TECHNICAL OPTIONS FOR RETROFITTING INDUSTRIES WITH BIOENERGY

A HANDBOOK

BIOFIT
Bioenergy Retrofits for Europe's Industry

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The BIOFIT project

Bioenergy is an essential form of renewable energy, providing approximately 60% of the current renewable energy supply in the EU28. Spurred by innovation, bioenergy technologies are becoming ever more advanced and diverse, leading to the energy-efficient production of power, heat and cooling, and a variety of transport fuels. Retrofitting – which means replacing a part of an existing facility or installation with state-of-the-art equipment – can be a cost-effective solution for expanding bioenergy use in certain industries. Retrofitting is one of the fast ways to increase Europe's renewable energy share by making the energy production of existing industries more sustainable.

The BIOFIT project, supported by the Horizon 2020 programme of the European Union, aims to facilitate the introduction of bioenergy retrofitting in European industries. Retrofitting means often lower capital costs, shorter lead times, faster implementation, fewer production time losses and lower risks. The project facilitates the introduction of bioenergy retrofitting in five specific sectors[1], namely:

- First-generation biofuels industry
- Pulp and paper industry
- Fossil refineries
- Fossil power generation
- Combined Heat and Power (CHP)

More specifically, the objectives of the BIOFIT project are:

- To develop 10 concrete proposals (Case Studies) for bioenergy retrofitting for each of the named industries, together with industry and market actors that are committed to implement BIOFIT results.
- To obtain an accurate and complete overview of options for bioenergy retrofitting in the targeted industries, as well as insight in the conditions under which each type of bioenergy retrofit is feasible and communicate this to the target groups.
- To involve, engage and support stakeholders and market actors, especially from industry by communicating results, disseminating knowledge, providing opportunity for dialogue, and developing best practices and tools.
- To evaluate framework conditions (legal, institutional and political) in order to identify general and industry-specific barriers and enablers.
- To provide advice to policy makers at national and regional level to serve as input for more informed policies, market support and financial frameworks.

Core actions in BIOFIT include the dissemination of existing best practice examples and the development of 10 retrofit case studies in collaboration with industrial partners. In parallel, the broader industry will be engaged and supported through five industry fora (working groups).

The three-year project started in October 2018. The BIOFIT consortium consists of fourteen partners from eight European countries: Sweden, The Netherlands, Germany, Spain, Finland, Austria, Bosnia-Herzegovina and Greece. The consortium consists of both industrial partners and academic / research partners.

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[1] The selection of these industries is due to the specifications of the call text in the Horizon 2020 programme, under which BIOFIT was submitted in the call for proposals.

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Content

1 Introduction

In the last few decades it has become increasingly clear that fossil fuel resources are scarce, finite and their use can harm the environment and our climate. Increasing renewable energy production will, besides reducing our CO_2 emissions according to the Paris Agreement (2015), ensure enhanced security of supply, stimulate innovation, create new jobs and contribute to economic development.

In the EU Renewable Energy Directive of 2009, national renewable energy targets were agreed which would lead to 20% renewable energy production in the EU by 2020. Since then, many Member States have experienced rapid growth of renewable energy production, often even beyond the mandated targets, which shows the broad consensus in Europe on this topic. In the EU's "Clean Energy for all Europeans" package of 2016, the unequivocal choice for renewable energy was further enshrined by adopting a binding target of 27% final energy consumption from renewable energy by 2030. In 2018, the target was revised upwards to share of at least 32% of renewable energies. This is in line with the EU 2050 roadmap which foresees a phasing out of fossil fuels to be replaced by renewables.

Bioenergy is an essential form of renewable energy, providing an estimated 60% of EU's renewable energy production in 2017[2]. In the future, bioenergy will remain important. The International Energy Agency (IEA) notes in its 2017 Roadmap[3] that bioenergy plays an essential role in its 2DS (2°C Scenario), providing almost 20% of the global cumulative CO_2 emission savings by 2060. Bioenergy is a complex and sometimes controversial topic. There is an increasing understanding that only bioenergy that is supplied and used in a sustainable manner has a place in a low carbon energy future.

