Drivers and barriers in retrofitting pulp and paper industry with bioenergy for more efficient production of liquid, solid and gaseous biofuels: A review

Mäki Elina, Saastamoinen Heidi, Melin Kristian, Matschegg Doris, Pihkola Hanna

DOI: 10.1016/j.biombioe.2021.106036

Please cite the publication as follows:

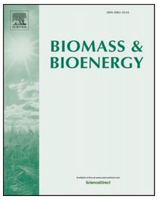
Elina Mäki, Heidi Saastamoinen, Kristian Melin, Doris Matschegg, Hanna Pihkola, Drivers and barriers in retrofitting pulp and paper industry with bioenergy for more efficient production of liquid, solid and gaseous biofuels: A review, Biomass and Bioenergy, Volume 148, 2021,106036, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2021.106036. (https://www.sciencedirect.com/science/article/pii/S0961953421000738)

Biomass and Bioenergy 148 (2021) 106036

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe



Drivers and barriers in retrofitting pulp and paper industry with bioenergy for more efficient production of liquid, solid and gaseous biofuels: A review

Elina Mäki [a,*], Heidi Saastamoinen [a], Kristian Melin [a,c], Doris Matschegg [b], Hanna Pihkola [a]

[a] VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, FI-02044, VTT, Finland
[b] BEST - Bioenergy and Sustainable Technologies GmbH, Inffeldgasse 21b, A-8010, Graz, Austria
[c] LUT University, Mukkulankatu 19, 15210, Lahti, Finland

ARTICLE INFO

Keywords:
Bioenergy
Advanced biofuels
Retrofit
Pulp and paper industry
Renewable energy

ABSTRACT

Ample interest for more efficient utilization of bio-based residues has emerged in the Nordic pulp and paper (P&P) industry, which uses virgin wood as feedstock. Although different bioenergy retrofit technologies for production of liquid, solid, and gaseous bioenergy products have been applied in the existing P&P mills, the number of installations remains small. The lack of profound knowledge of existing bioenergy retrofits hinders the replication and market uptake of potential technologies. This review synthesises the existing knowledge of European installations and identifies the key drivers and barriers for implementation to foster the market uptake of potential technologies. The bioenergy retrofits were reviewed in terms of technical maturity, drivers, barriers and market potential. Based on this evaluation, common drivers and barriers towards wider market uptake were outlined from political, economic, social, technical, environmental, and legal perspective. Technologies already commercially applied include anaerobic fermentation of sludge, bark gasification, tall oil diesel and bioethanol production, whereas lignin extraction, biomethanol production, hydrothermal liquefaction and hydrothermal carbonization are being demonstrated or first applications are under construction. The findings of this review show that a stable flow of residues at P&P mills creates a solid base for retrofitting. New innovative bio-based products would allow widening the companies' product portfolios and creating new businesses. Also, European Union's (EU) legislation drives towards advanced biofuels production. Wider uptake of the retrofitting technologies requires overcoming the barriers related to uncertainty of economic feasibility and unestablished markets for new products rather than technical immaturity.

1. Introduction

Since the establishment of pulp and paper industry in the Nordic countries in 19th century, it has had a significant impact on countries' incomes, employment and energy consumption and production. For example in Finland, almost 70% of renewable energy is generated within the forest industry [1] and its share of manufacturing industry employment in 2017 was over 20% [2]. In addition to traditional P&P business, the industry has shown ample interest in developing and producing new high-value products, such as biofuels, bio-composites and bio-based plastics, and revising their business models, which could lead to additional revenue streams from diversified product portfolio and enhanced competitiveness [3–5]. P&P industry experts have predicted that energy and material efficiency, sustainability, as well as new innovations in processes and products that meet both regulatory requirements and changing customer needs are the main drivers for sector's competitiveness in 2030 [6]. At the same time, climate change mitigation increases the demand for energy, fuels and products from renewable sources, while the role of forests as carbon sinks is getting more important and may limit the direct use of virgin wood.

P&P industry has always been tightly coupled with bioenergy due to its consumption of wood as feedstock, although paper and board recycling rate has been increasing [7]. It is a large energy consumer with annual consumption of 373.9 TWh (1346 PJ) in Europe and today, over half of which is supplied by bioenergy [7]. Many pulp mills especially in Northern Europe are already free (such as Äänekoski bioproduct mill, Finland [8]) or close to free from fossil fuels consumption thanks to bioenergy. In addition, the mills are even producing heat and power for external use, for example in Finland, waste liquor from forest industry

---

* Corresponding author.

E-mail addresses: Elina.Maki@vtt.fi (E. Mäki), Heidi.Saastamoinen@vtt.fi (H. Saastamoinen), Kristian.Melin@lut.fi (K. Melin), Doris.Matschegg@best-research.eu (D. Matschegg), Hanna.Pihkola@vtt.fi (H. Pihkola).

https://doi.org/10.1016/j.biombioe.2021.106036
Received 15 May 2020; Received in revised form 26 February 2021; Accepted 28 February 2021

Nomenclature

ADt	Air dry ton
CEPI	The Confederation of European Paper industries
CFB	Circulating fluidized bed
COD	Chemical oxygen demand
CO_2	Carbon dioxide
CTO	Crude tall oil
DME	Dimethyl ether
EBC	European Biochar Certificate
EGSB	Expanded granular sludge bed
ENPAC	Energy price and carbon balances scenarios tool
EoW	End-of-Waste criteria
ETBE	Ethyl tert-butyl ether
ETD	Energy Taxation Directive
ETS	Emissions trading system
EU	European Union
FT	Fischer-Tropsch
GHG	Greenhouse gas
HTC	Hydrothermal carbonization
HTL	Hydrothermal liquefaction
HVO	Hydrotreated Vegetable Oil
IC	Internal circulation
ILUC	Indirect land use change
IRENA	International Renewable Energy Agency
ISCC	International Sustainability and Carbon Certification
LBG	Liquefied biogas
MTBE	Methyl tert-butyl ether
NECP	National Energy and Climate Plan
NPE	Non-process element
PESTEL	Political, economic, social, technical, environmental and legal
P&P	Pulp and paper
RSB	Roundtable on Sustainable Biomaterials
TRL	Technology readiness level
UASB	Upflow anaerobic sludge blanket
WAS	Waste activated sludge
WWTP	Wastewater treatment plant

accounted for 12% (46 TWh) of the total national energy consumption in 2018 [9]. Still, the mills may produce excess heat that cannot be exploited especially if the site is located in remote district. Exploiting the residues partly for higher-value products instead of energy production can, thus, increase the overall resource-efficiency. The sector development includes increase in energy efficiency and also transition from integrated P&P mills to separate sites and, thus, the energy requirements in the pulp mill sites are lower than before. While approximately 45% of the raw wood can be converted to pulp, the remaining share creates potential to increase the sector's resource-efficiency [10].

In this review, bioenergy retrofits are defined as technical measures applied to existing production plants that support bioenergy utilization as an alternative to fossil energy as in Ref. [11]. The definition includes 1) using additional biomass as an input to the production plant, 2) and producing additional output from biomass at the production plant. The review covers the retrofits that produce outputs that can be sold to external markets as transport fuels or intermediate bioenergy carriers, and is limited to the ones already implemented in the P&P sector. Anyhow, the possibilities for on-site process energy use of the products will be discussed as well in the context of close to energy self-sufficient Nordic pulp mills, while import energy dependent recycling mills are excluded from the scope. Depending on the pulping process, several different residues are potentially exploitable, such as primary and secondary sludge, bark, black and brown liquor, lignin, and tall oil [12].

P&P mills are in favourable position to be evolved into so called forest biorefineries and there is need for such development [4]. P&P mills with bioenergy retrofits fulfil the definition of biorefinery, which refers to delivery of wide variety of products, including chemicals, materials, fuels and energy, from biomass feedstock [13]. Borregaard, where bioethanol retrofit takes place, has successfully followed biorefinery based strategy already for decades [14]. However, cost-efficiency remains a challenge for further deployment of biorefineries [13,14]. Different technical options for bioenergy retrofitting have been reported in literature. Identification and quantification of available residues, as done by Hassan et al. [12] for Finnish forest industry, reveals the theoretical potential. In Kumar & Christopher [4], value-added products originating from residue streams from different dissolving pulp processes were identified. Different valorisation options for P&P mills' waste are stated to reduce waste volume, produce energy and products, and reduce contaminants in waste [15]. One of the widely studied bioenergy retrofit concepts is valorisation of P&P mills' sludge, especially for biogas production [16,17]. Since lime kiln is typically the only part in pulping process consuming fossil fuels, technologies and resources for replacing fossil fuel consumption and consequently cutting related carbon dioxide (CO_2) emissions have been assessed in Kuparinen & Vakkilainen [18]. The covered resources included producer gas, torrefied biomass, lignin and pulverized wood. However, though some technical retrofitting measures for P&P sector are well-documented, the literature shows that a comprehensive review of bioenergy retrofitting options is currently lacking. Lack of structured knowledge regarding the effects of the retrofits on the main pulp and paper making process, related drivers and barriers, and market potential hinders their wider market uptake.

This review gathers together and elaborates the information of existing bioenergy retrofits to aid the P&P sector to realise the potential in retrofitting and to facilitate the introduction of less familiar retrofits. The retrofitting options fundamentally rely on using the residues available at the mills more efficiently, which aspect has seldom been considered in literature. Furthermore, the site specific possibilities for implementing certain retrofitting technologies have not been assessed. This review also creates understanding about relations between different retrofit options, which is important since different retrofits may compete of the same residue stream and implementation of a certain retrofit may prevent implementing other retrofits. Since EU legislation drives towards production of advanced biofuels [19,20], this review mainly focuses on those, but includes also bioenergy products for other end-uses, such as on-site use. Studied retrofitting technologies were selected based on those identified in the EU BIOFIT project [21] in Europe and those discovered in a more extensive search. The identified retrofits are bioethanol production, black liquor gasification, lignin extraction, tall oil diesel production, hydrothermal carbonization, hydrothermal liquefaction, bark gasification, and anaerobic fermentation of sludge.

This paper presents different theoretical options to retrofit P&P mills with bioenergy and considers existing retrofits in terms of technical maturity, drivers, barriers and market potential based on a comprehensive literature review. Based on technology-specific findings, common drivers and barriers towards wider market uptake of different retrofits are outlined from political, economic, social, technical, environmental and legal perspective.

2. Material and methods

This paper represents a review, which collects and elaborates information of existing bioenergy retrofits in P&P industry in Europe in order to increase the knowledge of retrofitting possibilities and to unlock their implementation potential. Retrofitting measures, as defined in Ref. [11], implemented after the initial investment in P&P mills were taken into account as retrofits, while similar measures implemented already at the first place were not considered as retrofits. Studied retrofit technologies are summarized in Table 1. All the retrofit cases, which we identified from the publicly available information sources, were covered. Retrofits identified in the EU BIOFIT project [21] were used as a starting point, and a more extensive search resulted in identification of more retrofits. Retrofits were searched with different search engines, including Google, Scopus and ScienceDirect, with headwords 'pulp and paper', 'pulp mill', 'paper mill', or 'pulp and paper industry', combined with 'retrofit' or 'investment'. In addition, technology specific headwords, such as 'bark gasification' and 'hydrothermal carbonization' were used. The searches were made mainly in English, but also Finnish and Swedish were used for technology specific searches. Retrofits were identified from scientific publications, press releases and technical reports. Detailed information of the identified retrofit installations was obtained from public sources, such as environmental permits. The construction year of the retrofit was not limited in the search. The first identified retrofit was implemented in 1987, while other retrofits have been taken in use in 21st century or are currently under construction. The authors acknowledge that there might be other older retrofits, which may not be that well documented in publicly available sources. Scientific literature from high-quality journals was used to top up the knowledge of retrofits, especially regarding less mature technologies and future potential. Mostly recent publication from 2010 to 2020 were used. Also older publications from the beginning of 21st century were considered when relevant.

The review (Section 3) covers existing retrofit cases, drivers and barriers for market uptake, and market potential. Both internal (e.g. directly related to technical, economic and environmental aspects) and external (e.g. market and policy conditions affecting retrofitting) factors were taken into account in identification of drivers and barriers. Since retrofits are still low in number, all existing cases identified are explicitly summarized in Table 2. The selection criteria to compile the list of retrofits include that the retrofit is implemented or in the planning or construction phase, and the retrofit produces bio-based output that can be sold to the external markets as transport fuel or intermediate bioenergy carrier, or used on-site. Consequently, most of the identified retrofits locate in Northern Europe, whereas retrofits in the paper mills using recycled raw material are not in the scope of this review. The identified retrofits were classified according to retrofitting technology, and P&P process the technologies are usable for, namely sulphite pulping, sulphate/Kraft pulping, all pulp mills, and all P&P mills. Technological maturity (TRL) estimated by the authors is presented for all retrofits, while investment cost and environmental benefit (CO_2 reduction) announced by the company are presented if such data was publicly available.

Based on the literature review and existing cases, common political, economic, social, technical, environmental and legal drivers and barriers for deployment of different bioenergy retrofits were derived (Section 4). These results applicable for different bioenergy retrofits in general are summarized according to PESTEL framework in Table 3.

3. Options in retrofitting pulp and paper industries and their market perspectives

The P&P sector used 197.4 TWh (710.5 PJ) biomass in 2017, which is 59.8% of total fuels consumption and 52.8% of total primary energy consumption [7]. The use of bioenergy and its share of the fuels and total primary energy consumption have increased over years. Fossil fuels account for 38.7% of total fuels consumption in P&P industry [7]. In Nordic countries, where virgin wood is the main raw material for pulping process, the biomass share is much higher, while fossil fuels consumption is close to zero.

In Europe, there exists 151 pulp mills and 746 paper mills (2018), which produce annually 38.3 million tons of pulp and 92.2 million tons of paper [7]. Majority of the pulp production in Europe, 72.7%, relies on chemical pulping processes (Fig. 1), of which sulphate pulping, also known as Kraft pulping is the favoured option with total annual production of 26.2 million tons and market share of 68.4% in Europe (CEPI countries) (2018). Globally, Kraft pulping is estimated to account for more than 90% of the pulp production [22]. Sulphite pulp production accounted for 4.4% of the total European pulp production in 2018, which means 1,678,000 tons of pulp [7]. The trend of sulphite pulp production has been decreasing. The largest pulp producers in Europe are Sweden (31.2%) and Finland (30.2%) [7]. Europe represents 25.3% of global pulp production [7].

Bioenergy retrofits in P&P industry can be divided in two main groups in terms of their purpose: 1) replacing fossil fuels consumption with bioenergy for energy production on-site (see Fig. 2) and 2) producing new renewable fuels or boosting existing production from process residues (see Figs. 3 and 4). This review focuses on the P&P mills with access to the virgin wood resources and thus, considers mainly different options in the latter retrofit group, but gives examples also of the first group. The key performance indicator for the first group is reduction in CO_2 emissions, while in the second group, there are several indicators depending on the case, such as CO_2 emissions reduction and raw material efficiency. In general, retrofitting means often lower

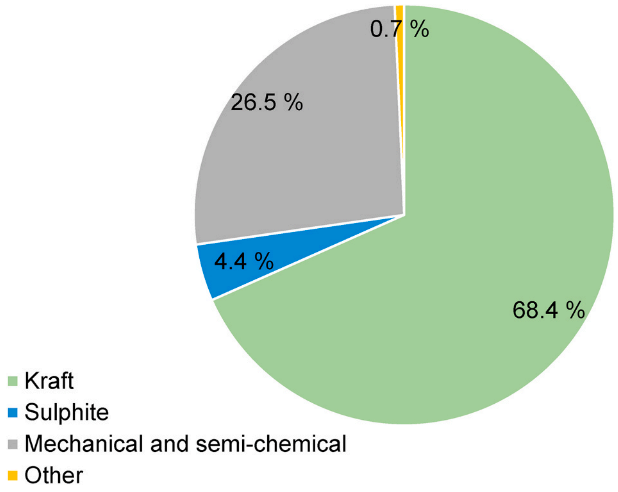


Fig. 1. The share of pulp produced by different pulping processes in 2018 in Europe (CEPI countries); data retrieved from Ref. [7].

