation of the *BM* value is presented in Appendix 4. Historical activity levels are calculated as the arithmetic mean of annual production values during the baseline period. The baseline period is 2014-2018 for 2021-2025 and 2019-2023 for 2026 onwards. However, as the modelled paper machine started operating in 2022, no historical data is available. In cases where the installation has been in operation for less than two years of the baseline period, the activity level is determined by the first full year of operation. It is assumed that the entire production capacity of the FBB machine is utilised annually. Thus, for the modelled FBB mill, the *HAL* equals the activity level of 2023, which is 270 kt.

As seen in table 4, in the 100% self-sufficiency base scenario, a small amount of steam (8 GWh) is exported in concept 4. As explained in chapter 6.4, heat production at the site is eligible for basic allocation. However, the value is insignificant in total heat consumption (2280 GWh), and as reported in chapter 6.4, only coated cartonboard product benchmark is included in the scope of the study. Hence, from the viewpoint of allocation calculation, heat export is left out of the scope.

Therefore, the preliminary annual basic allocation of 2023-2025 for the modelled mill is calculated using equation 1.

$$F_{prel} = 0.207 \ \frac{EUA}{Adt\ of\ product} \ * 270\ 000\ Ad\ t * 1.0 = 55\ 890\ EUA \qquad (1)$$

For 2021-2025 *CSCF* is 100% per European Commission Implementing Decision (EU 2021/927). Hence, the final basic annual allocation for the mill is 55 890 EUA in 2023-2025.

As explained above, for 2026-2030, *CLEF* remains 1.0. The activity level of the mill does not change, thus remaining at 270 kt/a for each year. The parameter changing from the allocation in 2023-2025 is the product *BM* value. According to the current regulation, the *BM* value of coated carton board for 2026-2030 will be 0.186 EUA/Adt of the product (appendix 4)

$$F_{prel} = 0.186 \ \frac{EUA}{Adt\ of\ product} \ * 270\ 000\ Adt * 1.0 = 50\ 123\ EUA$$

For 2026-3030, *CSCF* has not been set yet; however, according to the baseline regulation and scenario assessments of the European Commission, one of the most prominent possibilities is that *CSCF* will not be triggered and thus stay at 100% (Climact 2022; European Commission 2021a; ICAP 2022). Thus, it is assumed that CSCF will stay the same for 2026-2030. Therefore, the final annual allocation for the mill is 50 123 EUA in 2026-2030.

7.3.3. Allowance balances

First, to get the CO2 costs for FBB production, allowance balances need to be calculated. As the annual allocation is the same for 2023 and 2025, the allowance balances are identical. For concept 1 allowance balance in the 100% self-sufficiency scenario is calculated as follows

$$\text{Allowance balance}_1 = 84\ 010\ t\frac{CO2}{a} - 55\ 890\frac{EUAs}{a} = 28\ 120\ EUA \tag{3}$$

Thus, the RDF-based energy production causes more emissions than the allocation to the plant is. Therefore, the mill is short of emission allowances which adds up to 28 120 t CO2 emissions, for which allowances must be purchased. For other concepts, the calculation results are presented in table 6 for both base scenarios.

Table 6. Annual emissions and allowance balance of each concept applicable for 2023 and 2025. [1] biomass CO2 emissions not included. [2] biomass CO2 emissions included.

	Emissions t CO2/a	**Final allocation EUA/a**	**Allowance balance EUA/a**
100% power self-sufficiency			
Concept 1	84 010	55 890	28 120
Concept 2[1]	3 610	55 890	-52 280
Concept 2[2]	270 740	55 890	214 850
Concept 3	132 280	55 890	76 390
Concept 4[1]	8 180	55 890	-47 710
150% power self-sufficiency			
Concept 1	110 130	55 890	54 240
Concept 2[1]	3 610	55 890	-52 280
Concept 2[2]	359 450	55 890	303 610
Concept 3	258 710	55 890	202 820
Concept 4[1]	8 180	55 890	-47 710
Concept 4[2]	130 320	55 890	74 430

As seen in the table, in the 100 % power self-sufficiency base scenario, in concept 1, the mill must purchase 28 120 EUAs. In contrast, in concept 3, the mill must purchase 76 390 EUAs, in addition to the final allocation, to cover the mill's emissions. Whereas concept 2[2] results in the mill having a deficit of over 210 000 EUAs, the overwhelmingly highest number of allowances to be purchased. On the contrary, concepts 2[1] and 4[1] end up with surplus allowances. In concept 2[1], the mill is left with 52 280 surplus EUAs; in concept 4[1], the number is -47 710 EUAs. The results are directly caused by fuels used in the concepts and the biomass CO2 emissions accounting status.

In the second base scenario, 150 % power self-sufficiency, allowance balance increases according to the increase in electricity production for concepts 1, 2[2], 3 and 4[2] increasing the number of allowances to be purchased. In contrast, in concepts 2[1] and 4[2], the balance remains at the same level. The emissions do not change as the natural gas usage in the pulp line and board machine does remain at the same level.

The allowance balances for 2030 are presented below (table 7).

Table 7. Annual emissions and allowance balance of each concept applicable for 2030. [1] biomass CO2 emissions not included. [2] biomass CO2 emissions included.

	Emissions t CO2/a	**Final allocation EUA/a**	**Allowance balance EUA/a**
100% power self-sufficiency			
Concept 1	84 010	50 120	33 890
Concept 2[1]	3 610	50 120	-46 510
Concept 2[2]	270 740	50 120	220 620
Concept 3	132 280	50 120	82 160
Concept 4[1]	8 180	50 120	-41 950
150% power self-sufficiency			
Concept 1	110 130	50 120	60 010
Concept 2[1]	3 610	50 120	-46 510
Concept 2[2]	359 500	50 120	309 380
Concept 3	258 710	50 120	208 580
Concept 4[1]	8 180	50 120	-41 950
Concept 4[2]	130 320	50 120	80 200

Due to the decreased annual allocation, the allowance balances differ from 2023 and 2025 values. In concepts 1, 2[1] and 3 the mill must purchase up to 5 750 more EUAs to cover the decreased free allocation, while in concepts 2[2] and 4[1] the mill has fewer surplus allowances.