Modern bioenergy takes on many forms. Relatively straight-forward applications, such as the generation of heat by combustion of wood is implemented alongside biogas production through anaerobic digestion (AD) and production of transport fuels. Spurred by innovation, technologies are becoming more advanced and diverse, leading to the production of a variety of advanced transport fuels (first and second-generation bioethanol, biodiesel and bio-kerosene), intermediate bioenergy carriers and high-efficiency, low carbon emission production of power, heating and cooling.

Besides erecting entirely new bioenergy plants, retrofitting, which means replacing parts of a factory or installation with state-of-the-art equipment, can be an alternative to replace fossil fuels or to upgrade outdated renewable energy technologies. Retrofitting means often lower capital expenditure (CAPEX), shorter lead times, faster implementation, fewer production time losses and lower risks, compared to the complete demolition of old plants and the erection of entirely new bioenergy plants.

The BIOFIT project, supported by the Horizon 2020 programme of the European Union, supports bioenergy retrofitting in Europe's first-generation biofuels industry, pulp and paper industry, fossil refineries, fossil power plants, and in combined heat and power (CHP) industries. The selection of these industries is due to the specifications of the call text in the Horizon 2020 programme, under which BIOFIT was submitted in the call for proposals.

To present the technical opportunities of retrofitting, this handbook on "Technical options for retrofitting industries with bioenergy" was written by the BIOFIT consortium members. The handbook paints a broad picture of technical solutions for the targeted industries, which are very different, but which may face similar challenges. The objective is to provide this information to stakeholders and decision makers in the relevant industries who might have little technical background knowledge. The handbook should facilitate the technical understanding

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[2] http://www.europeanbioenergyday.eu/

[3] http://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

of bioenergy opportunities for their industries. It is presented in simple language and includes many easy-to-understand graphs and illustrations.

2 The retrofitting process

Bioenergy retrofitting is the replacement of parts of a factory or installation with state-of-the-art biomass technologies. Thereby, it can replace fossil fuels or upgrade outdated renewable energy technologies. The alternative to retrofitting would be the erection of entirely new bioenergy plants, involving the demolition of the old factory or installation. Potential advantages of retrofitting can be lower capital expenditures (CAPEX), shorter lead times, faster implementation, fewer production time losses and lower risks.

However, in practice, retrofitting very much depends on the type of the industry and on the objectives. The retrofitting process can be characterized by the following parameters:

- **Type and scale of the industry**: The type and size of the industry influences many factors of retrofitting, such as the technologies, financing, objectives, etc.
- **Core product of the industry**: The biomass used for retrofitting can be used as process energy for the industry (e.g. in the pulp and paper sector) or can constitute the product of the industry itself (e.g. 2nd generation biofuels)
- **Number of implementation "steps" of the retrofitting**: The retrofitting can be one project that is implemented in a relatively short period of time, or it could be a multi-step process that includes various individual projects.
- **Completeness of retrofitting**: The retrofitting can be a complete switch from the old system to only biomass use, or it could be a partial switch to biomass systems.
- **Time frame of the retrofitting**: depending on the size and the type of the industry, the retrofitting can be implemented within a very short time (e.g. within one year) or within a long timeframe (several years).

The general steps of the retrofitting process are shown simplified in Figure 1. Depending on the size of the retrofitting measure, its implementation can be very time consuming, long-lasting and capital intensive, especially for large retrofitting projects.