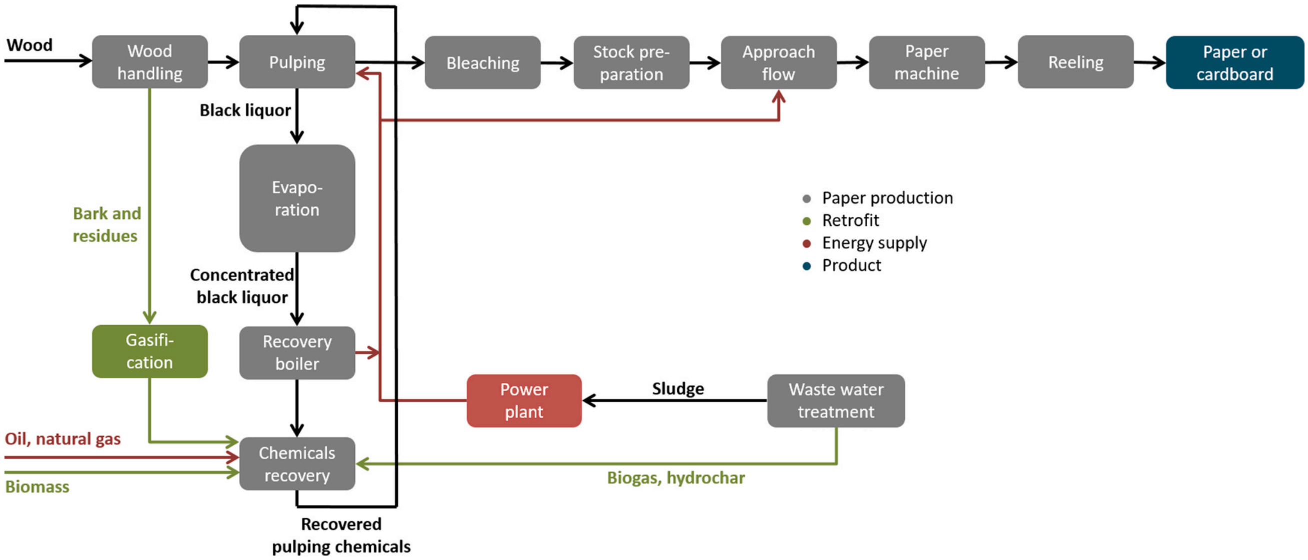


Fig. 2. Retrofits for energy supply in pulping process.

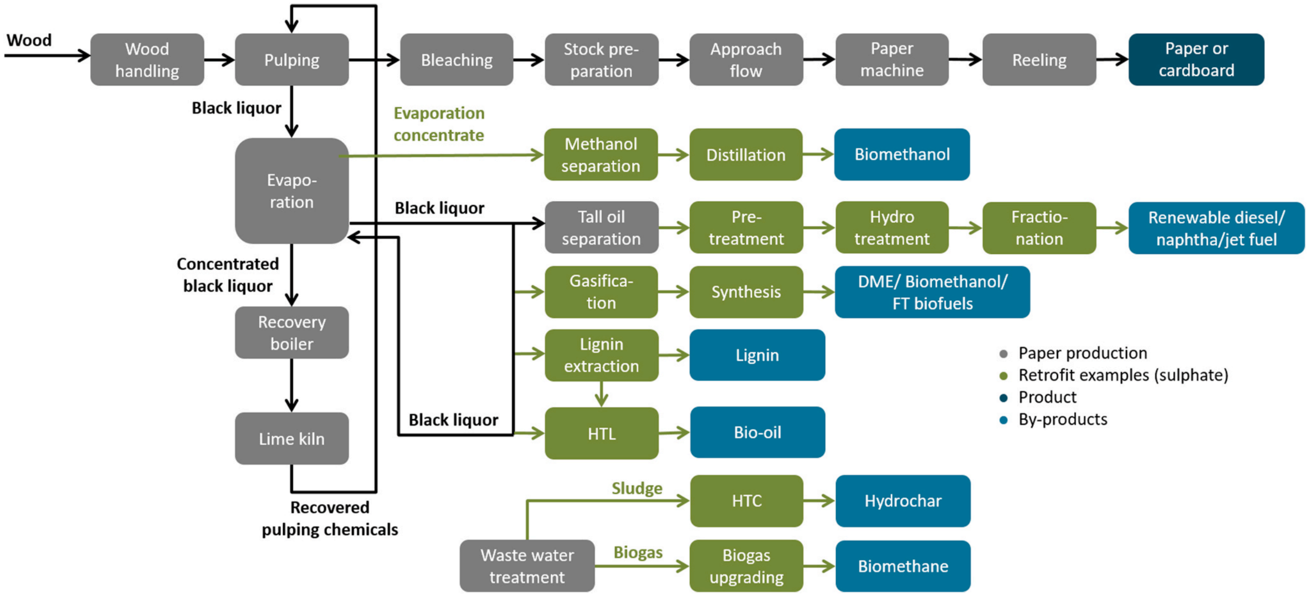


Fig. 3. Retrofits for Kraft/sulphate pulping process.

capital costs, shorter lead times, faster implementation, less production time losses and lower risks [23]. The retrofitting possibilities vary between pulping process, i.e. sulphate/Kraft pulping and sulphite pulping. In addition, the magnitude of exploitable residues depends on the magnitude of the pulp production as well as on the utilized residue. Black liquor, bark, and sludge are by far the largest exploitable residue streams as shown in Table 1.

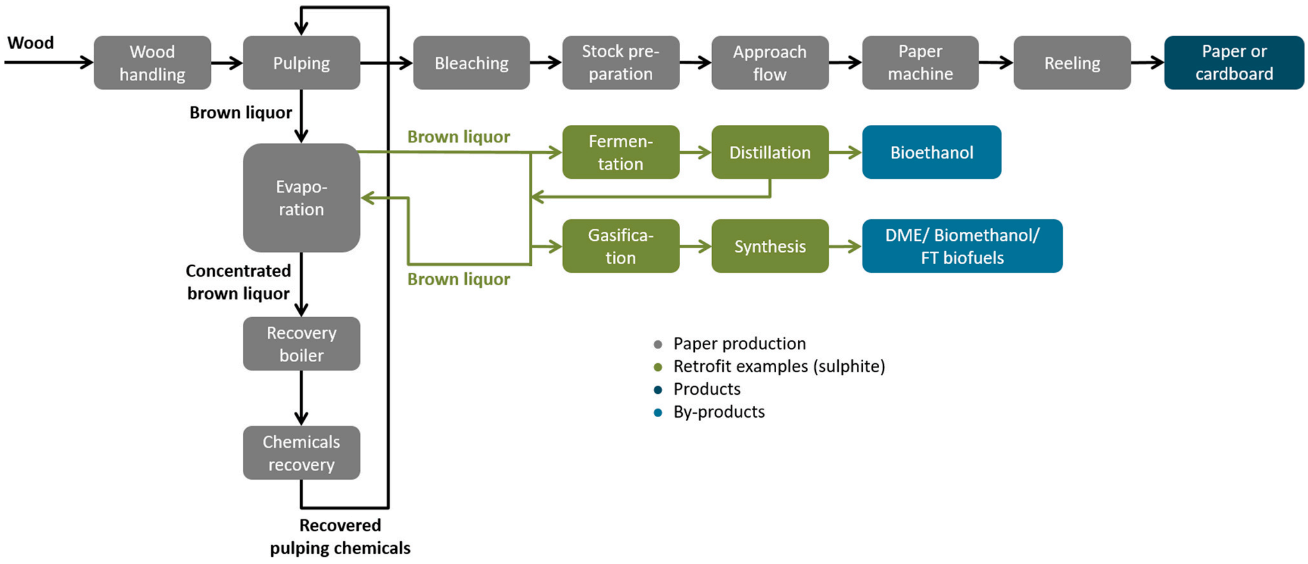


Fig. 4. Retrofits for sulphite pulping process.

Table 1
Summary of different residues available for bioenergy retrofits in P&P industry.

Residue	Yield	Retrofit technology	Applicable process for retrofit
Bioethanol	50 L/ton DS (spruce) [24]	Bioethanol production from brown liquor	Sulphite pulping
Biomethanol	10–15 kg of raw methanol per ADt pulp [25]	Raw methanol purification	Kraft pulping
Lignin	340–510 kg/ADt Kraft pulp [26]	Kraft lignin extraction from black liquor, Hydrothermal liquefaction (HTL) of lignin	Kraft pulping
Tall oil	20–50 kg/ADt pulp [27]	Renewable diesel production from tall oil	Kraft pulping
Black liquor	1.7–1.8 t dry black liquor/ADt pulp [28]	Black liquor gasification to DME/biomethanol/Fischer-Tropsch (FT) biofuels, Hydrothermal liquefaction (HTL) of black liquor	Kraft pulping
Bark	10% of round wood volume [29]	Bark gasification	All pulp mills
Sludge	0.25–0.30 kgTSS/kgCOD_{red} [30]	Anaerobic fermentation, hydrothermal carbonization (HTC) of sludge	All P&P mills

3.1. *Bioethanol production from brown liquor*

In acidic sulphite pulping process, hemicellulose dissolves into simple fermentable monomers during the cooking phase. Since cellulose is used in the pulp production, costly enzymatic hydrolysis step is not needed. The monomeric sugars in brown liquor can be fermented to bioethanol by yeast. In addition, unfermented sugars remaining after bioethanol production can be treated by anaerobic fermentation to produce biogas.

Bioethanol production is either on-going or planned at three of the European sulphite pulp mills (Domsjö, Sweden; Borregaard, Norway; AustroCel, Austria). At Domsjö, bioethanol has been produced since 1940 as by-product of the specialty cellulose production; at first for chemicals production. Since 2010, bioethanol production at the plant has almost doubled. Today, the produced bioethanol is sold to SEKAB Biofuels & Chemicals AB, a Swedish chemical and cleantech company, for further refining and used both for chemicals and as biofuel [31].

At Borregaard, bioethanol has been produced since 1938 as a side product of cooking spruce chips with acidic calcium biosulphite cooking liquor [31]. In 2018, the bioethanol plant was rebuild to guarantee the quality of the product and to store and capture more biogas for internal use [32]. Today, Borregaard is the world's largest 2nd generation bioethanol manufacturer with the capacity of 20,000 million litres per year and delivers bioethanol to Statoil to be mixed with conventional fuels [33].

AustroCel is building a plant for advanced bioethanol production with an investment volume of about 42 million euros [34]. The plant is scheduled to go into operation at the end of 2020. AustroCel processes spruce and dissolves pulp for cellulose applications. The resulting sugar will be distilled and subsequently fermented to bioethanol. The planned capacity of 30 million litres per year will be sold to OMV, an Austrian multinational integrated oil and gas company and the only Austrian fossil refinery, in order to substitute about 1% of the Austrian petrol consumption [34].

According to IRENA [35], the production costs of conventional starch and sugar crops based bioethanol are dominated by feedstock costs and the feedstock supply competes with food production. When brown liquor is used for bioethanol production, the feedstock does not compete with food production and is readily available at the mill. However, the scale of production is limited by the volume of the residue stream. Bioethanol production from hemicellulose sugars also require less pre-treatment than virgin feedstock.

Fore-mentioned mills account for more than 30% of the total sulphite pulp production in Europe, which indicates that introduction of this specific retrofit within the pulping industry cannot become widespread. The estimated total bioethanol production from the three mills is 67 million litres per year. In comparison, the total renewable ethanol production in Europe accounted for 5.81 billion litres in 2018 [36].

According to Ref. [37], the bioethanol price of 650 €/m^3 represents an estimated European biofuels selling price including policy support in 2020 as given by the scenario tool ENPAC. In Gregg et al. [31], it is stated that in forestry based industry, the cellulosic ethanol production is motivated by diversification of the product portfolio, which also attracts public R&D support. In addition to bioethanol production, hemicellulose sugars can be used for more valuable products (e.g. bio-chemicals), and thus, the bioenergy product market competes with alternative product markets using bioethanol.

Gasoline sold in Europe is typically blended with ethanol; E5 petrol that is generally the default option at refilling stations contains up to 5% ethanol. According to Refs. [38,39], E10 petrol that can be used by 90% of the petrol driven car fleet is available in five European countries, where its share in petrol sales varied from 12.3% to 63% in 2016. Development towards E20 compatible vehicles and E20 standard is on-going. Although it was forecasted that the biogasoline (including bioethanol) consumption would more than double during 2010's, the actual uptake has been quite stable being 2640 ktoe in 2016 [36]. Bioethanol-to-jet fuel production is also under development [40].

3.2. Raw methanol purification and black liquor gasification to DME

Methanol (CH_3OH) is one of the most traded bulk chemical and chemical intermediates worldwide, but it is also used in engine fuel applications [41]. In the Kraft pulping process methanol condenses to foul condensate during the evaporation stage of chemical recovery. Valmet [25] estimates that a typical Kraft pulp mill produces 10–15 kg of methanol per ton of air dry pulp (ADt). The foul condensate contains many impurities. It is often considered as waste stream to be disposed either with effluent treatment system or by incineration, but can be liquefied to transportation fuel if its nitrogen and sulphur content is reduced. Technologies for methanol purification have been developed, e.g. by Valmet [25], Fpinnovations [42] and Invico Metanol [43]. These technologies are not commonly in use, although the production route is simple compared to e.g. production through gasification or with power-to-methane process.

Although methanol condensate is commonly disposed at the pulp mill by combusting it either in recovery boiler or in lime kiln, raw methanol is seldom purified to fulfil the standard for transportation fuel additive. Some pulp mills instead buy pure biomethanol to be used in producing chlorine dioxide, which is used as a bleaching chemical. Swedish company Södra is investing to a biomethanol plant that will produce annually 5000 tons biomethanol to markets [44].

Furthermore, DME can be produced either through methanol dehydration in the presence of a catalyst, or through direct synthesis using a dual-catalyst system, which allows both methanol synthesis and dehydration to take place in the same process [45]. Chemrec demonstrated a black liquor-to-fuels plant in Luleå in 2005–2011 [45]. The plant was a combination of black liquor gasification plant by Chemrec and Haldor-Thopsoe's syngas to biomethanol and DME technology. For the Chemrec's 100 MW output biomethanol plant, specific investment of 3450 €/kW is given [46].

Global methanol production capacity in 2018 was 140 million tons and it is expected to double by 2030 [47]. Methanol can be blended to gasoline, but blending is restricted to 3 vol-% by Directive 2009/30/EC [48] according to standard EN 228:2018. Methanol can be used as gasoline additive by converting it to methyl tert-butyl ether (MTBE) and diesel additive by converting it to DME [49]. In 2016, 22.12% of produced methanol was used for gasoline production globally [50]. Today, fossil methanol is typically produced via catalytic conversion of pressurised synthesis gas, which is derived from natural gas [51]. According to Methanol Institute [51], global demand for methanol to gasoline production was 11.6 million tons, for biodiesel production 1.2 million tons and for DME 5.0 million tons in 2015. They estimate that potential demand for fore mentioned uses would be 75–105 million tons.

Due to high production costs of biomethanol and low market price for renewable methanol, profitability is not easily achieved when retrofitting pulping process. According to Bergins et al. [52], profitability can be reached if production costs are 50% below price for the product. In Bergins et al. [52], it is estimated that nominal market prices for methanol energy vary from 60 to 110 €/MWh; price of methanol derived from natural gas or coal being 60–80 €/MWh and renewable methanol between 90 and 110 €/MWh. Production costs heavily depend on feedstock price. In Maniatis et al. [46], it is concluded that methanol and DME from waste and biomass via gasification have production cost of 60–80 €/MWh and it is summarized that production prices of methanol from wood depend on feedstock price being 71–91 €/MWh for 20 €/MWh feedstock price and 56–75 €/MWh for 10–15 €/MWh feedstock price. It is furthermore estimated in Maniatis et al. [46] that methanol production via black liquor gasification in an average sized pulp mill would altogether cost 69 €/MWh including capital, feedstock, auxiliary power and operation and maintenance costs.

3.3. Kraft lignin extraction from black liquor

During the Kraft pulping process, lignin in wood chips degrades and dissolves in cooking liquor [53]. Traditionally dissolved lignin, approximately 98%, has been combusted along with black liquor in the recovery boiler to produce heat and power [54,55]. Another option is to extract it from black liquor, which enables decreasing the recovery boiler load, which can be a bottleneck for pulp production capacity increase. According to Valmet [56], removal of 25% of lignin can enable 20–25% increase in pulp production. Extracted lignin is an easily transportable energy carrier and can be used as a feedstock for multiple purposes such as binders, adhesives, coatings and bioplastics, but also processed to bioenergy products (e.g. gasified with Fischer-Tropsch method to renewable diesel or used directly as a fuel in the lime kiln or power production) [57].

Lignosulfonates i.e. water soluble sulphonated lignin by-product from sulphite pulping dominate the lignin market with over 90% market share (1.8 Mt/a) [55,58]. However, since separation of lignosulfonates from sulphite spent liquor can be considered as business-as-usual technology, used for example at Borregaard and Domsjö, it is not considered as bioenergy retrofit. Several processes have been introduced for unmodified Kraft lignin extraction from black liquor, such as Valmet's LignoBoost [57] and FPInnovations' LignoForce System™ [53]. These can be considered as bioenergy retrofits and are an attractive pathway towards added-value products due to high market share of Kraft pulp. At existing lignin recovery plants, lignin is sold to external markets.