7.3.4. CO2 costs

Using the allowance balances and CO2 price of q1 2023, the CO2 costs of manufacturing FBB in the modelled mill are examined in the four energy concepts. The net manufacturing costs including the effect of CO2 costs in q1 of 2023 are presented in figures 30 and 31. The results are also presented in table format in appendix 5.

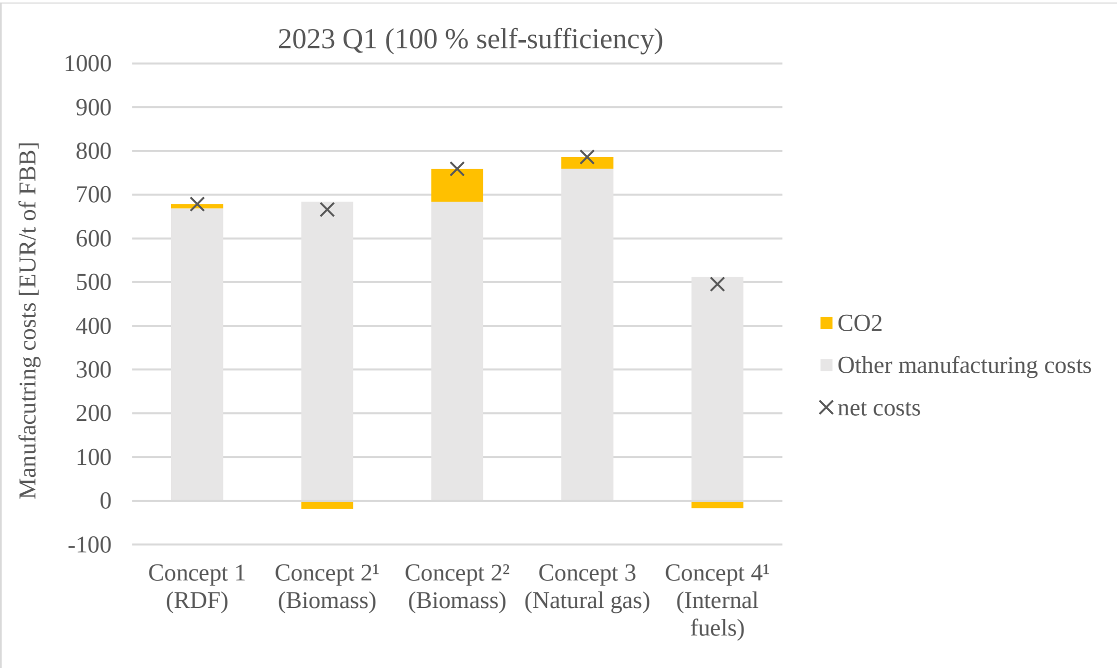


Figure 30. Manufacturing costs of concepts 1-4 in 100% power self-sufficiency scenario including the effect of CO2 costs in the first quarter of 2023. [1] biomass CO2 emissions not included. [2] biomass CO2 emissions included.

As seen in the emission balances presented in chapter 7.3.3, in concepts 1, 2[2] and 3 CO2 costs increase the net manufacturing costs, while in concepts 2[2] and 4, the net costs decrease. This applies to both 100 % and 150 % power self-sufficiencies. The criteria for defining the emission inclusion status of emission from biomass combustion has a considerable effect on the net costs of FBB manufacturing. As seen in concept 1, the CO2 factor is lowered by the biomass fraction of the waste, which is considered emission free, which in turn affects the CO2 costs of RDF usage. Whether biomass used in the power plant is emission free or the emissions are included, affects the net cost level of biomass-based power plant concept manufacturing costs. It determines whether the manufacturing costs are lower than concept 1 or whether the costs are closer to concept 3. Concept 3 has the highest CO2 costs, when the biomass CO2 emissions are not included. In concept 3, the results are apparent. As fossil fuel, natural gas is in a weaker position in the emission trading system, thus it does not perform well in CO2 cost comparison.

In the 150 % self-sufficiency scenario, the CO2 costs are more notable due to higher usage of fuel. Additionally, the other manufacturing costs change depending on the concept, as examined more in depth in chapters 7.1.1 and 7.1.2. This creates greater variation between the net costs of different concepts. The CO2 costs of concept 3 are closer to the CO2 costs of concept 2^{1}, compared to 100% self-sufficiency scenario. However, in the case of the mill profiting from the allowances, as in cases 2^{2} and 4^{1}, the potential profit does not increase.