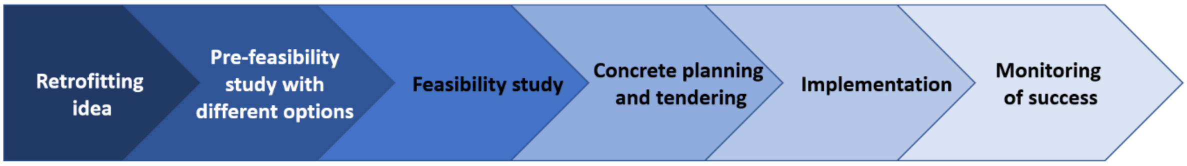

Figure 1: Simplified scheme of the retrofitting process

2.1 Involved stakeholders

The retrofitting of larger industries usually involves several stakeholders within the company (internal stakeholders) and stakeholders that are external to the company. The potential involvement and interest in the retrofitting process from the internal and external stakeholders are presented in Table 1 and Table 2. The special role of citizens and consumers is described in chapter 2.2. It is important to identify the relevant stakeholders for each retrofitting process and to involve them at the right stage of project implementation: often it is better to involve them as early as possible and not too late in order to anticipate the key steps for implementation, as well as possible barriers that need to be addressed in a timely manner.

Table 1: Internal stakeholders involved in the retrofitting process

Internal stakeholders	*Involvement and interest in the retrofitting process*
Top management of the company	• Makes the main decisions in the company • The management support of the retrofitting project depends on the overall company goals • May need to be convinced about the advantages of retrofitting • Retrofitting may contribute to a good image of the company
R&D Department	• Often responsible for the planning and implementation of the retrofitting • Responsible to bring innovations to the company
Other departments	• Depending on the complexity of the retrofitting, several company departments may need to be involved, such as departments for financing, procurement, operation, technologies, environmental issues, etc.
Operational staff and technicians	• The technicians and operational staff need to contribute their technical knowledge and experience

Table 2: External stakeholders involved in the retrofitting process

External stakeholders	*Involvement and interest in the retrofitting process*
Policy makers and politicians	• Define political targets and legislation which could affect the company • Benefit positively from industrial retrofitting as it contributes to political targets
Industry associations and industry lobby groups	• Influence politicians, but also company decisions • May promote or discourage retrofitting, depending on the objectives of the association/ industry group • Are interested in a positive image for the industry they represent
Environmentalists, NGOs	• Retrofitting with high impacts is acknowledged by environmentalists • Bioenergy supply needs to be sustainable and avoid negative environmental impacts • Retrofitting with low impacts may be seen by some environmentalists as “greenwashing”
Local authorities	• Responsible for relevant permits, necessary for carrying out the retrofit project. • Can provide incentives.

Financial institutes, banks	- Provide financing (loans)
Citizens and consumers	- Interested in low prices of environmentally friendly products (e.g. district heating companies want heat from biomass instead of coal to sell more sustainable heat to their consumers) - Influence policies through the election of politicians
Technology providers	- Are crucial for the implementation of the retrofitting - Want to sell their technologies: they are interested in delivering good services to develop a good reputation and problem-free operation
External consultants and experts (companies, universities, etc.)	- Are crucial in the retrofitting process, if the industry lacks expertise or if the external expertise is cheaper than the internal one - Want to sell their consulting services - Special consultants may be needed for technology approvals (e.g. related to safety issues)
Public press and media	- Are interested in stories about successful retrofittings - Can transfer information to the public, and thus contribute to a positive image

2.2 The roles of citizens and consumers

Climate change, biodiversity loss or greenhouse gas emissions have gained significant societal, political and media attention in recent years. This has resulted in a gradual increase of public awareness about the drawbacks and boundaries of the fossil fuel-based economy. The alternative bioeconomy aims to replace fossil fuels by using renewable biomass in products and energy. Within the larger context of the bioeconomy, there is a paradigm shift evolving towards production and consumption modes that are more responsible and responsive to the carrying capacity of the planet. Particularly Sustainable Development Goal 12, which focuses on responsible consumption and production by, among others, promoting resource and energy efficiency, is noteworthy here.

Considering that retrofitting practices and their economic advantages and sustainability merits are central, it is also important to realise that industries do not operate in a societal vacuum. Next to the dimensions of *Profit* and *Planet*, the **Triple P** is completed with *People*. The idea of Triple P suggests that innovative retrofitting practices devoted to making better use of non-fossil fuel sources of energy are about more than just improving technological feasibility and economic viability. Retrofitting, then, is not only a matter of business performance and environmental impact reduction, but also of social responsibility and public acceptance. It is important to investigate whether and how retrofitting serves efficiency (Profit) and sustainability (Planet) goals, it is also important to explore whether and to what extent retrofitting initiatives and investments are considered socially appreciated or interpreted by **citizen-consumers**[4] as socially and morally responsible (People).