In Valmet's LignoBoost process, lignin is precipitated by lowering the pH of black liquor stream separated from the evaporation process, which decreases solubility of lignin [18,59]. Two commercial plants have been supplied [56]. The first full-scale plant was started in 2013 at Domtar's Plymouth, North Carolina mill, which is producing 466,000 ADMT of softwood Kraft pulp annually. The lignin plant has capacity of 25,000 t/a and it was established to reduce recovery boiler load [60]. Initially, the idea was to use produced lignin for own energy, but the BioChoice™ lignin is sold to external markets [60]. Another commercial plant has been running at Stora Enso's Sunila mill, Finland since 2015. Sunila mill has the annual capacity of 270,000 ADMT of softwood Kraft pulp and 50,000 tons of lignin is extracted from the process [61]. Lignin is used in the mill's lime kiln to replace 90% of the natural gas consumption and sold to external markets as Lineo™ [61]. Valmet demonstrates LignoBoost process at Bäckhammar, Sweden, in which 8000 tons of lignin is produced annually [62].

In FPInnovations' LignoForce™ process, oxidisation of filtered black liquor is applied to prevent release of H_2S and mercaptans later in lignin extraction and to reduce the amount of acidifying agents needed [63]. LignoForce™ commercial demonstration plant was constructed to West Fraser pulp mill in Hinton, Alberta, Canada in 2014 [64]. The capacity of the plant is 30 tons of lignin per day [63]. Produced lignin is used to displace petrochemical equivalents [65].

Analysis of replacing lime kiln fuel with renewable alternatives at a mill producing 4286 ADt of pulp per day, presented in Kuparinen [66], shows that enough lignin can be produced on-site to cover fuel demand of the lime kiln, while consumption of electricity due to lignin extraction (1.2 MW_e) is significantly smaller compared to producing biogas (5.2 MW_e), pulverized fuel (7.0 MW_e) or torrefied biomass (5.3 MW_e), and significant CO_2 emission savings (172,000 tCO_2/a) can be obtained.

Drawback is that sellable power is reduced due to decreased amount of organics in recovery boiler.

Lignin has not been widely utilized in industrial scale due to challenges related to lignin's unique chemical reactivity, the presence of various organic and inorganic impurities and a non-uniform structure [55]. Lignin sulphur content is one of the properties affecting its usability for value-added products. Most of the sulphur containing lignin originate from P&P industry (Kraft lignin: 0.7–3.0%, sulphite lignin: 3.5–8.0%) [55]. Exact information about the effects of lignin extraction for the remaining processes, such as sodium and sulphur balance (Na/S balance), in not available due to low number of existing retrofits. In the case of Sunila, Finland it is estimated that chemical consumption will increase as well as sulphur dioxide and nitrogen emissions from lime kiln [67]. On the contrary, emission control of the recovery boiler becomes easier and nitrogen emissions decrease, while sulphur dioxide emissions might increase [67]. Sulphuric acid is added during the washing operations in Lignoboost process to minimise sodium content in the lignin product [59]. Consequently, recovery boiler dust needs to be removed to maintain Na/S balance and more sodium make-up is needed due to lost Na [59].

Lignosulfonates dominate the lignin markets due to growing demand from the building and construction industry [68]. However, the largest potential in terms of volume is in Kraft pulping [68]. During the last decade, interest in value-added lignin-derived products has increased due to ageing P&P mills seeking wider product portfolios and increasing demand for high quality concrete admixtures and dispersants [55]. Many of the high added-value industrial applications identified for lignin remain within R&D phase, which hinders the evolvement of the lignin market. In 2016, there was no market price for lignin according to Pöyry [69]. In Barret [70], it is estimated that lignin price was between 650 €/t to 1000 €/t, but high-purity lignin-based products can reach prices up to 6500 €/t. According to Bajwa et al. [55], the price of lignin obtained from Kraft pulping process is 260–500 USD/t. It is stated in Raunio [61] that Pöyry forecasts rapid growth in production potential of Kraft lignin, the production being 1.7 million tons in 2025. In Miller & Faleiros [71], RISI's lignin production base case forecast for 2025 is 250,000 tons and optimistic forecast 2.5 million tons. Global lignin market is dominated by North America followed by Europe, where also rapid growth is expected [68].

3.4. Renewable diesel and naphtha production from tall oil

Crude tall oil (CTO) is a residue from Kraft pulping process and obtained in separation of the crude sulphate soap from the black liquor after Kraft pulp cooking. The soap is acidified in order to separate out the CTO. The CTO can further undergo purification, hydrogenation treatment and fractionation based on different boiling points. Tall oil is an attractive feedstock for biofuels production due to its low oxygen content. Thus, it requires less treatment compared to other feedstock. The yield of CTO is 20–50 kg per ton of pulp [27].

UPM and SunPine are the only users of CTO for renewable diesel production. UPM's Biorefinery [72] in Lappeenranta, Finland, located at the same site with the existing P&P mills, produces renewable wood-based BioVerno diesel and naphtha. Naphtha can be used either for gasoline or as a renewable alternative for fossil raw materials in plastics and other chemical industry products. Tall oil production in the adjacent pulp mill does not cover the whole feedstock demand, and tall oil is imported from other mills. The capacity of the facility is 120 million litres (100,000 tons) of renewable diesel and naphtha per year. As an advanced biofuel, BioVerno does not have a blending limit like first generation biofuels do.

SunPine [73] in Northern Sweden esterifies tall oil to methyl ester and the product is further converted into transportation fuels at the Preem's refinery in Sweden. In the same process, also bio-oil, turpentine, rosin and district heating are produced [74]. The current renewable diesel production capacity is 100 million litres (approximately 83,000 tons), and will be further increased by 50% by 2020 [75]. In addition, another biorefinery is planned in Sweden by St1 and SCA. The refinery is planned to utilize tall oil from SCA's pulp mills and to supply 100,000 t/a advanced renewable fuels [76].

Key driver for tall oil diesel production are added-value for the mill compared to CTO and the regulatory framework for the transport sector. EU legislation classifies CTO as a residue, which leads to its double counting towards renewable energy targets in transport sector and thus supports its utilization for renewable diesel production over other end-uses. CTO is also shown to be a low-ILUC risk feedstock [77]. Tall oil diesel has higher quality (e.g. low aromatic content and high cetane number) compared to regular diesel fuel and first generation ester-type diesel fuel [27]. Existing infrastructure and standards for hydrotreated vegetable oil (HVO) support the deployment of tall oil diesel. In Europe, market floor price is determined by heavy fuel oil price and EU ETS price for avoided tCO_2, and topped with market value of distilled products [77]. While the global CTO demand for traditional uses has dropped due to decreasing fuel oil prices, the demand for biorefining has increased in recent years, accounting for 230,000 tons [77]. It is estimated in Peters & Stojcheva [77] that global excess CTO potential is 850,000 tons, but only 250,000 tons if distillers run at full capacity. Thus, the global excess potential equals from 1.1 up to 3.7 the current CTO demand for biorefining. Scandinavia is already a net importer of CTO, mainly from US but a minor amount is imported from Russia. [77] Tall oil pitch that is heavy residue from distillation of tall oil can also serve as feedstock for biofuels production having less other uses in chemical industry.

CTO production is shown to be feasible on-site at pulp mills, whereas it is hard to find a business case as a stand-alone off-site plant [77]. Economic production also requires a sufficiently large feedstock [78]. Risks in tall oil diesel production include feedstock availability in limited quantities, dependency of chemical softwood pulping markets and potential competition as feedstock for more valuable chemicals. Due to the limited availability of the resource, the replicability potential of SunPine's and UPM's solutions is low at local and regional level, but higher at international level [79]. According to analysis by Fraunhofer Umsicht [80], chemicals from CTO available in EU generate four times higher economic added value compared to biodiesel. Large investments in tall oil diesel production in Finland and Sweden might be hindered by needs for increasing CTO imports. It is foreseen by Fraunhofer Umsicht [80] that competition for the same feedstock between chemical and fuel sector will raise the price of the feedstock.

CTO is a globally traded material, and its monetary value is estimated to be 2–4.4% of the value of pulp [77]. According to Peters & Stojcheva [77], its global potential is relatively small at 2.6 million tons and dictated by available crude sulphate soap from chemical softwood (pine) pulping, which limits its main potential to North America, Scandinavia and Russia. The potential is expected to increase in the future following the expected increase in softwood pulping capacity. In Scandinavia, capacity addition of 80,000 tons is expected [77]. Currently, the demand and supply of CTO is about 1.75 million tons, while estimates vary from 1.6 to 2.0 million tons [77]. CTO demand is dominated by chemical sector and the majority of CTO, 1.4 million tons, is used in a traditional way by distilling variety of products [77]. In Europe, the majority of the pulp mills with CTO production have a CTO facility, while globally the share is less than 50% [77]. It is estimated that the CTO production potential in Europe is 650,000–700,000 tons, leading to global market share of 28%, while 530,000 tons of the potential is located in Scandinavia (Finland and Sweden) [77,80]. SunPine's production equates to 2% of the annual diesel consumption in Sweden [79], while Fraunhofer Umsicht [80] estimates that in the best case CTO potential in EU could supply 0.2% of EU's transport demand.

3.5. Hydrothermal liquefaction of black liquor and lignin

Hydrothermal liquefaction (HTL) process is used to produce bio-oil typically from wet feedstock without drying. The production takes place at 280–400 °C and 250–380 bar and takes up to 30 min [81–83]. According to Gollakota et al. [83], energy efficiency of the HTL process is high as it only consumes 10–15% of the energy in the feedstock biomass and more than 70% of the feedstock carbon content can be captured. The product biocrude can be further refined to biofuels, although the quality of the product is significantly lower compared to fossil crude oil [82]. However, according to Gollakota et al. [83], better quality compared to pyrolysis crude oil can be obtained.

HTL technology is still under demonstration. Two of the demonstrations are related to P&P industry. RenFuel built up a pilot plant at Bäckhammar, Sweden to demonstrate the production of Lignol®, which is lignin transformed into a liquid hydrocarbon-based catalytic lignin oil [84]. To furthermore transform lignin oil into transport fuel, refinery process is needed. Thus, there is a major production plant under construction with Preem and Rottneros in Vallvik, Sweden [85]. Expected launch is in the beginning of 2021. Silva Green fuel is constructing a demonstration plant to test their biofuel production technology to woody residues at Statkraft Tofte site, Norway. The aim is to produce up to 4000 L of biofuel per day during the test period of 2019–2020 [86]. One of the benefits of exploiting HTL in connection with P&P industry is that the aqueous phase can be sent to evaporation in order to remove water and then combusted in the recovery boiler.

3.6. *Bark gasification*

In the pulp mills using virgin wood as feedstock, lime kiln is typically the only part using fossil fuels, mainly natural gas or fuel oil. Pulp mill's residues are often co-combusted in the kiln for disposal purposes, but only a few kilns exist using solely these resources [87]. Hydrogen, producer gas from biomass gasification, torrefied biomass, lignin, and pulverized biomass have been proposed as substitutes for fossil fuels [18]. At Södra Cell's Mönsterås mill, Sweden, two lime kilns are fired with pulverized bark (70%) and tall oil pitch (30%) [88,89].

Bark gasification system is comprised of biomass pre-treatment (drying, chipping, and grinding), gasifier and lime kiln. The existing lime kiln does not have to be replaced when fossil fuel burner is converted to biogas. Both fixed bed and circulating fluidized bed (CFB) gasifiers have been implemented in P&P industry, but most experience is obtained from CFB gasifiers [90]. CFB gasifiers for lime kiln applications are a proven, commercial technology [18,87,90,91]. At the eighties, six CFB gasifiers were installed in Finland, Sweden, Austria and Portugal with capacity varying from 15 to 35 MW_{th} [90,91]. A bark gasifier installed in 1987 in Södra Cell's Värö mill, Sweden, offers over 30 years of experience of retrofitting lime kiln from oil to gasifier gas [92]. In 2008, an air-blown CFB gasifier was built in Varkaus, Finland to replace most of the oil used in a lime kiln [93]. During 2009–2011, the gasifier was operated in the oxygen-steam mode to demonstrate biomass-to-liquids (biodiesel) technology [93]. In Metsä Fibre's mill in Joutseno, Finland, a 48 MW_{th} bark gasifier was installed in 2012 replacing 95% of natural gas use in the lime kiln, reducing the mill's fossil fuel consumption close to zero [94]. Previously, bark generated at the site was sold to a local CHP plant. Today, the gasifier consumes 175, 000 t/a bark [95]. Wet bark is dried from moisture content of 50-60% to 15% and heated to 95 °C by using residual hot water and low-pressure steam from the pulp mill [95]. The gasifier is an atmospheric air-blown CFB gasifier operating at the temperature of 750–800 °C [95].

The main drivers for the investments in lime kiln gasifiers are environmental and economic. Bark is a low-cost fuel, which is often available at pulp mills at high quantities. Low heating value of moist bark decreases its competitiveness against other feedstocks. The utilization of low-cost residue increases the pulp mill's self-sufficiency and reduces the dependency of variation in fossil fuel prices. During 2018–2019, the price of the natural gas for industrial use has varied from 29.5 to 35 €/MWh (with certain assumption affecting the transfer cost) [96]. Though CFB gasifiers are typically used in large scale (60 MW_{th}) [90], the investment in Joutseno shows that a short pay-back period is achievable.

A technical challenge in bark gasification relates to non-uniform composition of feedstock [97]. However, the use of CFB boiler compensates fuel quality variations with turbulent mixing of feedstock [98]. Biofuels pose a higher risk for availability of the lime kiln and white liquor preparation compared to traditional systems. In the case of bark gasification, possible problems in the process are caused by unplanned stops in drying and bed agglomeration in the gasifiers [99]. Alternative biofuels may include non-process elements (NPEs), which can affect the lime quality and chemical recovery process, and accumulate in the closed-cycle process, leading to increased consumption of make-up lime [18]. Biofuels can also cause changes in temperature profile and flame stability in the kiln. However, Wadsborn et al. [99] has shown that using gasified bark does not lead to major changes either in kiln capacity or in lime quality. According to Kuparinen et al. [100], higher flue gas exit temperature compared to natural gas or oil firing results in higher flue gas heat losses and fuel consumption. Gasifier increases the mill's power consumption, mainly through biomass pre-treatment and gasifier air fans [18].

Applicability of bark gasification to all pulp mills creates significant potential for retrofitting. A global survey for pulp mill operators, conducted in 2011 by Francey et al. [87], shows that there are only a few lime kilns burning alternative fuels (and only one kiln burning biogas). However, most of the respondents showed interest in alternative fuels, motivated mainly by lower energy costs and renewable energy use [87]. Bark gasification creates potential for further revenues to mills if the gas would be upgraded and sold to external markets. Potential risk related to investments in bark gasification systems is the increasing market demand for bark for other uses outside the mills.

3.7. *Hydrothermal carbonization of sludge*

In hydrothermal carbonization (HTC), wet lignocellulosic biomass feedstock is converted to stable coal-like product commonly called hydrochar, biochar, biocoal, or HTC-coal. In Reza et al. [101], HTC process is also referred to with names hydrothermal pre-treatment and wet torrefaction. The process is relatively flexible towards the used feedstock and enables exploiting wet low-value feedstock that would otherwise be unexploited or disposed with minimum or negative value. The wastewater treatment sludge from pulping industry that is commonly treated by combustion, composting or digestion forms a possible feedstock for hydrochar production. With HTC, the volume and water content of sludge can be significantly reduced and harmful substances captured into the product. This can be beneficial for the P&P mills, but it can also hamper some of the possible end-uses for the product. This depends on the product composition, which again depends on the feedstock. The end-product is stable for transport and storage. Apart from using the hydrochar as a solid fuel in energy production [101–103], its use e.g. as fertilizer/soil amendment [101,104,105] has been studied.

The HTC process is implemented first time to P&P mill at Stora Enso Heinola fluting mill in Finland to process wastewater treatment sludge [106]. C-Green Technology AB's patented OxyPower HTC process is exploited. The product will be used at the mill for energy production to replace fossil fuels. The plant has capacity to process 20,000 tons of wet biosludge per day [106]. The aim in Heinola is to demonstrate the new process and production of hydrochar for the needs of the forest industry. The effect of the raw material to the end product composition will be analysed in order to produce necessary data for productising hydrochar from pulping industry. HTC process is self-sufficient in heat, since heat is generated in the oxidation of the HTC effluent. In addition, biogas can be produced from the liquid effluent.