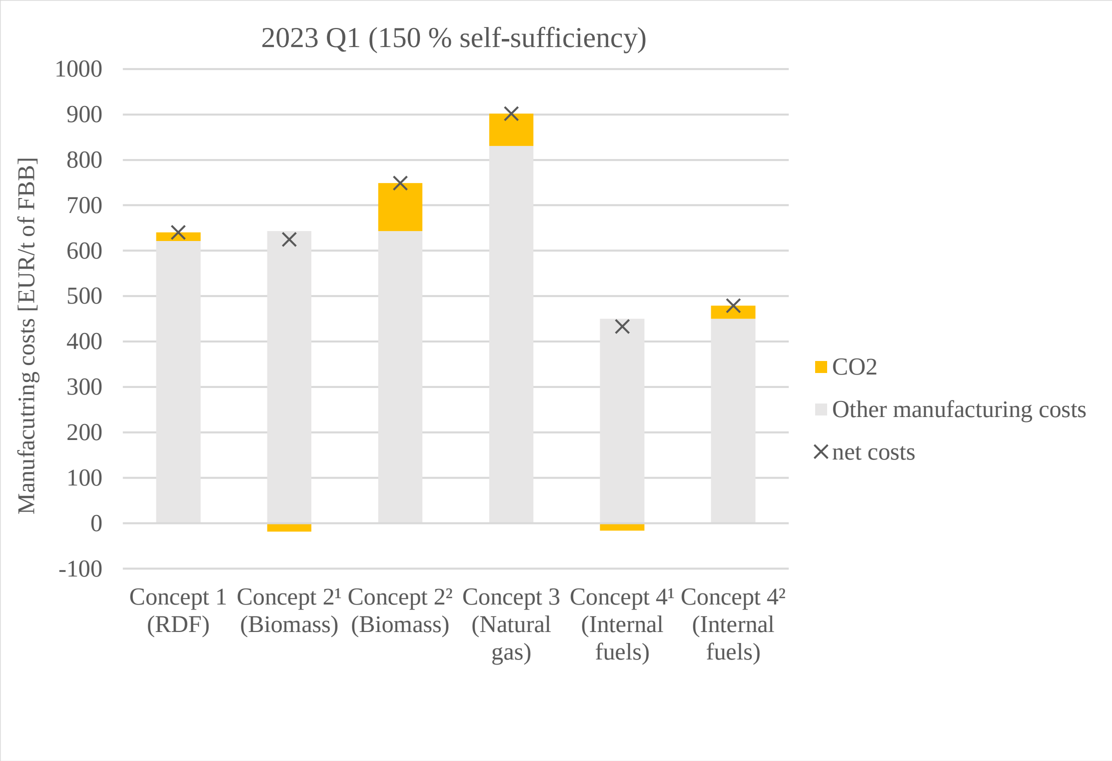


Figure 31. Manufacturing costs of concepts 1-4 in 150% power self-sufficiency scenario including the effect of CO2 costs in the first quarter of 2023. [1]biomass CO2 emissions not included. [2] biomass CO2 emissions included.

Predictions for 2025 and 2030 only include price changes for carbon credits, all other cost components remain at the price levels of q1 2023. Thus, the results can only be used to compare variations between potential CO2 costs. For 100 % self-sufficiency scenario the results are presented in figure 32 for 2025 and in figure 33 for 2030.

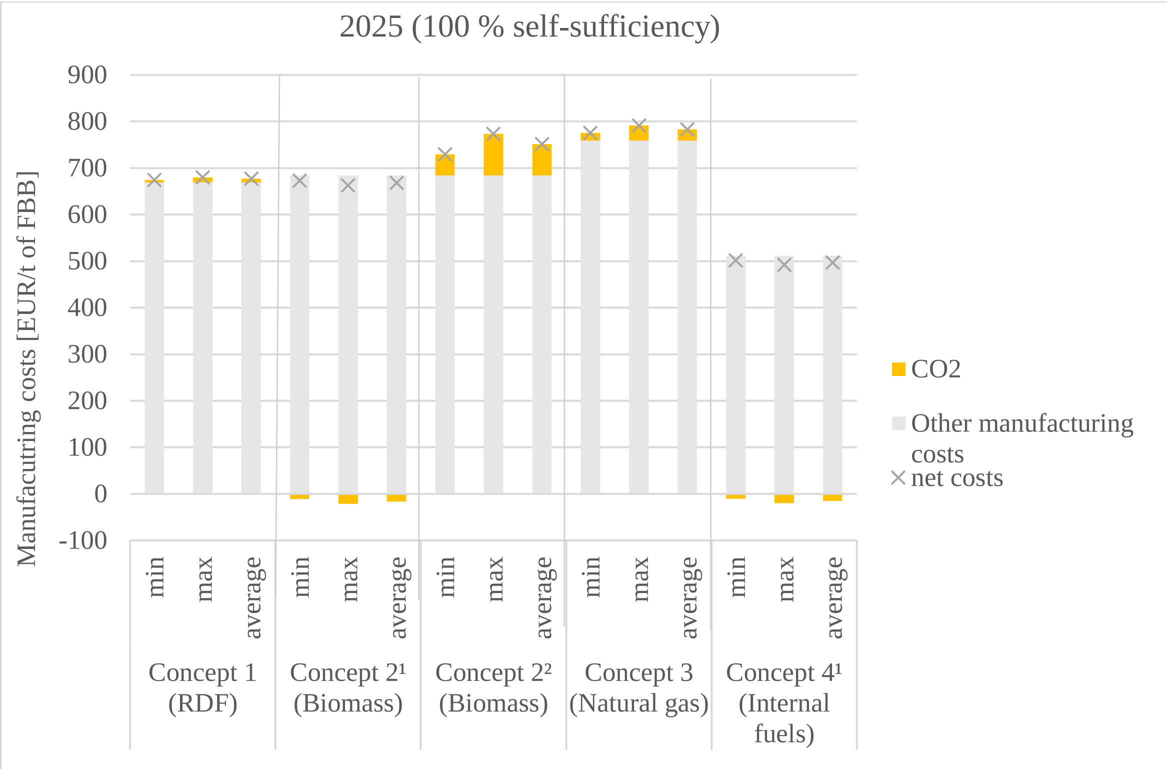


Figure 32. Manufacturing costs of concepts 1-4 in the 100% power self-sufficiency scenario with minimum, maximum, and average CO2 allowance price predictions for 2025. [1]biomass CO2 emissions not included. [2] biomass CO2 emissions included.

For 2025, the predictions range from lower than the q1 2023 net costs to higher than the current net cost level. As the annual emissions do not vary, the carbon credit prices cause variation in the results compared to the q1 2023 levels. The average price scenarios have lower CO2 costs compared to 2023 due to the average price forecast being below the current prices. The minimum price scenario also results in lower CO2 costs, while the maximum price scenario forecasts higher CO2 costs in comparison to current levels.

The 2030 price scenarios convey another story. The predicted carbon credit prices for 2030 are higher than in 2023 q1 and 2025, with the minimum 2030 price being near same as the 2025 average price, 84 EUR/t CO2 and 84.5 EUR/t CO2, respectively. Additionally, the basic allocation is lower compared to 2023-2025. This is visible in the CO2 costs as the net manufacturing costs in the 2030 minimum price scenario are at the same level as 2025 average net prices. In addition, the 2030 average price scenario leads to higher CO2 costs compared to the 2025 maximum price scenario. The share of CO2 costs of total manufacturing costs is highest in the 2030 price scenarios.