Hydrochar can be used as a solid fuel in several industries, for example to replace fossil fuels in combustion and gasification processes. However, the hydrochar produced from P&P wastewater treatment sludge is still declared as waste and End-of-Waste procedure is required

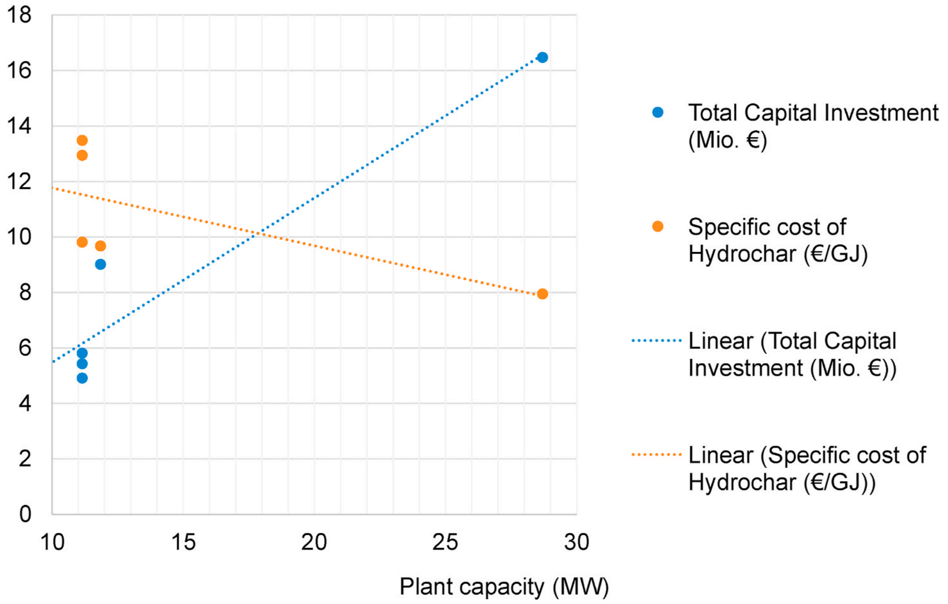


Fig. 5. Capital costs of HTC plant and specific cost of hydrochar according to Refs. [108,109].

to productise it. Long-term tests within the industry are still needed to evaluate the environmental impacts of the production and characteristics of the product. Without standardisation the hydrochar from pulping industry might not reach markets.

Studies related to renewable energy production using hydrochar are only few [78,79], and none of them is directly related to hydrochar originating from P&P industry. It has been observed in Liu et al. [102] that introduction of hydrochar is beneficial to co-combustion efficiency of lignite, although differences between hydrochars from different origins were observed. It is also found that by co-firing of hydrochar investments required to fire sole hydrochar can be avoided [107]. Depending on HTC time and temperature, the product hydrochar can be comparable to peat or lignite in Krevelen diagram [101]. According to simulations by Erlach et al. [103], the gasification of hydrochar is more efficient than the gasification of wood. However, the overall efficiency from biomass through HTC process to syngas was observed to be lower compared to direct biomass gasification due to losses and auxiliary energy consumption during HTC process.

In order to enter the markets the price of hydrochar should be competitive with available solid biofuels used in heat and electricity production. Group of researchers from TU Berlin [108,109] has estimated that the HTC module cost is 15% of the total capital investment cost, which varies from 0.6 to 1.3 million €/MW (see Fig. 5). High investment costs form a barrier to wider market uptake. Erlach et al. [109] state that equipment cost for HTC process are two times higher compared to wood pelletizing cost and the plant is more complex, which increases operation and maintenance costs.

According to Stemann et al. [108], specific cost of the product hydrochar is 7.9–9.7 €/GJ, whereas according to Erlach et al. [109], they can be up to 13.38 €/GJ depending on the feedstock costs. Thus, it is beneficial if feedstock is available at zero costs, which can be the case in P&P industry with unexploited residues such as sludge and bark. The specific costs for fuel can decrease if the cost of CO_2 avoided by using substitute to coal [109] or the cost of avoiding methane emissions by utilizing biodegradable feedstock is credited [108]. To reduce lifecycle emissions and transportation costs it is beneficial if the HTC plant is located close to its feedstock and/or hydrochar use. According to scenarios by Medick et al. [107], transportation costs can be 27.9–36.9% of the total annual net costs for HTC. Uncertainty of production profitability may hinder the market uptake of the technology.

3.8. *Anaerobic fermentation of sludge*

P&P mills produce large amounts of wastewater at different process stages, debarking, wood chipping, pulping, bleaching, chemical recovery, and papermaking, and most of this is treated with primary clarification and aerobic treatment, producing primary/fibre sludge and waste activated sludge (WAS). Typically, sludge from different stages is combined, dewatered and disposed through incineration or landfilling, while energy content and nutrients are lost [17,110,111]. Traditionally, wastewater treatment has aimed at sludge reduction (i.e. chemical oxygen demand (COD) removal) rather than energy production and nutrient recycling. Since the wastewater includes large amounts of organic matter the biogas potential is substantial [17]. Several commercial technical possibilities exist to use anaerobic fermentation instead of aerobic technologies.

Biogas production through fermentation is a complex process with several stages, namely hydrolysis, acidogenesis, acetogenesis/dehydrogenation, and methanation [112]. Amongst various types of anaerobic systems the most commonly used for P&P industry's effluents are upflow anaerobic sludge blanket (UASB) and internal circulation (IC) reactor, which are able to handle large volumetric flows and high COD loads [17,113].

One strategy for biogas valorisation for the mill is to sell it to external markets. Norske Skog invested in biogas plant to produce biogas from P&P mill effluents in Saugsbrugs, Norway, and the solution was replicated in Golbey, France. At Saugsbrugs, 490 Nm^3/h biogas is produced by a multi-stage membrane-based upgrading system [114], compressed and sold to an external gas supplier, which provides gas for heavy vehicles [115]. At Golbey, the biogas plant is integrated to an existing biological-chemical wastewater treatment plant (WWTP) and the produced gas is sold to the public gas distribution system [116]. Biogas produced at Stora Enso's Nymölla mill, Sweden by energy company Gasum will be converted into liquefied biogas (LBG) and also sold for transportation use [117].

An alternative approach for selling the biogas is to use it at the mill. At Stora Enso's Heinola fluting mill, Finland, the produced biogas is used for energy production to replace fossil fuels [118]. Domsjö sulphite pulp mill, Sweden produces 90 GWh/a biogas, which is used to dry lignin in Domsjö's lignin plant and to produce energy in the local energy company's CHP plant [119]. Biogas produced at Rottneros mill, Sweden will be used to preheat the air entering the pulp flash dryer instead of oil

[120,121].

WWTP capacity as bottleneck for P&P production, regulations on emissions and use of renewable energy have been identified as drivers for anaerobic fermentation investments [17]. Anaerobic fermentation of P&P mills' effluents offers several benefits, such as reduction of the sludge volume and related handling costs, production of biogas as an energy carrier, reduced demand for external nutrient additions, reduced aeration power demand [17,110] and reduced GHG emissions at the mill [112,113], increased self-sufficiency [122] and WWTP capacity, production of biofertilizers to replace mineral fertilizers, and additional revenues from selling the gas. For example at Heinola mill, the amount of sludge is expected to be reduced by 6000 t/year, the fossil fuel consumption is to be cut by 5% and WWTP's energy by 35%, while produced heat is also sold to local district heating company [118]. The major benefits from biogas production in Norske Skog's own biogas plants include increased revenue from sale of gas, reduced operating costs related to paper production, reduced WWT costs, power and chemicals for effluent treatment and reduced GHG emissions, and attractive off-take agreements [123,124]. The revenues for the external plant operator in Skogn are formed of selling biogas and collecting gate-fees [125].

Anaerobic fermentation at P&P mills, in particular in Kraft mills, includes challenges, such as low biodegradability, inhibition of the micro-organisms and large waste volumes, which have slowed down the implementation until recent years [17]. The composition of wastewater and consequently its potential for anaerobic fermentation is affected by the type of the pulping process, the product produced, the raw material used, the bleaching sequence, the internal water circulation and the amount of supplied fresh water in the wastewater treatment [110]. According to Ekstrand et al. [110], previous work mainly focuses on reducing toxicity of the P&P mills' effluents, while the potential for biogas production remains disregarded. Wastewater originating from P&P mills potentially has large variation in composition. The process design of biogas production must be well adapted to the substrate properties in order to achieve a complete degradation of substrate [112], which might pose a challenge in the case of varying substrate properties.

Mainly mechanical and sulphite pulp mills and paper mills using recycled paper as a feedstock have implemented anaerobic fermentation. Ekstrand [17] concludes that effluents from thermo-mechanical, chemical thermo-mechanical and neutral sulphite semi-chemical pulping have the highest potential for anaerobic fermentation due to high organic content and low toxicity of effluents. While the technology is not widely implemented in Kraft pulp mills, these mills with 68.4% market share in Europe (CEPI countries) hold a large untapped potential [17]. Options to improve the feasibility of anaerobic fermentation in Kraft pulp mills are lowering the sludge age and thus improving the degradability, as proposed by Ekstrand [17], and co-fermentation with an external effluent or fibre sludge to improve the methane yield. These actions have been demonstrated in WWTP at Norske Skog's P&P mill, Skogn, Norway within EffiSludge for LIFE demonstration project (2018) [126]. According to Ekstrand [17], The retrofit includes an expanded granular sludge bed (EGSB) unit for aerobic treatment of effluent from primary clarification. WAS is digested in continuous stirred tank reactor (CSTR) together with fish waste as external substrate. The high nutrient content of fish waste allows recirculation of nutrients and reducing external nutrient use. The power consumption was reduced by 40% due to lower sludge residence time in aerobic treatment stage [17].

Scandinavian Biogas [126] estimates that around 1 TWh of biomethane could be produced in Swedish P&P mills from wastewater and residues. Magnusson & Alvfors [127] estimate a theoretical methane potential of 0.5 TWh in the case of converting all Swedish mechanical pulp mills (30% of Swedish pulp production) from conventional aerobic WWT to anaerobic treatment, and concludes that the action would significantly increase biogas production in Sweden. Donnér [128] estimates that Scandinavian Biogas' EffiSludge solution could reduce CO_2 emissions by 6–8 $kgCO_2$-eq/kg pulp, leading to total annual reduction of 55–180 million $kgCO_2$-eq if installed to all Nordic P&P mills, thus cutting total CO_2 emissions from European P&P industry by 0.2–0.5%.

3.9. *Summary of bioenergy retrofits in Europe*

Identified bioenergy retrofits in P&P industry in Europe are summarized in Table 2 according to the process they are suitable for. TRL of the retrofits is estimated by the authors based on the publicly available information of the retrofits. Investment costs and CO_2 emissions are estimates announced by the companies using retrofit technologies or delivering the solutions.

4. Discussion on drivers and barriers for bioenergy retrofitting in pulp and paper sector

In this Section, common drivers and barriers for bioenergy retrofits in the P&P sector are gathered and discussed from Political, Economic, Social, Technical, Environmental and Legal perspectives (PESTEL). The main findings are summarized in Table 3.

4.1. *Political*

Transformation to bio-economy increases the risks, costs and constraints in doing business [6]. High upfront investments in retrofitting technologies and long lifetime expected require long-term political commitment and consistence to support investments and scale-up of retrofits. As an example, political uncertainty in terms of unstable regulation and taxation, and lack of long-term commitment are stated to be the biggest threats at Domsjö, where bioethanol retrofit takes place [146]. The report [146] calls for national support system, which is aligned with the EU support rules.

Member States' national targets for 2030 set in National Energy and Climate Plans (NECPs) are partly creating a favourable political environment for long-term investment decisions. As an example of NECPs, Finland has set an overall renewable energy target of 51% by 2030 [151]. Specific target for liquid biofuels in road transport was set to 30% in 2030, while the share of advanced biofuels of all liquid road transportation fuels was set to 10% [151]. In Sweden, the overall target is 65% renewables of gross energy consumption [152]. Sweden has set several measures to achieve its target of carbon-free transport sector, such as reduction obligation for petrol and diesel. The consumption of liquid biofuels, mainly renewable diesel in the form of HVO, is predicted to increase by 3 TWh by 2020 and then remain constant [152].

European Commission recognises several voluntary schemes [145], which help to ensure that biofuels are sustainably produced and increase the transparency towards customers. Voluntary schemes confirm that biofuel production does not take place on land with high biodiversity, land with high carbon content has not been converted to biofuel feedstock production, and biofuel production results in sufficient GHG savings. As an example of voluntary schemes, UPM's BioVerno has been granted International Sustainability and Carbon Certification (ISCC EU) and Roundtable on Sustainable Biomaterials (RSB) EU RED certification [153]. In addition to certificates recognized by the EC, there are also other certificates, such as European Biochar Certificate (EBC) developed by scientists [154].

Toppinen et al. [6] present a scenario for P&P industry for 2030 based on a Delphi method. Inquiries to form expert elicitation opinion brought up two key topics: regulatory environment and political uncertainty, and multiple policy targets. Multiple targets set for developing forest based industries may lead to competition for wood raw material [6]. This has already been the case for tall oil, which can serve as a raw material both for renewable fuels and chemicals, but its production is limited by softwood pulping capacity. In REDII tall oil is defined as eligible for double counting as transportation fuel and some Member States have set measures to support its use for biofuels over other higher added-value products which has led to increased competition for raw

Table 2
Bioenergy retrofits in Europe (extended from Ref. [129]).

Industry	Retrofit technology	User	State	Capacity	Estimated TRL of retrofit	Company's announcement on the investment cost of the retrofit	Company's estimation on CO_2 emission savings compared to situation before retrofit
Sulphite pulping	Bioethanol production from brown liquor	Domsjö Fabriker AB, Örnsköldsvik, Sweden	On-going since 1940, upgraded recently	17,000 t/a	9	n.a.	n.a.
		Borregaard biorefinery, Sarpsborg, Norway	On-going since 1938, upgraded in 2018	20,000 m^3/a [24]	9	n.a.	n.a.
		AustroCel Hallein GmbH, Hallein, Austria	Under construction (operation scheduled for the end of 2020)	30,000 m^3/a (planned) [130]	9	€ 42 million [130]	Approx. 50,000 tCO_2 saved by replacing fossil fuel in gasoline [130]
Kraft/sulphate pulping	Raw methanol purification	Södra Cell, Mönsterås, Sweden	Under construction	5000 t/a [44]	8	SEK 100 million [44]	99% CO_2 emission reduction [44]
	Black liquor gasification to DME/biomethanol/FT biofuels	Chemrec & HaldorTopsoe, Luleå, Sweden	Demonstrations, 2005–2012	4 tons DME/d [45]	7	n.a.	n.a.
	Kraft lignin extraction from black liquor	Stora Enso, Sunila, Finland	On-going since 2015	50,000 tons as dry (95% DS) lignin/a [57,131]	9	€ 32 million [132], € 4 million energy subsidy from the Ministry of Economic Affairs and Employment of Finland in demonstration phase [133]	34,650 tCO_2 saved by replacing 90% of natural gas used in lime kiln [61]
		Bäckhammar, Sweden	Demonstration, since 2006	8000 tons as dry (65% DS) lignin/a [57]	8	n.a.	n.a.
	Renewable diesel production from tall oil	UPM, Lappeenranta, Finland	On-going since 2015	100,000 t/a i.e. 120 million litres/a renewable diesel, naphtha [134]	9	€ 179 million [134], no subsidies	Over 80% reduction in GHG emissions [134] and up to 10% reduction in tailpipe emissions [135] compared to traditional fossil diesel
		SunPine, Gothenburg, Sweden	On-going since 2010, upgraded in 2015 to produce also rosin, renewable diesel capacity increase by 2020	100 million litres/a renewable diesel [73], 24,000 t/a rosin, 50,000 t/a bio-oil. 2000 t/a turpentine, 1.5 GWh district heating [74]	9	Initial investment SEK 350 million, upgrading SEK 210 million [73], capacity increase SEK 250 million [75]	250,000 tCO_2/a replaced by using renewable diesel [74]
		St1 & SCA, Gothenburg, Sweden	Planned to be operational in 2021 [76]	100,000 t/a [76]	9	€ 48.65 million [76]	n.a.
	Hydrothermal liquefaction (HTL) of black liquor and lignin	Bäckhammar, Sweden	Demonstration	n.a.	6	n.a.	n.a.
		Vallvik, Sweden	Under construction	n.a.	7	n.a.	n.a.
		Silva Green, Tofte, Norway	Demonstration, under construction	4000 L/d [86]	7	n.a.	n.a.
All pulp mills	Bark gasification	Metsä Fibre, Joutseno, Finland	On-going since 2011	48 MW_{th} [98]	9	€ 20 million, € 4.2 million Energy Aid from the Ministry of Economic Affairs and Employment of Finland [98]	GHG emissions reduced by 72,000 t/a and annual specific GHG emission from fossil sources reduced by 105 $kgCO_2eq/t_{pulp}$ [98]
		Stora Enso, Varkaus, Finland	On-going since 2008	12 MW_{th} [93]	9	n.a.	Oil consumption reduced by approx. 7000 t/a (80 GWh) [136]
		Södra Cell, Värö, Sweden	On-going since 1987	35 MW_{th}	9	n.a.	Oil consumption reduced by 90%, when the system is working properly [137]
All P&P mills	Hydrothermal carbonization (HTC) of sludge	Stora Enso, Heinola, Finland	Demonstration, on-going since 2020	13 GWh/a renewable biofuel [138], 20,000 t/a raw material	7	€ 2.2 million grant from The Swedish Energy Agency [139]	GHG emissions will be reduced by approx. 2500 tCO2eq/a [106]
	Anaerobic fermentation of sludge	Scandinavian biogas/Norske Skog, Skogn, Norway	Demonstration, on-going since 2018	125 GWh/a biogas (incl. biogas from fish waste)	8	SEK 30 million, EU grant SEK 16 million [140]	Estimated GHG reduction 500 g CO_2eq/m^3 wastewater [141], 4500 tCO_2eq/a [17], power consumption

(*continued on next page*)

Table 2 (*continued*)

Industry	Retrofit technology	User	State	Capacity	Estimated TRL of retrofit	Company's announcement on the investment cost of the retrofit	Company's estimation on CO_2 emission savings compared to situation before retrofit
							reduced by 40% (approx. 6000 MWh/a) [17]
		Norske Skog, Golbey, France	On-going since 2018	17 GWh/a biogas	9	€ 7.1 million [116]	GHG reduction 3100 tCO_2/a [116]
		Norske Skog, Saugbrugs, Halden, Norway	On-going since 2017	490 m^3/h biogas, 27 GWh/a [123]	9	NOK 152 million (approx. € 17 million), NOK 52 million support [115]	GHG reduction 6500 tCO_2/a [115]
		Domsjö, Örnsköldsvik, Sweden	On-going since 2016	90 GWh/a biogas (13 million m^3) [119]	9	n.a.	n.a.
		Rottneros, Sweden	On-going since 2018, biogas burner installation in 2020	Biogas, heat	9	SEK 15 million for biogas burner [121]	Replacement of equivalent of 1000 m^3 fossil oil [121]
		Stora Enso, Heinola, Finland	On-going since 2016	Biogas, heat, electricity	9	€ 5 million [142]	n.a.
		Stora Enso/Gasum, Nymölla, Sweden	Under construction, planned to be operational in 2020	75–90 GWh/a LBG [143]	9	€ 32 million (€ 27 million for Gasum, € 5 million for Stora Enso), € 12.7 million investment subsidy by the Swedish Environmental Protection Agency under the Climate Leap programme [117]	GHG reduction of 20,000 tCO_2eq/a when replacing conventional diesel in transportation [143]

material [80]. Additionally, low price of the emission allowance in EU ETS and uncertain future price development are examples of political uncertainty.

4.2. *Economic*

According to Toppinen et al. [6], 40% of the P&P industry's turnover in 2030 will come from genuinely new products, to which bioenergy retrofits covered in this review are mostly contributing to (see Table 2). The core strategy to a low-carbon bio-economy in CEPI's Forest Fibre Industry Roadmap 2050 [148] is to get the highest possible value from resources. It was stated that since the P&P industry is one of the largest bioenergy producers, it will continue to produce bioenergy and to provide logistics and platforms for others to produce bioenergy and biofuels. This will likely lead to development of biorefinery type of complexes, although industry's willingness to take risks is seen to have a decisive impact on the diffusion of refinery concepts [155]. Production of large quantity of bioenergy, the first 2nd generation lignocellulosic biofuel projects, waste-to-energy and anaerobic fermentation were mentioned already back in the 2011 as a part of the strategy [148]. Also, biofuels produced by biomass torrefaction, carbonization and pyrolysis were seen as possibilities for pulping industry [148]. However, it was stated that they do not necessarily reduce sites' CO_2 emissions.

It is stated in CEPI's Forest Fibre Industry Roadmap 2050 [148] that the global action scenario is needed in energy and carbon price developments, since increased prices at certain area can result in business leaving due to unprofitable investments required for emission reductions. On the other hand, regulatory requirements such as goals related to carbon neutrality can work as drivers improving the competitiveness of new products and innovative processes [6], such as bioenergy retrofits.

As shown in Section 3, several retrofits producing bioenergy products from process residues have been developed, demonstrated and commercially used. The bioenergy product retrofits in the P&P industry are still rare and some of the plants are first-of-a-kind plants, such as the methanol purification plant in Mönsterås, Sweden, the black liquor gasification demonstration in Piteå, Sweden, and the pilot HTC-plant in Heinola, Finland. On the other hand, some of the retrofit products do have clear markets and demand (e.g. brown liquor bioethanol, tall oil diesel), but their implementation is restricted by the amount of residues available at pulp mills. For some of the retrofits (e.g. bark gasification, anaerobic fermentation, HTC, HTL) the profitability of retrofitting depends on the site specific conditions (e.g. the need to replace fossil fuels on-site or in local energy production, possibilities for further refining the product) and local markets (e.g. the possibility to sell the product locally and the possibilities for transportation). It can be expected that retrofitting is more cost-efficient than building up a stand-alone bioproduct mill, since at the P&P mills, the feedstock is produced on-site and depending on the technology, several of the required components or sub-processes are already in place. For example, WWTP required by HTC plant is an integral part of any P&P mill.

It is clear that implementing most of the fore mentioned retrofits still requires subsidies, incentives and investment grants. Of the existing bioenergy retrofits in Europe, investment grants have been allocated and publicly announced to the facilities producing lignin, gasification gas, HTC coal and biogas (see Table 2). In these cases, the support has been granted from national sources (e.g. from ministries and energy or environmental agencies). According to Toppinen et al. [6], applying new concepts in the sector requires financial resources not only due to investment, research and development related to products and processes, but also to integrate the production into new value chain, and understanding of new markets and customers. Furthermore, renewable energy products such as renewable diesel, bioethanol, and biomethanol have received national tax incentives.

Bioenergy retrofits exploit residues that are commonly disposed efficiently with well-known low-cost manners within the P&P industry

Table 3
PESTEL analysis for bioenergy retrofits in the P&P industry.

	Drivers	Barriers
Political	• Retrofit technologies require stable political environment due to long-term investments • National targets to phase out fossil fuels in energy and transportation, NECPs [144] • Voluntary schemes [145]	• Lack of long-term political commitment and consistence [146] • Multiple policy targets for developing forest based industry [6] • Low emission allowance price in EU ETS and uncertainty of the future price
Economic	• Wider product portfolio [147,148] • Companies are actively looking for new ways to use residues and related business opportunities • Bioethanol production from brown liquor and renewable diesel production from tall oil do have good prerequisites for market growth within the boundaries of raw material production capacity	• Many of the residues are considered as waste and can be easily and even economically disposed in the P&P mill processes • Competing, higher value products, which already have established markets are made out of raw materials (bioethanol, biomethanol, lignin, tall oil) • Bioenergy retrofits are not widespread in the sector and some of the existing retrofits are still first-of-a-kind plants or in demonstration. Thus, cost estimations for the retrofits are rare.
Social	• Solutions to boost bio-economy and circular economy • Corporate image [18] • New local ecosystems and businesses • Positive impact on employment [19]	• Uncertain acceptance of new fuels • Low knowledge by the general public
Technical	• Retrofit technologies increase the exploitability of the feedstock • Retrofit can increase pulp production capacity by reducing load of process bottlenecks through removal of residues from the process (e.g. recovery boiler and WWTP) • Availability of excess heat at P&P mills enables new products	• Production capacity is limited by the quantity of available residues • Technical uncertainties and unknown impacts of new technologies and novel integrations, which still require research (e.g. effects on recovery boiler and lime kiln operations and emissions) • Feasibility of the retrofits is case-specific and hard to estimate due to low number of existing cases
Environmental	• Replacement of fossil alternatives • Reducing fossil GHG emissions from transport • Reducing fossil GHG emissions from P&P industry • Producing liquid, solid and gaseous biofuels from residues instead of virgin feedstock	• Sufficiency of biomass resource • Limited access to biomass feedstock [149] • Environmental impacts related to increasing use of biomass
Legal	• Green Deal growth strategy • Demand to increase renewable share in transport fuels increases the need for renewable alternatives • RED II drives for renewable investments • ILUC directive and related Delegated Act support the deployment of advanced biofuels • National taxation for biofuels • Blending obligations	• Energy Taxation Directive (ETD) effects the investment decisions and consumption of fuels • Classification and taxation of biofuels vary between countries, which creates insecure business environment for cross-border operations • Procedures required for new products (e.g. REACH, End-of-Waste criteria) • Industrial Emissions Directive [150]

Table 4
Markets for energy products from bioenergy retrofits in P&P industry.

Product	Market size	Production volume	Current and potential production volume in P&P industry in Europe	Market price estimate
Renewable ethanol	EU-28 Biogasoline (bioethanol/bio-ETBE) consumption forecast for 2020 was 7318 ktoe [156]	In Europe, 5.81 billion litres in 2018 [36]	67 million litres in 2019	650 €/m^3 [37]
Renewable methanol	Global demand of methanol for gasoline, biodiesel and DME production was 17.7 million tons in 2006 and potential demand 75–105 million tons in 2015 [51]	Global production capacity in 2018 was 140 million tons (for all end uses) and it is expected to double by 2030 [47]; more than 95 billion litres [157]	5000 t/a	60-110 €/MWh [52]
Lignin	1.8 million tons annually of lignosulfonates from sulphite pulping was produced in 2017, which counted for 90% of total market of commercial lignin [58].	Global production estimates for Kraft lignin by 2025 is 1.7 million tons [61].	58,000 t/a	Lignin with low purity 50–280 USD/t, lignin from Kraft process 260–500 USD/t, lignosulfonates 180–500 USD/t [55]
Tall oil	Global technical potential 2.6 million tons, currently 1.6–2.0 million tons produced [77]. Crude tall oil demand for biofuels production is expected to increase [158].	Out of the total CTO demand, 230,000 tons is directed to biofuel production [158].	Current tall oil production 440,000 tons (Scandinavia), potential 650,000–700,000 tons (Europe) [77,80]	550 €/t (2013, high quality floor price), 280 €/t (fuel quality CTO in Europe) [77]
Syngas/ gasification gas/biogas	Natural gas production 4388 PJ and consumption 18,168 PJ in EU in 2018 [159]	Global biogas production in 2014 1.28 EJ, 59 billion m^3; EU biogas production in 2015 654 PJ, 28 billion m^3 methane equivalent [160], 19,352 GWh biogas was produced in Europe in 2017 [161]	95 MW_{th} of gasification gas, 259 MW_{th} biogas from anaerobic fermentation	Natural gas price for industrial use has varied from 29.5 to 35 €/MWh during 2018–2019 in Finland [97], average price 32.7 €/MWh in 2017 in EU [162]
Hydrochar	Can be used to replace various solid fuels in energy production. Market not established.	n.a.	20,000 t/a	Product has been used to replace peat on site. Price of milled peat in Finnish markets was 16.31 €/MWh in 2019 [163]

itself. This may lower the willingness to invest into innovative processes for further refining the streams. Residues such as tall oil, bark and hemicellulosic sugars are valuable as such, whereas black liquor, raw methanol, lignin and wastewater treatment sludge are typically disposed by combustion in the recovery boiler. Purified biomethanol, bioethanol, tall oil and lignin do have several valuable uses in addition to bioenergy, which may create competition for raw material between sectors. Hydrochar still needs to be productised and the most valuable and suitable market would need to be discovered. Black liquor can be exploited by several retrofitting technologies e.g. by gasification and HTL biocrude production, which may lead to competition between different retrofitting technologies. The recovery cycle also requires part of the residues to function properly, which limits the volume that can be extracted.

The market size, production volume and price estimate for the retrofit products are estimated in Table 4. Most of the products compete with large volumes of fossil and renewable alternatives (e.g. ethanol, methanol, and diesel), while the production volumes in the P&P sector are relatively small. Though the retrofits covered in this review mostly locate in Northern Europe, the end-product markets are global. The general impression is that the global markets for the products as well as the production volumes in the sector are growing. The deployment of retrofit technologies is in many cases limited to a certain number of P&P mills using wood-based raw materials, but use for other feedstocks in other industries could open up new export possibilities for technology providers.

4.3. Social

Bioenergy retrofitting in P&P industry often requires networking with stakeholders beyond the traditional business partners. The retrofit products may require establishing a new value chain from production to customer delivery. Some of the products (e.g. lignin, biocrude) also require collaboration in further refining in case that is not done at the plant itself. Sometimes, the product can be used by the plant itself and often that is the first step before the product enters the markets, particularly if the specific market is not yet well-established. The required networking can, on the other hand, work as a driver for creating new local business and boosting local bio-economy. In addition, new ways of collaborating within the industry have been created to demonstrate the production [86] and to create the necessary value chain [29,113].

Bioenergy retrofits, and in the wider context also biomass energy [164], are generally not very familiar to general public. Thus, opinion may be shaped by public communication. In the case of the listed retrofits it has mainly underlined the positive environmental impacts of the retrofits, e.g. replacement of fossil fuels. Based on a litterature review focusing on public perceptions related to biomass energy, Radics et al. [164] found out that public support towards second-generation biofuels from cellulosic feedstock is greater when the public is informed about them. Moula et al. [165] concluded based on their study in Finland that public sector should take a role in informing people, since lack of information is currently hindering the deployment of biofuels in the transport sector.

Job creation and rural development deriving from bioenergy projects are important to consumers [164], and small-scale, decentralised local facilities are associated with higher acceptance than larger, centralised facilities [164,166,167]. Since forest industry has traditionally had a strong local presence and creates both direct and indirect employment in the area, local support can be strong. This has been reported in the case of Örnsköldsvik, Sweden, where Domsjö's mill and retrofit for bioethanol production takes place [146]. Not only consumers and landowners affect market acceptance of bioenergy products, but also other stakeholder groups, such as industry personnel, investment groups, government, academia, non-profit organisations and policy makers, may have an influence [164].

Since some of the products and technologies are new and not familiar to markets, the industry has to ensure their sustainability, product quality and applicability. Necessary procedures related to productising, standardisation, and certification may hinder market entry. These difficulties may decrease producer's interest towards some of the products from the retrofits that in first place appear interesting. Another important social aspect is related to workers' health and safety which has to be ensured also in the context of retrofit installations, even if this topic has not been in the focus of this review. Within the Nordic P&P industry, issues related to workers' health and safety are among top priorities [168,169].

4.4. Technical

Bioenergy retrofits aim at exploiting the feedstock more efficiently and increasing the value of residues instead of considering the residues merely as disposables with some energy value. Some of the retrofits can alleviate the physical bottlenecks in the pulping process by decreasing their load through residue extraction. Examples of this are lignin extraction to decrease the load of the recovery boiler, and anaerobic fermentation in the WWTP. Surplus heat and steam from the pulping process are already utilized in the integrated mills for paper manufacturing processes. The surplus energy can be further used in retrofits to improve the energy efficiency of the mill, e.g. for bark drying before gasification.

All of the bioenergy retrofits presented in this review have only been used at few P&P mills in Europe, although most of the technologies are technically proven and commercial (TRL 9), such as renewable diesel and bioethanol production, bark gasification, anaerobic fermentation and lignin extraction. Black liquor gasification (TRL 7), hydrothermal liquefaction (TRL 6–7) and hydrothermal carbonization (TRL 7) are still in the demonstration phase. Other than technical reasons can be considered to hinder market entry or wider deployment of the technologies.

The low number of existing retrofits leads to uncertainties related to potential impacts to the environment and existing processes, such as the effects of lignin extraction on black liquor properties and recovery boiler operation, and effects of alternative fuels on lime kiln operation. It is estimated in Vakkilainen & Välimäki [170] that 20% of lignin could be removed without causing major changes to recovery boiler operation. Further research and higher number of retrofits would provide new data to create more confidence for investments from technical perspective. Low number of existing retrofits hampers also the assessment of the economic feasibility of the investments.

The amount of retrofit products is limited by the residue availability. Retrofitting does not change the P&P making processes themselves and the residue volumes depend on the main product. For some retrofit investments, such as tall oil diesel plant, the CTO volume from one mill may not be enough to justify the investment, and more CTO must be transported from other mills. Also other conditions, such as pulping process and feedstock affect the total technical potential of retrofits. For example, tall oil diesel production is limited by the softwood pulping capacity, and bioethanol production by the comparatively small number of sulphite pulp mills. The existing sulphite pulp mills are generally quite old, which does not attract investments in new processes [171].