As the forecasted carbon credit prices are higher compared to 2023 q1 and 2025, concepts 2^2 and 4^1 gain greater benefit from the allowance sales, while concepts 1, 2^2 and 3 are at disadvantage due to the increased prices. In the highest predicted price scenario, the net costs of concept 2^2, with inclusion of biomass CO2 emissions, exceed the net costs of fossil fuel concept 3. Overall, concept 2^2 has the highest CO2 costs amongst the concepts.

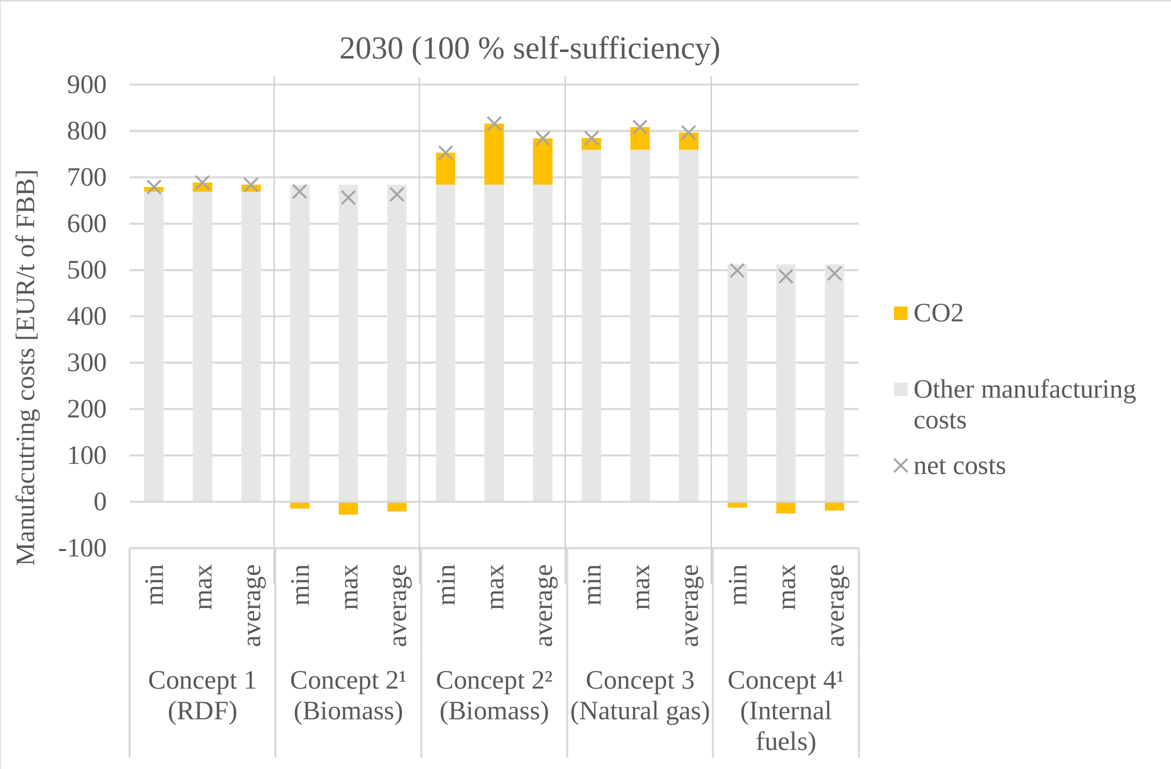


Figure 33. Manufacturing costs of concepts 1-4 in the 100% power self-sufficiency scenario with minimum, maximum, and average CO2 allowance price predictions for 2030. [1]biomass CO2 emissions not included. [2] biomass CO2 emissions included.

For 150 % self-sufficiency scenario the results are presented in figure 34 for 2025 and in figure 35 for 2030.