4.5. Environmental

Lime kiln is typically the only unit that consumes fossil fuels during normal operations in a modern virgin wood based Kraft mill. Thus, efforts to reduce GHG emissions originating from the lime kilns have gained interest. It is not clear though, whether sufficient amounts of biogas can be produced to replace on-site natural gas use. It is estimated that biogas production from an anaerobic WWT could account for up to 10% of energy consumption in a paper mill utilizing recycled fibres [149]. Residue gasification for lime kiln fuel production has started in several mills [137,172], and development of black liquor gasification is seen as a stepping stone towards that direction [148]. Anaerobic WWT is considered as a mature technology, which could be adopted more widely in the sector [149]. It is estimated that fuel mix change in lime kilns and in energy production to biomass, pellets, biocoal, pyrolysis oil and biogas could reduce emissions by 5–6 Mt in Europe [148].

Another environmental driver for implementing retrofits relates to producing bioenergy products that could substitute their fossil counterparts. In Ref. [148], it is estimated that more than 20 full-scale plants producing second generation wood-based renewable diesel (e.g. Fischer-Tropsch plants), utilizing 30–40 million m^3 of wood as feedstock, would cover the biofuel needed for transportation in the P&P industry. This could reduce industry's total emissions equivalent to 3–3.5 million tons of fossil diesel and could be implemented by 2050 [148].

P&P mills often treat residues as waste to be disposed. This is usually done in the recovery cycle by evaporation and combustion (e.g. in the case of black liquor, methanol, lignin and sludge), which on the other hand can increase heat and electricity production at the mill, but may also increase the amount of harmful substances in the recovery cycle. If the residue can be utilized for biofuels' production, the environmental impacts from the mill or its WWTP may be reduced since these harmful substances are captured into the product. However, the product may not be automatically accepted to markets due to its content and may need further processing in order to meet the requirements of prevailing standards and regulations.

There have been growing concerns about increased forest harvests and their impacts on forest carbon sinks and biodiversity. Unsustainable intensification of forest management activities for bioenergy purposes should be avoided, and use of whole trees for energy production should be minimised [173]. It has also been proposed that instead of pulp and paper, wood should be rather used for long-living products that could act as carbon sinks. Since the P&P mills are optimised according to their main products, pulp and paper, retrofitting is not expected to affect the use of virgin feedstock. According to Ref. [174], biofuels produced from wood processing industry residues are likely to have low-ILUC risk. However, tightening sustainability criteria and concerns related to carbon sinks and potential biodiversity impacts related to use of forests may affect raw material availability in future. This may be the case, even if sustainability matters (e.g. use of raw materials, energy, material and water efficiency, air and water emission, land-use changes) have been highlighted and discussed within the industry sector itself [175]. Retrofits often contribute positively to material and energy efficiency of the mill. Hansson et al. [176] suggest that biofuels production could be a potential increasing CO_2 point source to be utilized for electrofuels production, since biofuel producers have to decrease CO_2 emissions according to CO_2 saving criteria.

It must be noted that some of the reviewed retrofit technologies are applicable to pulp mills and integrated P&P mills, but not to stand-alone paper mills. When considering the paper sector, bioenergy already accounts for close to 60% of fuel consumption [149]. However, other than technical reasons are foreseen to limit the further use of biomass, such as limited access to biomass feedstock, lack of public acceptance in local communities, lack of storage facilities and logistics constraints [149].

4.6. Legal

According to the European Green Deal [177], 90% reduction in transport emissions is needed by 2050, and the production and deployment of sustainable alternative transport fuels must be ramped-up. EU's RED II (Directive (EU) 2018/2001) [178] sets target of 14% of the transport fuel in every EU country coming from renewable sources by 2030, In addition, there is a dedicated target for advanced biofuels and biogas, which shall contribute at least 0.2% in 2022, at least 1% in 2025 and at least 3.5% in 2030 to the final consumption of energy in transport sector. Furthermore, the Directive limits the maximum share of 1st generation biofuels counted in the national share of renewables in transport at 1% higher than the 2020 national share of these fuels in final energy consumption in rail and road transport (maximum of 7%). In addition, the share of high ILUC-risk fuels shall gradually decrease to 0% by 2030. Each Member State sets obligation on fuel suppliers on national level. RED II sets threshold values for GHG savings that biofuels must comply in order to be counted towards renewable energy target in transport sector. Delegated Act [179] amending Renewable Energy Directive sets criteria both for determining high ILUC-risk feedstock and certifying low ILUC-risk biofuels, bioliquids and biomass fuels. RED II and ILUC criteria promote bioenergy retrofits for production of advanced biofuels from waste streams and lignocelluloses.

According to RED II Annex IX, bark, black liquor, brown liquor, fibre sludge, lignin and tall oil are considered as residues from forestry and forest-based industries and thus, eligible for double counting of their energy content towards the targets for advanced biofuels. Furthermore, RED II defines 'biomass' as a 'biodegradable fraction of products, waste and residues from forestry and related industries'. However, for instance, waste liquors of pulping industry are excluded from the definition of biomass in German legislation called Biomasseverordnung.

Energy Taxation Directive (ETD) (Directive 2003/96/EC) [180] sets minimum taxation levels for energy products. ETD dates back to 2003, when renewable fuels were niche alternatives to fossil ones, and it has been criticized to be outdated and in need of review due to inconsistencies with EU's climate, energy and transport objectives [181, 182]. ETD does not differentiate biofuels from fossil ones and consequently, Member States apply their own classifications, which results in insecure business environment for biofuel producers exporting their products in terms of tax treatment. Lack of differentiation of biofuels also leads to misalignment with RED II, which includes sustainability criteria for biofuels, which is lacking in ETD. It is stated in SWD(2019) 329 final [182] that in the worst case, fragmentation of internal markets and uncertainties resulting from the ETD hamper investments in low-carbon technologies. Taxation under ETD is based on volume, and it has been suggested to be changed to taxation based on both energy and carbon content. Volume based taxation does not take into account the lower energy content of renewable fuels.

ETD grants Member States to give tax reductions and exemptions, e. g. for renewable energy sources, such as biofuels, and tax rates varies between EU countries. In 2018, tax exemption or reduction for biofuels was applied in Czech Republic, Germany, Hungary, Lithuania, Slovakia and Sweden, while a number of other countries, as least Austria, Croatia, Finland, France, Denmark, the Netherlands, Slovenia and Portugal apply other tax incentives for biofuels [182,183]. Of the before listed countries, Germany, Sweden, Austria, Finland, France and Portugal have significant P&P industry, which can benefit from the tax incentives. In Sweden, for example tall oil diesel benefits from exemption from energy and CO_2 taxes [79]. Varying tax incentives and mandates for biofuels and their blends in Member States may benefit markets for one biofuel at the expense of another.

New products entering the markets have to undergo different procedures. REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) [184] requires companies to identify and manage risks linked to the substances they manufacture and market in the EU to protect human health and environment. Companies must register their substances, which requires working together with other companies registering the same substance. End-of-Waste (EoW) criteria is part of the Waste Framework Directive (2008/98/EC) [185] and provides the status of 'product' for a certain waste if specific criteria is fulfilled. The aim of the criteria is to enhance recycling in the EU by creating legal certainty and removing administrative burden [186]. 'Waste' cannot be used as a raw material for a new product before ending the status as waste. In the long run, the 'product' status is likely to improve the market potential of new energy products produced at P&P mills, while in the short term, it causes extra efforts for the producer. In EU-scale, EoW criteria has been laid down for five priority waste streams [186], which, however do not relate to P&P sector, while new criteria are not under preparation. Instead, national or case-specific criteria can be developed. Case-specific criteria are bind to certain site and its environmental permit. For example, hydrochar has still waste status and is subject to undergo the EoW process.

P&P sector is covered in Industrial Emissions Directive (IED) (2010/75/EU) [150]. IED classifies as biomass 'fibrous vegetable waste from virgin pulp production and from production of paper from pulp, if it is co-incinerated at the place of production and the heat generated is recovered'. Thus, the emissions limits set out in IED apply for P&P mills' boilers with capacity equal or greater than 50 MW. However, they do not apply to pulp mill recovery boilers. All European P&P mills must consider new BAT conclusions, legally binding after IED adoption, and adhere them in their permit to operate [187]. P&P sector is already efficient in terms of using residues it generates, but complete elimination is not feasible. Typical residues combusted on-site include bark, lignin and WWTP sludge. However, the retrofits aim to decrease such use of residues.

5. Conclusions

The aim of this review was to collect and to elaborate information of bioenergy retrofits in the European P&P sector in order to unlock their potential and to foster their implementation. The review covers both potential retrofit options and existing retrofit installations in Europe. Technical maturity, existing drivers and barriers and market potential were discussed based on a comprehensive literature review. Within this review, particular attention was paid to resource efficiency and site-specific conditions, as these aspects are rarely covered in the literature concerning the P&P sector. Common drivers and barriers for wider market uptake were discussed from political, economic, social, technical, environmental and legal point of views.

As a conclusion, several drivers for bioenergy retrofits in the sector were identified. Though the P&P sector in Northern Europe is already highly relying on bioenergy in primary energy consumption, retrofits can aid further decreasing the CO_2 emissions originating from the sector. The retrofit products can be used e.g. as alternative fuels for renewable transport and for energy production at the mills. Legislation at the EU level drives towards increasing the share of biofuels both in transportation and in energy production. Renewable product portfolios of the existing mills could be diversified through the studied retrofit products. Retrofits are also often considered as more cost-efficient options for biofuels' production than stand-alone plants.

Bioenergy retrofit technologies are not directly replicable from one mill to another, but their suitability to an existing pulp and/or paper mill depends on the used pulping technology, local operational environment and markets. Thus, feasibility of retrofits must be assessed case by case. Our findings show that the learning process during the first retrofit establishment can lead to further retrofitting (e.g. biogas production at Norske Skog's mills). Thus, knowledge gained from the first retrofit implementations are valuable. Availability of local networks is in essential role when retrofits are considered; value chain needs to be build up from the production to customers and some of the products need further refining or productising before entering the markets.

The number of existing retrofits has remained low though no major technical barriers for the market uptake were identified. According to our review, there are already mature retrofitting technologies, such as bark gasification and anaerobic fermentation, while several technologies are still in the demonstration stage. Factors limiting market uptake relate to uncertainty regarding economic feasibility, and unestablished markets for new products, rather than immaturity of the technologies. The economic feasibility of the retrofit technologies must be verified before wider implementation can take place. However, this is challenging due to low number of existing cases and different country-specific support schemes they are subject to. Both national and EU level legislation are in important role in promoting bioenergy retrofits, and national policies should be aligned with EU-level policies. Policy framework should be stable and consistent to encourage long-term investments in retrofits.

P&P sector produces a stable flow of residues to be used for added-value bioenergy products, which creates a good base for retrofit investments and in wider scale for bio-economy development. At the same time, utilization of residues as feedstock improves resource efficiency of the sector. However, it must be noted that the limited volume of residues from the sector may constrain also the potential of derived products.

Disclaimer

The contents of this article are the sole responsibility of the authors and do not reflect the views of the EU or the INEA Agency.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 817999. The authors also wish to thank Mrs. Dina Bacovsky for valuable comments.

References

[1] Finnish Forest Industries, Energy, 2010. https://www.forestindustries.fi/uploads/2017/03/30041743/886.pdf.
[2] Finnish Forest Industries, Forest Industry in Finnish Manufacturing, Statistics, Ber), 2018.
[3] CEPI, Resource Efficiency in the Pulp and Paper Industry - Making More from Our Natural Resources, 2015. https://www.cepi.org/resource-efficiency-in-the-pulp-and-paper-industry-making-more-from-our-natural-resources/.
[4] H. Kumar, L.P. Christopher, Recent trends and developments in dissolving pulp production and application, Cellulose 24 (2017) 2347–2365, https://doi.org/10.1007/s10570-017-1285-y.
[5] M. Benali, Z. Périn-Levasseur, L. Savulescu, L. Kouisni, N. Jemaa, T. Kudra, M. Paleologou, Implementation of lignin-based biorefinery into a Canadian softwood kraft pulp mill: optimal resources integration and economic viability assessment, Biomass Bioenergy 67 (2014) 473–482, https://doi.org/10.1016/j.biombioe.2013.08.022.
[6] A. Toppinen, S. Pätäri, A. Tuppura, A. Jantunen, The European Pulp and Paper Industry in Transition to a Bio-Economy: A Delphi Study, 2017, https://doi.org/10.1016/j.futures.2017.02.002. Futures.
[7] Confederation of european paper industries (CEPI), Key Statistics 2018 - European Pulp & Paper Industry, 2018. https://www.cepi.org/wp-content/uploads/2020/10/Final-Key-Statistics-2018.pdf.
[8] Metsä Fibre - Äänekoski Bioproduct Mill, (n.d.). https://www.metsafibre.com/en/about-us/Production-units/Bioproduct-mill/Pages/default.aspx (accessed October 18, 2019).
[9] Statistics Finland, Statistics Finland's PxWeb Databases, Total Energy Consumption by Source (Detailed), 2019. http://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin_ene_ehk/. accessed April 19, 2020.
[10] Confederation of European Paper Industries (CEPI), Types of Pulping Processes, (n.d.). http://www.cepi.org/node/22334 (accessed October 25, 2019).
[11] BIOFIT - Bioenergy Retrofits for Europe's Industry, (n.d.). https://www.biofit-h2020.eu/(accessed October 18, 2019).
[12] M.K. Hassan, A. Villa, S. Kuittinen, J. Jänis, A. Pappinen, An assessment of side-stream generation from Finnish forest industry, J. Mater. Cycles Waste Manag. 21 (2019) 265–280, https://doi.org/10.1007/s10163-018-0787-5.
[13] C.K. Yamakawa, F. Qin, S.I. Mussatto, Advances and opportunities in biomass conversion technologies and biorefineries for the development of a bio-based economy, Biomass Bioenergy 119 (2018) 54–60, https://doi.org/10.1016/j.biombioe.2018.09.007.
[14] G. Rødsrud, M. Lersch, A. Sjöde, History and future of world's most advanced biorefinery in operation, Biomass Bioenergy 46 (2012) 46–59, https://doi.org/10.1016/j.biombioe.2012.03.028.
[15] G. Mandeep, Kumar Gupta, P. Shukla, Insights into the resources generation from pulp and paper industry wastes: challenges, perspectives and innovations, Bioresour. Technol. (2020), https://doi.org/10.1016/j.biortech.2019.122496.
[16] L.D. Gottumukkala, K. Haigh, F.X. Collard, E. van Rensburg, J. Görgens, Opportunities and prospects of biorefinery-based valorisation of pulp and paper sludge, Bioresour. Technol. (2016), https://doi.org/10.1016/j.biortech.2016.04.015.
[17] E.-M. Ekstrand, Anaerobic Digestion in the Kraft Pulp and Paper Industry – Challenges and Possibilities for Implementation, 2019, https://doi.org/10.3384/diss.diva-156667.
[18] K. Kuparinen, E. Vakkilainen, Green pulp mill: renewable alternatives to fossil fuels in lime kiln operations, BioResources 12 (2017) 4031–4048, https://doi.org/10.15376/biores.12.2.4031-4048.

[19] D. Chiaramonti, T. Goumas, Impacts on industrial-scale market deployment of advanced biofuels and recycled carbon fuels from the EU Renewable Energy Directive II, Appl. Energy (2019), https://doi.org/10.1016/j.apenergy.2019.113351.

[20] S.Y. Searle, C.J. Malins, Waste and Residue Availability for Advanced Biofuel Production in EU Member States, Biomass and Bioenergy, 2016, https://doi.org/10.1016/j.biombioe.2016.01.008.

[21] D. Rutz, R. Janssen, P. Reumerman, J. Spekreijse, D. Matschegg, D. Bacovsky, A. Gröngröft, S. Hauschild, N. Dögnitz, P. Karampinis, K. Melin, H. Saastamoinen, A.I.S. Torres, R. Iglesias, M. Ballesteros, G. Gustavsson, D. Johansson, A. Kazagić, A. Merzić, D. Trešnjo, H. Dagevos, S.J. Sijtsema, M.J. Reinders, M. Meeusen, Technical Options for Retrofitting Industries with Bioenergy - A Handbook, WIP Renewable Energies, 2020. https://www.biofit-h2020.eu/publications-reports/BioFitHandbook-2020-03-18.pdf.

[22] S. Hanhikoski, High Yield Nucleophile Cooking of Wood Chips, 2013, p. 92. https://aaltodoc.aalto.fi/handle/123456789/11138.

[23] D. Rutz, R. Janssen, N. van den Berg, J. Spekreijse, P. Reumerman, D. Matschegg, D. Bacovsky, A. Gröngröft, N. Dögnitz, D.-S. Kourkoumpas, E. Karampinis, P. Grammelis, K. Koponen, H. Saastamoinen, E. Tsupari, A.I. Susmozas, R. Iglesias, M.B. Perdices, D. Johansson, G. Gustavsson, A. Kazagić, D. Trešnjo, A. Merzić, BIOFIT D2.5 Framework Conditions for Retrofitting Europe's Industry with Bioenergy, WIP Renewable Energies, 2020. https://www.biofit-h2020.eu/D2.5_BIOFIT.frameworks_2019-08-02-final-updated-acknowledged.pdf.

[24] European Biofuels Technology Platform, Borregaard – Commercial Plant in Sarpsborg, 2016. Norway, https://www.etipbioenergy.eu/images/Factsheet_Borregaard_final.pdf.

[25] Valmet, Methanol, from Waste Byproduct to Valuable Fuel, Valmet, 2018. https://www.valmet.com/globalassets/media/downloads/white-papers/power-and-recovery/methanol_waste_to_fuel_whitepaper.pdf.

[26] H. Wallmo, M. Wimby, A. Larsson, Increase production in your recovery boiler with LignoBoost, in: TAPPI Press - TAPPI Eng. Pulping Environ. Conf. 2009 - Innov. Energy, 2009, pp. 2568–2593. Fiber Compliance.

[27] B. Heuser, V. Vauhkonen, S. Mannonen, H. Rohs, A. Kolbeck, Crude tall oil-based renewable diesel as a blending component in passenger car diesel engines, SAE Int. J. Fuels Lubr. 6 (2013) 817–825, https://doi.org/10.4271/2013-01-2685.

[28] IEA Bioenergy, Black Liquor Gasification, 2007. https://www.ieabioenergy.com/wp-content/uploads/2013/10/Black-Liquor-Gasification-summary-and-conclusions3.pdf.

[29] S. Rasi, P. Kilpeläinen, K. Rasa, R. Korpinen, J.E. Raitanen, M. Vainio, V. Kitunen, H. Pulkkinen, T. Jyske, Cascade processing of softwood bark with hot water extraction, pyrolysis and anaerobic digestion, Bioresour. Technol. 292 (2019) 121893, https://doi.org/10.1016/j.biortech.2019.121893.

[30] F.O.A. Karlsson, X. Truong, C. Svedin, D. Donner, J. Ejlertsson, Sludge management within the pulp and paper industry, in: Proceeding of IWA Sludge Management in Circular Economy, 2018, pp. 1–16. http://scandinavianbiogas.com/effisludge/wp-content/uploads/2018/05/180524_OMETTO-FRANCESCO_SMICE2018_website.pdf.

[31] J.S. Gregg, S. Bolwig, T. Hansen, O. Solér, S. Ben Amer-Allam, J.P. Viladecans, A. Klitkou, A. Fevolden, Value chain structures that define European cellulosic ethanol production, Sustain. Times 9 (2017) 1–17, https://doi.org/10.3390/su9010118.

[32] Borregaard, Borregaard Invests in Bioethanol Upgrade, n.d. https://www.borregaard.com/News/Borregaard-invests-in-bioethanol-upgrade. accessed April 20, 2020

[33] Borregaard, Bioethanol from Borregaard in Petrol, n.d.), https://www.borregaard.com/News/Bioethanol-from-Borregaard-in-petrol. accessed April 20, 2020.

[34] Austrocel Hallein, Der Bau der neuen Bio-Ethanol-Anlage in Hallein hat begonnen, 2018. https://austrocel.com/wp-content/uploads/2018/04/AC_Bio-Ethanol_Baubeginn_Pressetext_final.pdf.

[35] International Renewable Energy Agency, Road transport: the cost of renewable solutions, IRENA Rep (2013) 83.

[36] ePure European Renewable Ethanol, European Renewable Ethanol – Key Figures 2018 EU Renewable Ethanol Market at a Glance – 2018, vol. 2018, Key Fig, 2018, pp. 2018–2019.

[37] E. Svensson, V. Lundberg, M. Jansson, C. Xiros, T. Berntsson, The effect of high solids loading in ethanol production integrated with a pulp mill, Chem. Eng. Res. Des. 111 (2016) 387–402, https://doi.org/10.1016/j.cherd.2016.05.026.

[38] ePure, About Ethanol, n.d. https://www.epure.org/about-ethanol/what-is-renewable-ethanol/. (Accessed 23 April 2020).

[39] ePure, E10 Ethanol Fuel Blend: what You Need to Know, 2016.

[40] W.-C. Wang, L. Tao, J. Markham, Y. Zhang, E. Tan, L. Batan, M. Biddy, W.-C. Wang, L. Tao, Y. Zhang, E. Tan, E. Warner, M. Biddy, Review of Biojet Fuel Conversion Technologies, Golden, CO, USA, 2016.

[41] S. Verhelst, J.W. Turner, L. Sileghem, J. Vancoillie, Methanol as a fuel for internal combustion engines, Prog. Energy Combust. Sci. 70 (2019) 43–88, https://doi.org/10.1016/j.pecs.2018.10.001.

[42] N. Jemaa, M. Paleologou, Method for Producing Bio-Methanol at Pulp Mills, 2016. US 2016/0122267.

[43] J. Warnqvist, J. Olsson Släger, A. Eliasson, Process for Removal of Sulphur from Raw Methanol, 2016. US 2016/0237011 A1.

[44] Södra, Södra Commences Biofuel Production, 2017, p. c2456420. https://news.cision.com/sodra/r/sodra-commences-biofuel-production. accessed March 20, 2020.

[45] I. Landälv, L. Waldheim, K. Maniatis, Continuing the Work of the Sub Group on Advanced Biofuels. Technology Status and Reliability of the Value Chains: 2018 Update, 2018.

[46] K. Maniatis, I. Landälv, L. Waldheim, E. van den Heuvel, S. Kalligeros, Building up the Future - Cost of Biofuel - Sub Group on Advanced Biofuels (SGAB): Final Report, 2017, https://doi.org/10.2832/494620.

[47] Statista, Production Capacity of Methanol Worldwide in 2018 and 2030 (In Million Metric Tons), Statistics (Ber). (n.d.).

[48] European Commissio, Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 Amending Directive 98/70/EC as Regards the Specification of Petrol, Diesel and Gas-Oil and Introducing a Mechanism to Monitor and Reduce Greenhouse Gas Emissions and Amend, 2009. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF.

[49] ETIP Bioenergy, Biofuel Fact Sheet - Dimethyl Ether (DME), 2016. https://www.etipbioenergy.eu/fact-sheets/dimethyl-ether-dme-fact-sheet. accessed February 21, 2020.

[50] Statista, Market Share of Methanol Worldwide in 2016, by Product, Statistics (Ber). (n.d.).

[51] Methanol Institute, Methanol Production, 2006.

[52] C. Bergins, K. Tran, E. Koytsoumpa, E. Kakaras, T. Buddenberg, Ó. Sigurbjörnsson, Power to Methanol Solutions for Flexible and Sustainable Operations in Power and Process Industries, 2015.

[53] L. Kouisni, P. Holt-Hindle, K. Maki, M. Paleologou, The LignoForce System^{TM}: a new process for the production of high-quality lignin from black liquor, Pulp Pap. Canada. 115 (2014) 18–22.

[54] R. Font, M. Esperanza, A.N. García, Toxic by-products from the combustion of Kraft lignin, Chemosphere 52 (2003) 1047–1058, https://doi.org/10.1016/S0045-6535(03)00294-7.

[55] D.S. Bajwa, G. Pourhashem, A.H. Ullah, S.G. Bajwa, A concise review of current lignin production, applications, products and their environment impact, Ind. Crop. Prod. 139 (2019) 111526, https://doi.org/10.1016/j.indcrop.2019.111526.

[56] Valmet, LignoBoost - Lignin from kraft black liquor - New Ligning Qualities with LignoBoost, ((n.d.)).

[57] Valmet, LignoBoost - Lignin from Kraft Black Liquor, (n.d.).

[58] T. Aro, P. Fatehi, Production and application of lignosulfonates and sulfonated lignin, ChemSusChem 10 (2017) 1861–1877, https://doi.org/10.1002/cssc.201700082.

[59] P. Tomani, The lignoboost process, Cellul. Chem. Technol. 44 (2010) 53–58.

[60] Valmet, First LignoBoost Plants Producing Large Volumes of Kraft Lignin to the Market Place, (n.d.).

[61] H. Raunio, Ligniinistä Kehitetään Hiilikuituja Ja Muovin Korvaajia, Tekniikka&Talous, 2016.

[62] Valmet, LignoBoost - Lignin from Pulp Mill Black Liquor, (n.d.).

[63] L. Kouisni, A. Gagné, K. Maki, P. Holt-Hindle, M. Paleologou, LignoForce system for the recovery of lignin from black liquor: feedstock options, odor profile, and product characterization, ACS Sustain. Chem. Eng. 4 (2016) 5152–5159, https://doi.org/10.1021/acssuschemeng.6b00907.

[64] LignoForce Lignin Recovery Plant, 2014.

[65] West Fraser's first-of-a-kind lignin recovery plant now on stream, Bioplastics Mag (2016).

[66] K. Kuparinen, TRANSFORMING THE CHEMICAL PULP INDUSTRY – FROM AN EMITTER TO A SOURCE OF NEGATIVE CO 2 EMISSIONS FROM AN EMITTER TO A SOURCE OF NEGATIVE, Lappenranta-Lahti University of Technology LUT, 2019.

[67] Aluehallintovirasto, Päätös (2014), https://doi.org/10.1017/CBO9781107415324.004, 232/2014/1.

[68] N. Mandlekar, A. Cayla, F. Rault, S. Giraud, F. Salaün, G. Malucelli, J.-P. Guan, An Overview on the Use of Lignin and its Derivatives in Fire Retardant Polymer Systems, 2016, p. 13, https://doi.org/10.5772/57353. Intech. i.

[69] Pöyry, The Recarbonisation Revolution, 2016.

[70] A. Barret, The European Commission Papers: the Lignin Briefing, (n.d.).

[71] J. Miller, M. Faleiros, Lignin: Technology, Applications, and Markets, 2016.

[72] U.P.M. UPM, Biofuels, n.d. https://www.upmbiofuels.com/. (Accessed 3 December 2019).

[73] SunPine, SunPine, n.d. https://www.sunpine.se/en/. (Accessed 4 December 2019).

[74] SunPine, Annual Report and Sustainability Report, 2011, 2012.

[75] Bioenergy International, SunPine to Invest SEK 250 Million in New Advanced Biofuel Capacity, 4.4.2018 n.d. https://bioenergyinternational.com/biofuels-oils/sunpine-invest-sek-250-million-new-advanced-biofuel-capacity. (Accessed 9 December 2019).

[76] Bioenergy International, St1 and SCA Form Partnership to Produce Renewable Fuels, (n.d.). https://bioenergyinternational.com/biofuels-oils/st1-sca-form-partnership-produce-renewable-fuels (accessed December 5, 2019).

[77] D. Peters, V. Stojcheva, Crude Tall Oil Low ILUC Risk Assessment - Comparing Global Supply and Demand, 2017, pp. 1–23. http://www.upmbiofuels.com/whats-new/other-publications/Documents/Publications/ecofys-crude-tall-oil-low-iluc-risk-assessment-report.pdf.

[78] T. Aro, P. Fatehi, Tall oil production from black liquor: challenges and opportunities, Separ. Purif. Technol. (2017), https://doi.org/10.1016/j.seppur.2016.10.027.

[79] IEA Bioenergy, SunPine Tall Oil Diesel, Sweden - Biofuel as Enabler of the Bioeonomy, 2018. https://www.ieabioenergy.com/wp-content/uploads/2018/02/6-Sunpine-TallOilDiesel_SE_Final.pdf.

[80] Franhofer umsicht, Analysis of the European Crude Tall Oil Industry - Environmental Impact, Socio-Economic Value & Downstream Potential, 2016.

[81] S. Koldste, A Brief History of Hydrothermal Liquefaction, Bio2oil, 2019.

[82] J. Sandquist, Biofuels from waste – what is hydrothermal liquefaction and why is it interesting? SINTEFblog (2019).

[83] A.R.K. Gollakota, N. Kishore, S. Gu, A review on hydrothermal liquefaction of biomass, Renew. Sustain. Energy Rev. 81 (2018) 1378–1392, https://doi.org/10.1016/j.rser.2017.05.178.

[84] RenFuel to build Lignol pilot at Nordic Paper pul mill, Bioenergy Int (2016). https://bioenergyinternational.com/biofuels-oils/renfuel-to-build-lignol-pilot-at-nordic-paper-pulp-mill. accessed January 15, 2020.

[85] RenFuel, New Technology - Revolutionary Cutting Edge Technology for the Production of Bio-Oil, (n.d.). https://renfuel.se/technology/?lang=en (accessed January 16, 2020).

[86] Statkraft, Silva Green Fuel, (n.d.). https://www.statkraft.com/about-statkraft/where-we-operate/norway/silva-green-fuel/(accessed January 26, 2020).

[87] S. Francey, H. Tran, N. Berglin, Global survey on lime kiln operation, energy consumption, and alternative fuel usage, Tappi J. 10 (2011) 19–26.

[88] H. Dernegård, H. Brelid, H. Theliander, Characterization of a dusting lime kiln - a mill study, Nord, Pulp Pap. Res. J. 32 (2017) 25–34, https://doi.org/10.3183/npprj-2017-32-01-p025-034.

[89] S. Francey, H. Tran, A. Jones, Current status of alternative fuel use in lime kilns, Tappi J. 8 (2009) 33–39.

[90] E. Vakkilainen, A. Kivistö, Fossil Fuel Replacement in the Pulp Mills, 2008.

[91] M. Towers, M. Ortiz-Cordova, B. Adams, R. Vandergriendt, P. Beaty, Gasification to Power Kraft Mill Lime Kilns, (n.d.).

[92] C. Breitholtz, The Gasifier at Värö Värö Pulp Mill, 2009.

[93] J. Hrbek, Status report on thermal biomass gasification in countries participating in IEA Bioenergy Task. http://www.ieatask33.org/content/publications/Status_report%5Cnhttp://www.ieatask33.org/app/webroot/files/file/2016/Status_report.pdf, 2016, 33, 163.

[94] Horizon 2020 BIOFIT Project, Retrofit of Metsä Fibre Joutseno Pulp Mill, Factsheet, 2019. Finland.

[95] Bioenergy International, World's Largest Single-Line Pulp Mill Carbon Neutral, 2014. https://bioenergyinternational.com/heat-power/worlds-largest-single-line-pulp-mill-carbon-neutral. (Accessed 11 December 2019).

[96] Energy authority, Maakaasun Hintatilastot, (n.d.). https://energiavirasto.fi/maakaasun-hintatilastot (accessed December 16, 2019).

[97] Valmet, Pulp Mill Lime Kilns Go Fossil Free, 2019. https://www.valmet.com/media/articles/pulping-and-fiber/chemical-pulping/lime-kilns-go-fossil-free/. (Accessed 11 December 2019).

[98] Horizon 2020 BIOFIT Project, Retrofit of Metsä Fibre Joutseno Pulp Mill (Finland), 2019. Factsheet, https://www.biofit-h2020.eu/files/pdfs/190318 - Biofit - Factsheet - Finland_Metsä Fibre_low.pdf.

[99] R. Wadsborn, N. Berglin, T. Richards, Konvertering Av Mesaugnar Från Olje- till Biobränsleeldning – Drifterfarenheter Och Modellering, 2007.

[100] K. Kuparinen, E. Vakkilainen, J. Kärki, Electrolysis and Biomass conversion as options to produce renewable alternatives for fossil lime kiln fuels, in: Pulping, Eng, Environ. Recycl. Sustain. Conf. 2016, vol. 1, PEERS, 2016, pp. 502–509, 2016.

[101] M.T. Reza, J. Andert, B. Wirth, D. Busch, J. Pielert, J.G. Lynam, J. Mumme, Hydrothermal carbonization of biomass for energy and crop production, Appl. Bioenergy 1 (2014) 11–29, https://doi.org/10.2478/apbi-2014-0001.

[102] Z. Liu, A. Quek, S. Kent Hoekman, M.P. Srinivasan, R. Balasubramanian, Thermogravimetric investigation of hydrochar-lignite co-combustion, Bioresour. Technol. 123 (2012) 646–652, https://doi.org/10.1016/j.biortech.2012.06.063.

[103] B. Erlach, B. Harder, G. Tsatsaronis, Combined hydrothermal carbonization and gasification of biomass with carbon capture, Energy 45 (2012) 329–338, https://doi.org/10.1016/j.energy.2012.01.057.

[104] M.C. Rillig, M. Wagner, M. Salem, P.M. Antunes, C. George, H.G. Ramke, M. M. Titirici, M. Antonietti, Material derived from hydrothermal carbonization: effects on plant growth and arbuscular mycorrhiza, Appl. Soil Ecol. 45 (2010) 238–242, https://doi.org/10.1016/j.apsoil.2010.04.011.

[105] A. Funke, Fate of plant available nutrients during hydrothermal carbonization of digestate, Chem. Ing. Tech. 87 (2015) 1713–1719, https://doi.org/10.1002/cite.201400182.