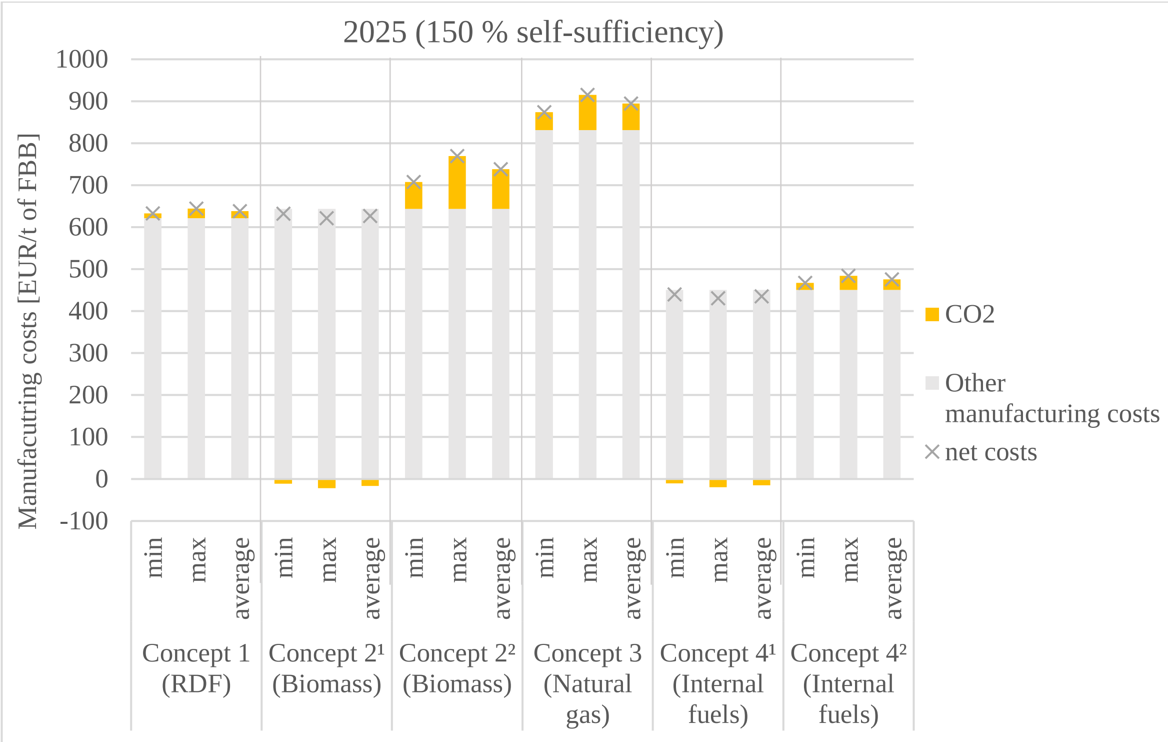


Figure 34. Manufacturing costs of concepts 1-4 in the 150% power self-sufficiency scenario with minimum, maximum, and average CO2 allowance price predictions for 2025. [1]biomass CO2 emissions not included. [2] biomass CO2 emissions included.

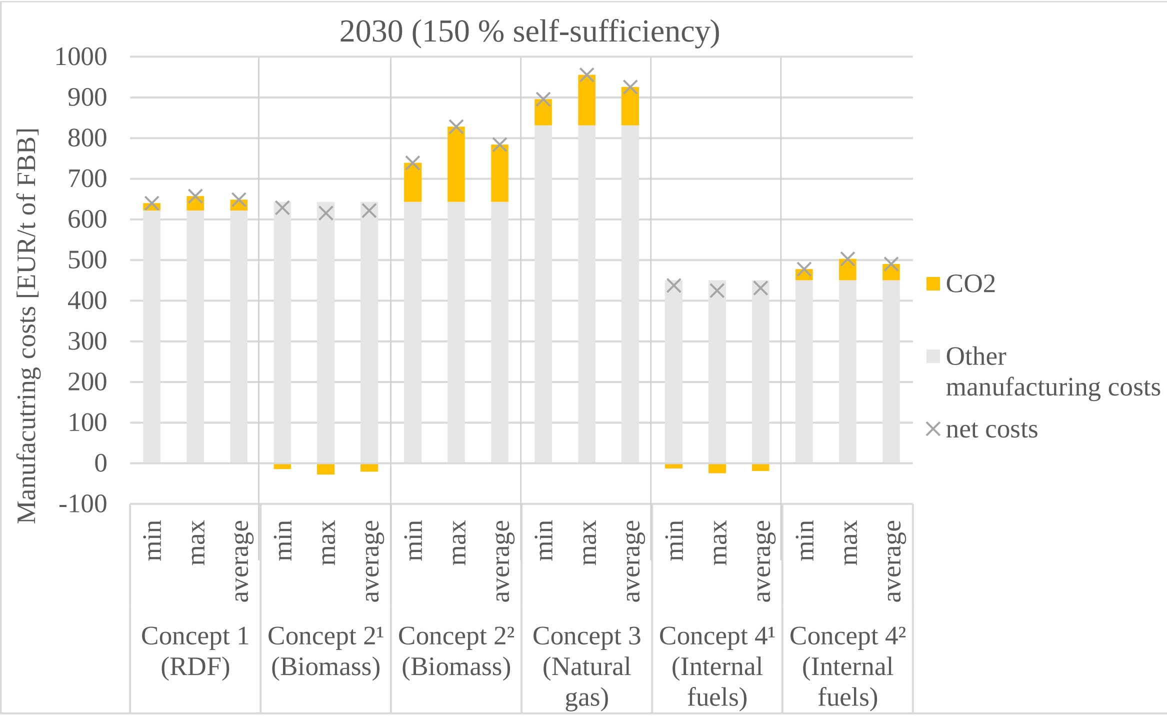


Figure 35. Manufacturing costs of concepts 1-4 in the 150% power self-sufficiency scenario with minimum, maximum, and average CO2 allowance price predictions for 2030. [1]biomass CO2 emissions not included. [2] biomass CO2 emissions included.

As seen in the 2023 q1 (figure 31), in the 150 % power self-sufficiency scenario the CO2 costs are higher and the variation between net costs of different concepts greater compared to 100 % self-sufficiency scenario. Thus, the significance of CO2 costs is highlighted when producing excess electricity for sale. This is visible especially in concept 3 and 2[2], where the CO2 costs are forecasted to be significantly higher in 2025 and 2030 compared to the respective years the 100 % self-sufficiency scenario.

The average shares of CO2 costs of total net costs for each examined year are presented below (table 8).

Table 8. The average CO_2 cost share of total manufacturing costs for 2023 q1, 2025 and 2030. [1] biomass CO_2 emissions not included. [2] biomass CO_2 emissions included.

CO2 cost share of total net cost			
	2023 q1	**2025 average**	**2030 average**
100% power self-sufficiency			
Concept 1	1.4 %	1.3 %	2.2 %
Concept 2[1]	-2.7 %	-2.4 %	-3.2 %
Concept 2[2]	9.9 %	8.9 %	12.8 %
Concept 3	3.4 %	3.1 %	4.7 %
Concept 4	-3.4 %	-3.0 %	-3.9 %
150% power self-sufficiency			
Concept 1	3.0 %	2.7 %	4.2 %
Concept 2[1]	-2.9 %	-2.6 %	-3.4 %
Concept 2[2]	14.1 %	12.9 %	17.9 %
Concept 3	7.8 %	7.1 %	10.2 %
Concept 4[1]	-3.8 %	-3.4 %	-4.4 %
Concept 4[2]	6.0 %	5.4 %	8.2 %

As previously presented, on average the CO_2 costs decrease in 2025 compared to 2023 q1 levels, however in 2030 the prices are predicted to increase. Therefore, even though the CO_2 costs are on average forecasted to decrease slightly in the short term, eventually CO_2 costs are predicted to increase for mills using CO_2 emission accountable fuels. This includes fossil fuels, fossil fuel fractions in waste fuels and biomass-based fuels which do not fulfil the sustainability criteria. This can also be expanded to cover black liquor and other internal fuels used in pulp and paper mills. However, if a mill uses fuel which is defined as renewable and causing no emissions, the increase in carbon credit prices will lead to greater profits from the sale of surplus allowances.

7.4. Limitations

The study includes assumptions and limitations. Some are posed by the modelling tool. As presented in chapter 6, the AFRY cost competitiveness tool best examines the relative differences of the concepts more so than the absolute values. Hence, the results should not be considered factual production and energy cost numbers but relativeness between each energy concept and CO_2 price scenario. In addition, the modelling is conducted on the current version of the tool, which has predefined calculation principles for energy consumption and efficiencies of machinery and the power plant. Furthermore, the machinery is assumed to be modern and brand-new, affecting energy consumption values compared to older machinery. These factors and process optimization principles affect the energy consumption values of the plant and, thus, the emitted CO_2 emissions. In addition, the study is conducted from the view of energy costs in manufacturing expenses and the effect of EU ETS on manufacturing costs. Hence, the scope excludes capital expenditures such as investment and maintenance costs. For instance, the study leaves out the aspect of investment costs of turbines for increasing the power generation capacity up to 150 % power self-sufficiency.

The chosen energy concepts are simplified while simultaneously being specific. However, realistically energy concepts of paper and pulp mills are more complex. For instance, used fuel mixes are 100 % based on one fuel type. Yet, it is common for paper and paperboard mills to utilize various fuels in energy production, for example, depending on fuel availability and pricing. Additionally, power plants can include multiple boilers or different heat recovery applications not included in the modelling.

Furthermore, the fuel mix selection was based on the most prominent fuels in the European paper industry. However, including natural gas as the only conventional fossil fuel makes it appear unbeneficial. For instance, including coal in the fuel mixes could have affected the position of natural gas amongst the other concepts. However, coal is losing popularity as a fuel in the paper industry and is thus not included. Additionally, including other renewable fuels along with biomass would have provided more insight into the status and possible development of renewable energy sources in the PPI, considering increased energy prices and the EU ETS. However, excluding biomass and hydropower, other renewable sources such as wind, solar and hydrogen energy, are currently in development for the modelling tool.

The impact of energy subsidies on the feasibility of the different energy concepts in cartonboard production is not included in the scope. For instance, the study provides feasibility and sensitivity analyses from the view of energy prices and fuel consumption figures; however, it does not account for the impact of possible subsidies provided by the local state, such as tax credits or fuel price support. However, various subsidies in use around European Union are presented in the theory section to provide insight into the possible effect of these subsidies.

The CO2 cost analysis also contains assumptions. These include the assumption that only the carbon credit price and basic allocation change in the different price scenarios of 2025 and 2030. Other cost components, such as employee salaries and raw material prices expected to remain at the 2023 q1 level. Furthermore, in the annual basic allocation calculation, the activity level of the plant was presented as constant and equal to the production capacity. However, actual production volumes of installations may vary annually and may not reach the full capacity of the machines. In this study, the assumption leads to the mill receiving a higher basic allocation than the mill would receive among production volume variations. Additionally, the market pulp product benchmark was excluded from the scope of the study. However, in concept 4, the mill would receive more free allowances, affecting the allowance balance. In addition, in concept 4, the mill profits, for instance, from market pulp sales. However, the study was conducted based on the cartonboard manufacturing expenses focusing on the energy production components, thus leaving other aspects of the mill’s operation out of the scope.

The effect of EU ETS on outsourced biomass fuels is examined in two concepts, with all biomass emissions being left out or all emissions being included depending on the fulfilment of sustainability criteria stated by regulation. Yet, a fraction of the biomass can comply with the sustainability criteria, with the rest not fulfilling the criteria. This would result in a CO2 emissions factor which is lower compared to the examined concept 2[2]. Other factors affecting the emission balance of the mill include potential air pollution control technologies. The number of emission allowances required to be obtained by the mill can be reduced by carbon capture if complying with the obligations for carbon transport and storage, as stated in the EU ETS directive article 12. Thus, the emissions included in the emission allowance coverage can be reduced using carbon capture. Additionally, if the captured CO_2 is recognized as credit in the EU ETS, the mill can benefit from it. This possibility is not included in the scope of the study as it is very uncommon; however, it has been researched in various studies by Santos et al. (2021), Kuparinen et al. (2019) and Onarheim et al. (2017), among others.

8. Conclusions

The energy crisis has accelerated the change away from conventional energy production applications in the European pulp and paper industry since late 2021. Moreover, in 2022 the industry experienced more radical impacts with increased and highly volatile fuel and energy prices, which even led to temporary shutdowns of production lines around Europe, indicating that conventional fossil energy production applications were no longer economical options. In addition to the energy crisis, the Renewable energy directive will be updated in 2023 to accelerate the clean energy transition, with the EU ETS also being in constant development. This will furthermore weaken the position of unsustainable fuel usage in paper mills and promote the deployment of renewable and emission-free fuels in the industry.

This thesis studied which components of common energy production concepts used in the paper industry affect the energy costs of paper production and, thus, which components are beneficial in the current energy market and the future. The focus was also on analysing under which conditions and using which concepts it is profitable to generate excess electricity for sale at the mill power plant. The results of this study achieved its objectives. The modelling results provide data for developing the cost competitiveness modelling, insight into the flexibility of different energy concepts in volatile energy markets, and present relative differences and decisive factors between the concepts.