[106] P. Axegård, C-Green's HTC-Solution for Conversion of Biosludge to Hydrochar - Hydrothermal Carbonization, 2019.

[107] J. Medick, I. Teichmann, C. Kemfert, Hydrothermal carbonization (HTC) of green waste: mitigation potentials, costs, and policy implications of HTC coal in the metropolitan region of Berlin, Germany, Energy Pol. 123 (2018) 503–513, https://doi.org/10.1016/j.enpol.2018.08.033.

[108] J. Stemann, B. Erlach, F. Ziegler, Hydrothermal carbonisation of empty palm oil fruit bunches: laboratory trials, plant simulation, carbon avoidance, and economic feasibility, Waste and Biomass Valorization 4 (2013) 441–454, https://doi.org/10.1007/s12649-012-9190-y.

[109] B. Erlach, B. Wirth, G. Tsatsaronis, Co-production of electricity, heat and biocoal pellets from biomass: a techno-economic comparison with wood pelletizing, Proc. World Renew. Energy Congr. – Sweden 57 (2011) 508–515, https://doi.org/10.3384/ecp11057508, 8–13 May, 2011, Linköping, Sweden.

[110] E.M. Ekstrand, M. Larsson, X. Bin Truong, L. Cardell, Y. Borgström, A. Björn, J. Ejlertsson, B.H. Svensson, F. Nilsson, A. Karlsson, Methane potentials of the Swedish pulp and paper industry - a screening of wastewater effluents, Appl. Energy (2013), https://doi.org/10.1016/j.apenergy.2012.12.072.

[111] A. Stoica, M. Sandberg, O. Holby, Energy use and recovery strategies within wastewater treatment and sludge handling at pulp and paper mills, Bioresour. Technol. (2009), https://doi.org/10.1016/j.biortech.2009.02.041.

[112] P. Weiland, Biogas production: current state and perspectives, Appl. Microbiol. Biotechnol. 85 (2010) 849–860, https://doi.org/10.1007/s00253-009-2246-7.

[113] L. Habets, W. Driessen, Anaerobic treatment of pulp and paper mill effluents – status quo and new developments, Water Sci. Technol. 55 (2007) 223–230, https://doi.org/10.2166/wst.2007.232.

[114] Union Engineering, Norske Skog Invest in Biogas Upgrade, 2017. https://union.dk/news-pr/all-news/innovative-biogas-upgrade-to-norske-skog/. accessed January 3, 2020.

[115] RISI Technology Channels, Norske Skog to Invest NOK 150 Million in New Biogas Facility at its Saugbrugs Mill in Norway, 2015. https://technology.risiinfo.com/bio-insight/west-europe/norske-skog-invest-nok-150-million-new-biogas-facility-its-saugbrugs-mill-norway. accessed January 3, 2020.

[116] Norske Skog Golbey, More than Paper - Our Corporate Social Responsibility, 2018. https://norskeskog-golbey.com/wp-content/uploads/2019/03/Norske-Skog_RSE_ENG_BD.pdf.

[117] Stora Enso, Stora Enso and Gasum to Make Renewable Energy from Wastewater in Sweden, n.d. https://www.storaenso.com/en/newsroom/regulatory-and-investor-releases/2018/10/stora-enso-and-gasum-to-make-renewable-energy-from-wastewater-in-sweden. accessed February 3, 2020

[118] Stora Enso, Renewable Energy from Wastewater, n.d. https://www.storaenso.com/en/newsroom/news/2016/9/renewable-energy-from-wastewater. (Accessed 5 February 2020).

[119] Domsjö, Biorefinery Products, n.d. http://www.domsjo.adityabirla.com/en/sidor/More-products.aspx. (Accessed 3 February 2020).

[120] Rottneros, Your pulp company - Rottneros annual report 2018. https://www.rottneros.com/media/1673/annual-report-2018.pdf, 2018.

[121] Rottneros, Rottneros Mill Invests in a Fossil-free Production Process, n.d. https://news.cision.com/rottneros-ab/r/rottneros-mill-invests-in-a-fossil-free-production-process,c2819724. (Accessed 3 February 2020).

[122] A. do Carmo Precci Lopes, C. Mudadu Silva, A. Pereira Rosa, F. de Ávila Rodrigues, Biogas production from thermophilic anaerobic digestion of kraft pulp mill sludge, Renew. Energy (2018), https://doi.org/10.1016/j.renene.2017.08.044.

[123] C. Dybevig, NOPA, (2017).

[124] Norske Skog Golbey, Projects & Bio-Economy, n.d. https://norskeskog-golbey.com/corporate-responsibility/projects-bio-economy/?lang=en. (Accessed 3 January 2020).

[125] F. Ometto, J. Ejlertsson, Integrated Biogas Production for Nutrients Recirculation : a Large-Scale Demonstration Project, 2017.

[126] Scandinavian Biogas, EffiSludge, (n.d.). http://scandinavianbiogas.com/effisludge/about/(accessed December 20, 2019).

[127] M. Magnusson, P. Alvfors, Biogas from mechanical pulping industry: potential improvement for increased biomass vehicle fuels, in: Proc. 25th Int. Conf. Effic. Cost, Optim. Simul. Energy Convers. Syst. Process. ECOS, 2012, pp. 56–67. Perugia, Italy.

[128] D. Donnér, Impact on Carbon Emissions Applying the Sustainable EffiSludge Wastewater Treatment Concept to the Nordic Pulp- and Paper Industry, 2018.

[129] BIOFIT Industry Map, (n.d.). https://www.biofit-h2020.eu/biofit-industry-map/(accessed March 30, 2020).

[130] M. Kapsalaki, V. Leal, Recent progress on net zero energy buildings, Adv. Build. Energy Res. 5 (2011) 129–162, https://doi.org/10.1080/17512549.2011.582352.

[131] M. Björk, J. Rinne, K. Nikunen, A. Kotilainen, V. Korhonen, H. Wallmo, A. Karlsson, Successful start-up of ligning extraction at Stora Enso Sunila mill, in: 6th Nord. Wood Bioerfinery Conf., VTT Technical Research Centre of Finland Ltd, Helsinki, 2015, pp. 185–192.

[132] V. Pisto, Suomessa Muhii Jättipotti - Tehdas Eristi Puusta Ainee, Josta Voi Tehdä Ympäristöystävällisiä Maaleja Ja Liimoja, Yle Uut., 2018.

[133] Tekniikka & Talous, Stora Enso Aikoo Investoida Sunilaan - Ministeriö Tukee, n.d. https://www.tekniikkatalous.fi/uutiset/ks-stora-enso-aikoo-investoida-sunilaan-ministerio-tukee/0cb5908c-17aa-34e2-8125-5abc76a61df4. (Accessed 18 February 2020).

[134] Greenreality, World's First Biorefinery Producing Wood-Based Renewable Diesel | Greenreality, n.d. https://www.greenreality.fi/en/acts/worlds-first-biorefinery-producing-wood-based-renewable-diesel. (Accessed 25 October 2019).

[135] UPM Biofuels, UPM BioVerno Diesel for Fuels, n.d. https://www.upmbiofuels.com/traffic-fuels/upm-bioverno-diesel-for-fuels/. (Accessed 25 October 2019).

[136] Itä-Suomen Ympäristölupavirasto, Päätös 45/08/2 Biomassan Kuivaus-, Kaasutus- Ja Koelaitoksen Ympäristölupa Ja Toiminnan Aloittamislupa, 2008.

[137] A. Martinsson, Lime Kiln & Pellets - Ongoing Projects at Södra Cell Värö, (n.d.).

[138] A. Sharrard, Swedish Energy Agency awards grant to HTC industrial demo project in Finland, Bioenergy Int (2018).

[139] A. Sherrard, Swedish Energy Agency awards grant to HTC industrial demo project in Finland, Bioenergy Int (2018).

[140] A.B. Scandinavian Biogas Fuels International, Scandinavian Biogas Annual Report 2018, 2018.

[141] F. Ometto, LBG from Industrial Biowaste: Plant Implementation and Fuel Utilisation, 2019, pp. 1–13.

[142] Promaint, Stora Enson Kartonkitehdas Laittaa Jätevedet Kuriin Uudella Biokaasureaktorilla, n.d. https://promaintlehti.fi/Turvallisuus-ja-ymparisto/Stora-Enson-kartonkitehdas-laittaa-jatevedet-kuriin-uudella-biokaasureaktorilla. (Accessed 17 February 2020).

[143] Stora Enso, Sustainability - Part of Stora Enso's Annual Report 2018, 2018. https://www.storaenso.com/-/media/Documents/Download-center/Documents/Annual-reports/2018/STORAENSO_Sustainability_2018.ashx.

[144] European Commission, National Energy and Climate Plans (NECPs), n.d. https://ec.europa.eu/info/energy-climate-change-environment/overall-targets/national-energy-and-climate-plans-necps_en. accessed April 1, 2020
[145] European Commission, Voluntary Schemes, n.d. https://ec.europa.eu/energy/node/74. (Accessed 25 March 2020).
[146] A. Berlina, N. Mikkola, Bioenergy Development in Finland and Sweden: the Cases of North Karelia, Jämtland, and Västernorrland, 2017.
[147] CEPI, The Age of Fibre - the Pulp and Paper Industry's Most Innovative Products, 2015. https://www.cepi.org/the-age-of-fibre-the-pulp-and-paper-industrys-most-innovative-products/.
[148] CEPI, The Forest Fibre Industry - 2050 Roadmap to a Low-Carbon Bio-Economy, 2011. https://www.cepi.org/wp-content/uploads/2020/08/2050_roadmap_final.pdf.
[149] Confederation of European Paper Industries (CEPI), The Challenge: Decarbonising whilst Being Recycling Pioneer, 2018.
[150] European Commission, Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control), Off. J. Eur. Union (2010).
[151] Ministry of Economic Affairs and Employment of Finland, Finland's Integrated Energy and Climate Plan, 2019.
[152] The Ministry of Infrastructure, Sweden's Integrated National Energy and Climate Plan, 2020.
[153] UPM Biofuels, Certification, n.d. https://www.upmbiofuels.com/sustainable-choice/certification/. accessed March 26, 2020
[154] EBC foundation, European Biochar Certificate, n.d. http://www.european-biochar.org/en/home. accessed March 26, 2020
[155] A. Näyhä, H.L. Pesonen, Diffusion of forest biorefineries in Scandinavia and North America, technol. Forecast, Soc. Change 79 (2012) 1111–1120, https://doi.org/10.1016/j.techfore.2012.01.006.
[156] ePure European Renewable Ethanol, European Renewable Network, 2018.
[157] C. Hobson, C. Márquez, Renewable Methanol Report, Methanol Inst, 2018, pp. 1–26.
[158] Research and Markets, Crude Tall Oil Derivatives Market - Growth, Trends, and Forecast, 2019 - 2024 n.d. https://www.researchandmarkets.com/reports/4536284/crude-tall-oil-derivatives-market-growth. (Accessed 5 December 2019).
[159] Eurostat, Natural Gas Supply Statistics, n.d. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics&oldid=447636#Consumption_trends. (Accessed 9 April 2020).
[160] N. Scarlat, J.F. Dallemand, F. Fahl, Biogas: developments and perspectives in Europe, Renew. Energy 129 (2018) 457–472, https://doi.org/10.1016/j.renene.2018.03.006.
[161] European Biogas Association, EBA Statistical Report 2018, 2018. http://european-biogas.eu/2017/12/14/eba-statistical-report-2017-published-soon/.
[162] Eurostat, Natural Gas Price Statistics, n.d. https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics#Natural_gas_prices_for_non-household_consumers. (Accessed 9 April 2020).
[163] Tilastokeskus (Finnish Statistics), Energian Hinnat, 2020.
[164] R. Radics, S. Dasmohapatra, S.S. Kelley, Systematic review of bioenergy perception studies, BioResources 10 (2015) 8770–8794, https://doi.org/10.15376/biores.10.4.Radics.
[165] M.M.E. Moula, J. Nyári, A. Bartel, Public acceptance of biofuels in the transport sector in Finland, Int. J. Sustain. Built Environ. 6 (2017) 434–441, https://doi.org/10.1016/j.ijsbe.2017.07.008.
[166] T. Kortsch, J. Hildebrand, P. Schweizer-Ries, Acceptance of biomass plants - results of a longitudinal study in the bioenergy-region Altmark, Renew. Energy 83 (2015) 690–697, https://doi.org/10.1016/j.renene.2015.04.059.
[167] A. Wüste, P. Schmuck, Social Acceptance of Bioenergy Useand the Success Factors of Communal Bioenergy Projects, Springer, 2013, https://doi.org/10.1007/978-94-007-6642-6.
[168] Stora Enso, Annual Report 2020, 2020. https://www.storaenso.com/-/media/Documents/Download-center/Documents/Annual-reports/2020/STORAENSO_Annual_Report_2020.pdf#page=64.
[169] UPM, Annu. Rep. (2019), https://doi.org/10.3934/math.2020i, 2019.
[170] E. Vakkilainen, E. Välimäki, Effect of lignin separation to black liquor and recovery boiler operation steam generation from biomass view project effect of lignin separation to black liquor and recovery boiler operation, in: TAPPI Eng. Pulping Environ. Conf., 2009, https://doi.org/10.13140/2.1.2039.6485.
[171] R. Deshpande, The Initial Phase of Sodium Sulfite Pulping of Softwood, 2016.
[172] Horizon 2020 BIOFIT Project, Retrofit of Metsä Fibre Joutseno Pulp Mill (Finland), 2019. https://www.biofit-h2020.eu/files/pdfs/190318-Biofit-Factsheet-Finland_Metsä Fibre_low.pdf.
[173] European Commisssion, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Stepping up Europe's 2030 Climate Ambition, Investing in a Climate-Neutral Future for the Benefit of O, 2020. https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf.
[174] Wageningen Economic Research, Netherlands Environmental Assessment Agency, Wageningen Environmental Research, National Renewable Energy Centre, Study Report on Reporting Requirements on Biofuels and Bioliquids Stemming from the Directive (EU) 2015/1513, 2017. https://ec.europa.eu/energy/sites/ener/files/documents/20170816_iluc_finalstudyreport.pdf.
[175] J. Ringman, B.A. Kennard, U. Leberle, B. de Galembert, N. Rega, reportSustainability Report, n.d.
[176] J. Hansson, R. Hackl, M. Taljegard, S. Brynolf, M. Grahn, The potential for electrofuels production in Sweden utilizing fossil and biogenic CO 2 point sources, Front. Energy Res. 5 (2017) 1–12, https://doi.org/10.3389/fenrg.2017.00004.
[177] European Commission, COM, 640 Final, The European Grean Deal, 2019, https://doi.org/10.1017/CBO9781107415324.004 n.d.
[178] European Union, Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, Off. J. Eur. Union (2018) 1–128, 2018.
[179] European Commisssion, Commission Delegated Regulation (EU) of 13.3, Supplementing Directive (EU) 2018/2001 as Regards the Determination of High Indirect Land-Use Change-Risk Feedstock for Which a Significant Expansion of the Production Area into Land with High Carbon Stock, 2019, https://doi.org/10.1017/CBO9781107415324.004, 2019.
[180] European Commission, Framework for the Taxation of Energy Products and Electricity, COUNCIL DIRECTIVE 2003/96/EC of 27 October 2003 restructuring the Community, Off. J. Eur. Union, 2003, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:283:0051:0070. EN:PDF.
[181] European Commission, Energy Taxation, 2019. https://ec.europa.eu/energy/en/topics/markets-and-consumers/energy-taxation. (Accessed 27 February 2020).
[182] European Commisssion, Commission Staff Working Document Evaluation of the Council Directive 2003/96/EC of 27 October 2003 Restructing the Community Framework for the Taxation of Energy Products and Electricity, 2019. https://ec.europa.eu/taxation_customs/sites/taxation/files/energy-tax-report-2019.pdf.
[183] ePure, European Renewable Ethanol - Overview of Biofuel Policies and Markets across the EU-28, 2018. http://www.europarl.europa.eu/RegData/etudes/etudes/join/2012/475085/IPOL-ITRE_ET%282012%29475085_EN.pdf.
[184] European Chemicals Agency, Understanding REACH, n.d. https://echa.europa.eu/regulations/reach/understanding-reach. (Accessed 27 February 2020).
[185] European Commisssion, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, Off. J. Eur. Union, 2008.
[186] European Commission, End-of-waste Criteria, 2019. https://ec.europa.eu/environment/waste/framework/end_of_waste.htm. (Accessed 27 February 2020).
[187] Confederation of European Paper Industries (CEPI), Best Available Technique (BAT) Conclusions for the Production of Pulp, Paper and Board - Implementation Guide, Discussion on the BAT Conclusions for the Pulp and Paper Sector, 2017, pp. 31–35, https://doi.org/10.1016/b978-0-12-811099-7.00003-4.