The studied concepts were RDF based fluidized bed boiler operating power plant with condensing turbine (1), an outsourced biomass-based power plant with a similar power plant (2), a CCGT power plant operating on natural gas (3), and a chemical pulp integrated mill with steam turbine-based power plant operating on internal fuels (4). Concept 1 is resilient towards energy price fluctuations and has beneficial results from excess electricity generation for sale, with manufacturing costs of 669 and 621 EUR/t in 100 % and 150 % self-sufficiency base scenarios, respectively. On the other hand, concept 2 modelling results indicate that biomass-fired power plant is more expensive than RDF, with manufacturing costs of 684 and 641 EUR/t, and less flexible due to the higher biomass price in the used price data. Energy costs are highest using the CCGT power plant, up to 259 EUR/t, which is over triple the cost of the other concepts. The total manufacturing costs of concept 3 reach 759 and 831 EUR/t in the base scenarios. Thus, the mill is the most vulnerable to fuel price fluctuations, even if natural gas prices decrease a couple of dozen per cent. Concept 4 has the lowest energy costs (0 and 20 EUR/t) and total manufacturing costs (512 and 450 EUR/t); however, the study scope excludes market pulp production costs. The energy modelling results indicate that the pinch fossil fuels fuelled mills experienced in 2022 is continuing in the beginning of 2023, whereas biomass and waste fuels are feasible options for energy production concepts. This implicates increase in the uncertainty of fossil fuels’ position in the PPI in the upcoming years.

The CO2 cost analysis provides a high-level understanding of the current effect of the EU ETS on the paper and paperboard manufacturing industry and in the short term. In the energy analysis results, fossil fuels are shown as the less profitable option, and when studying the impact of the EU ETS, the setting remains the same. On average, at the start of 2023, the share of CO2 costs of manufacturing costs for natural gas-based concept 3 was 3.4 %. The corresponding values for the other concepts were 1.4 % for concept 1 and below zero for concepts 2 and 4. However, the accounting of biomass emissions makes a difference in biomass-based power production. Biomass can be considered carbon-neutral fuel if the sustainability criteria of RED are fulfilled (concept 2^1), leading to biomass benefiting largely from the allowance scheme. However, in the case of biomass not reaching the required criteria (concept 2^2), the emissions from biomass combustion cause the mill to have high allowance expenses, as seen in the analysis. The results indicate up to 10 % CO2 cost share. This study considers internal fuels emission-free; thus, the chemical pulp integrated mill is well positioned among the CO2 allowance costs. However, the sustainability criteria can be expanded to cover black liquor in the future, changing the operating ground.

Currently, the effect of emissions allowances is minor; however, CO2 costs can create decisive changes in the manufacturing expenses of paper products going forward. The analysis results show that the CO2 costs in paper product manufacturing are predicted to increase considerably by 2030 for fuels with accounted emissions, 15-50%, depending on the fuel mix. On the other hand, the profit gained from using fuels with no accounted emissions increases. However, the EU ETS and the renewable energy directive development will likely be more prominent in the upcoming years. For instance, more proposals have been considered for tightening the free allocation, such as introducing stricter product benchmark values, in addition to the reduction already decided for 2026-2030. Furthermore, the price of CO2 allowances is forecasted to increase by 2030, while the updated RED will include stricter sustainability criteria for biomass-based fuels, including forest biomass, waste fractions and production side streams. As the results of this study and the energy and CO2 market prices indicate, low-emission options merge as the benefiting party in the European operating ground going forward, while fossil fuel utilisation faces increasing costs. The implications of renewable and low emissions fuels being “the winners” may be far reaching, as supported by the direction the upcoming developments to the RED and the EU ETS have.

The modelling and analyses are conducted from the view of manufacturing expenses, excluding the study into capital expenditures related to power plant operation. The topic of capital expenditures would require carrying out independent research. More energy concepts should be studied to provide more variable data to support the conclusions. In addition, due to the exclusion of the energy subsidies’ impact from the scope, further research should be conducted to examine the subsidies’ possible impact on the results more precisely. For instance, in 2022, multiple European governments introduced support schemes covering support for natural gas use in power production. The effect of these schemes is not seen in this study.

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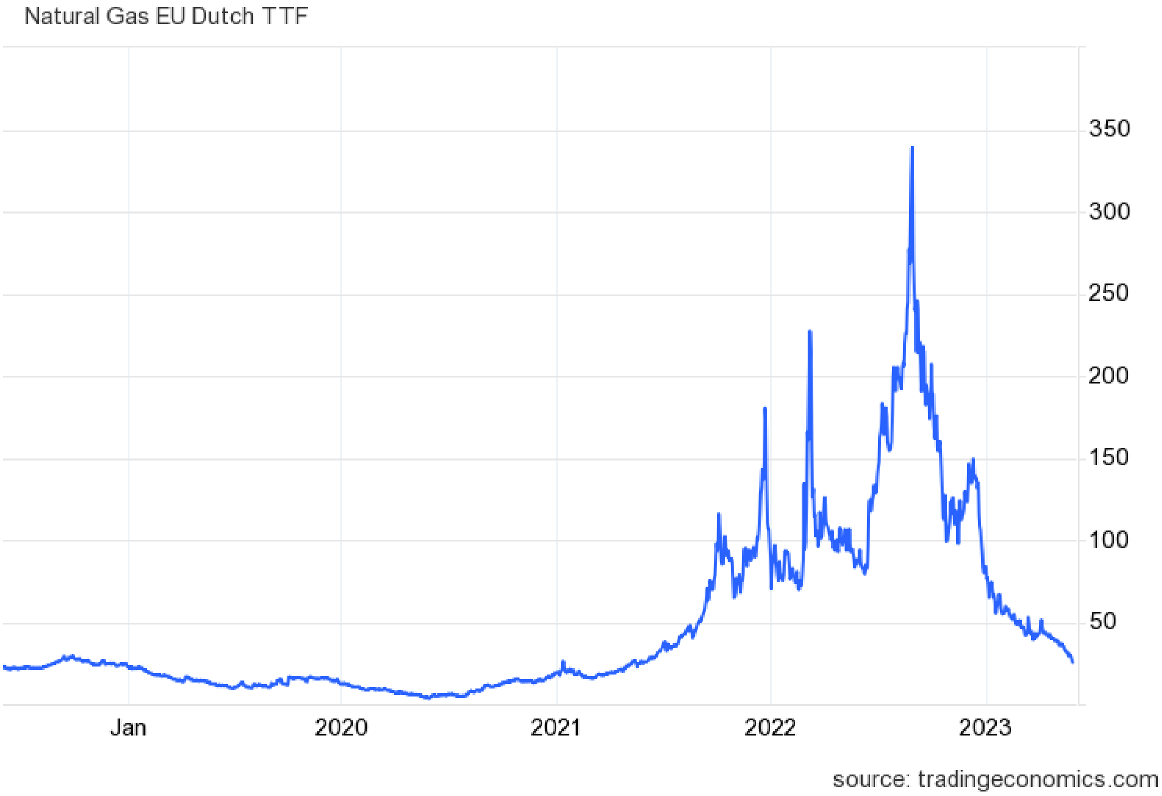
Appendix 1. List of Cepi member countries.

CEPI MEMBER COUNTRIES
Austria
Belgium
Czech Republic
Finland
France
Germany
Hungary
Italy
The Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Sweden
United Kingdom

Appendix 2. Natural gas price EU Dutch TTF [EUR/MWh] (Trading Economics 2023b).



Appendix 3. Pulp and paper benchmark products included in the EU ETS, benchmark values for 2021-2025 and the average emissions for the most efficient 10% of installations in 2016-2017 (t CO_2-eq/t) as stated in European Commission regulation (2021/447).

PRODUCT BENCHMARK	Benchmark [EUA/t of product unit]	Emissions [t CO_2-eq/t]
Short fibre kraft pulp	0.091	0.000
Long fibre kraft pulp	0.046	0.001
Sulphite pulp, thermo-mechanical and mechanical pulp	0.015	0.000
RCP pulp	0.030	0.000
Newsprint	0.226	0.007
Uncoated fine paper	0.242	0.011
Coated fine paper	0.242	0.043
Tissue	0.254	0.139
Testliner and fluting	0.188	0.071
Uncoated carton board	0.180	0.009
Coated carton board	0.207	0.011

Appendix 4. Principle of product benchmark calculation for EU ETS phase 4 (phase 4a and phase 4b).

$$BM = BM_{phase\ 3} * (1 - yearly\ adjustment * Da)$$

where *BM* is benchmark value in calculated EU ETS phase [EUA/t of product unit], BM_{phase3} is the benchmark value of EU ETS phase 3 [EUA/t of product unit], *yearly adjustment is* update rate of the benchmark value of phase 3 is and *Da* is the years between baseline year 2008 and middle year of calculated phase [a]. For phase 4a, *Da* is 2023 – 2008 = 15 a and for phase 4b it is 2028 - 2008 = 20 a. (European Commission 2019b.)

For coated carton board, BM_{phase3} is 0.273 EUA/Adt and *yearly adjustment* is 0.016 (European Commission 2021b).

Appendix 5. Net FBB manufacturing costs of concepts 1-4 including the effect and share of CO2 costs.

	100 % power self-sufficiency							**150 % power self-sufficiency**						
	2023	**2025**			**2030**			**2023**	**2025**			**2030**		
Price scenario	avg	min	max	avg	min	max	avg	avg	min	max	avg	min	max	avg
Concept 1 (RDF)														
CO2	10	6	12	9	11	20	15	19	11	22	17	19	36	27
Other costs	669	669	669	669	669	669	669	621	621	621	621	621	621	621
Net costs	678	674	680	677	679	689	684	640	633	644	638	640	657	649
% of CO2	1.4 %	0.9 %	1.7 %	1.3 %	1.6 %	2.9 %	2.2 %	3.0 %	1.8 %	3.5 %	2.7 %	2.9 %	5.4 %	4.2 %
Concept 2 (Biomass zero CO2)														
CO2	-18	-11	-22	-16	-14	-28	-21	-18	-11	-22	-16	-14	-28	-21
Other costs	684	684	684	684	684	684	684	643	643	643	643	643	643	643
Net costs	666	673	663	668	670	657	663	625	632	621	627	629	615	622
% of CO2	-2.7 %	-1.6 %	-3.3 %	-2.4 %	-2.2 %	-4.2 %	-3.2 %	-2.9 %	-1.7 %	-3.5 %	-2.6 %	-2.3 %	-4.5 %	-3.4 %
Concept 2 (Biomass CO2 included)														
CO2	75	45	89	67	69	132	100	106	64	126	95	96	184	140
Other costs	684	684	684	684	684	684	684	643	643	643	643	643	643	643
Net costs	759	730	773	751	753	816	784	749	707	769	738	739	828	784
% of CO2	9.9 %	6.2 %	11.5 %	8.9 %	9.1 %	16.1 %	12.8 %	14.1 %	9.1 %	16.4 %	12.9 %	13.0 %	22.3 %	17.9 %
Concept 3 (Natural gas)														
CO2	27	16	32	24	26	49	37	71	43	84	63	65	124	95
Other costs	759	759	759	759	759	759	759	831	831	831	831	831	831	831
Net costs	786	775	791	783	785	808	797	902	874	915	894	896	955	926
% of CO2	3.4 %	2.1 %	4.0 %	3.1 %	3.3 %	6.1 %	4.7 %	7.8 %	4.9 %	9.2 %	7.1 %	7.2 %	13.0 %	10.2 %
Concept 4 (Internal fuels, biomass zero CO2)														
CO2	-17	-10	-20	-15	-13	-25	-19	-17	-10	-20	-15	-13	-25	-19
Other costs	512	512	512	512	512	512	512	450	450	450	450	450	450	450
Net costs	495	502	492	497	499	487	493	434	440	430	435	437	425	431
% of CO2	-3.4 %	-2.0 %	-4.0 %	-3.0 %	-2.6 %	-5.1 %	-3.9 %	-3.8 %	-2.3 %	-4.6 %	-3.4 %	-3.0 %	-5.9 %	-4.4 %
Concept 4 (Internal fuels, biomass CO2 included)														
CO2	-	-	-	-	-	-	-	29	17	34	26	27	53	40
Other costs	-	-	-	-	-	-	-	450	450	450	450	450	450	450
Net costs	-	-	-	-	-	-	-	479	468	484	476	478	503	490
% of CO2	-	-	-	-	-	-	-	6.0 %	3.7 %	7.1 %	5.4 %	5.8 %	10.5 %	8.2 %