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[4] Throughout this chapter we use primarily the word **consumer** and occasionally use it interchangeably with citizen-consumer. The notion of consumer here is meant to be synonymous with citizen or general public. We realise that the terms consumer and citizen are often interpreted as a

Admittedly, this societal perspective on bioeconomy is not yet mainstream, and easily taken as far-fetched (“What does the general public have to do with retrofitting practices in bioenergy installations?”). The following sections, however, provide several arguments and considerations to illustrate that taking consumers into account is important to the further development of the emerging bioeconomy as well as bioenergy retrofitting.

2.2.1 *Importance of consumers in bioeconomy*

Several arguments are helpful in advocating the importance of consumption and consumers with respect to greening the economy.

We live in a consumer society that is characterised by the economic, social and cultural importance of consumption. Economic growth and prosperity are highly dependent on **consumption levels**. The socio-cultural importance of consumption manifests itself in the identity and symbolic value of consumer goods to contemporary people: “you are what you buy”. Given the pivotal role of consumption in today’s society, one could places one’s self outside reality when consumption is neglected. Thus, for a bioeconomy to thrive, supportive consumer engagement is better not ignored. As a result of public acceptance and legitimacy, consumers and society provide companies a licence to operate. General tendencies such as companies’ growing attention to **corporate social responsibility** (CSR), addressing societal challenges, as well as the recognition in business circles that societal support is critical to economic viability, are perhaps even more relevant in case of building an unconventional bioeconomy that aims to replace the well-known fossil-based economy. The creation of an alternative to the conventional implies confrontation and resistance, transition is never straightforward. A research focus on what positions consumers take and pathways they prefer to follow in bioeconomy transition is therefore of added value to our understanding of the social foundation underlying it. Consumer engagement could work as a catalyst or a grave challenge to the greening of the economy and bioenergy retrofitting as a part of this transition.

Another argument for not losing sight of consumer preferences and priorities can be found in the idea that transition is not only a matter of technological innovation, but also of societal commitment and changes in human behaviour.

Vainio et al. (2019) explicitly split the item “nature of change” into **technological change** on the one hand and **lifestyle change** on the other. Technological and lifestyle changes are not necessarily opposites and often interrelated. However, making a distinction between these shows more clearly what citizen-consumers believe they could do themselves and what bioeconomy transition could mean in terms of technological possibilities and consequences. This paper offers inspiration for the idea that consumer-oriented research makes sense when bioeconomy transition is concerned. It helps to look at bioeconomy transition more broadly and to realise that it is not solely a matter of taking efficiency measures, but ultimately aims to make a positive impact on greening of the production-consumption system at large. Consequently, citizen-consumers are participants in this process, have opinions and visions about it, and are important stakeholders in providing bioeconomy with necessary legitimacy and support.

While these statements are gaining approval recently, it is still not usual in bioeconomy and circular economy discourses to focus on **consumer behaviour** and engagement. On the contrary, it must be realised that discussions are primarily technology-driven and focused on technological innovations. Transitioning the fossil-based economy into a more sustainable economy is as yet first and foremost approached as a question of improving production and/or

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binary pair and defined in terms of different behavioural motives and goals – consumers portrayed as more individualistic and short-term oriented while prototypical citizens are presented as more collectivistic of nature and taking possible long-term consequences of their behavioural choices into account. Citizen-consumer is used in scholarly literature to nuance or neutralise this division between the two. We will not delve into these matters in this chapter but simply note that when we use consumer engagement one is free to read citizen or public engagement.

logistic processes. Having said this, among academics and policymakers growing recognition can be noticed lately that consumers are part of this transition too. Consumers are seen in the light of the social basis for greening the economy, or because of their purchasing power to buy "green" products. Usually consumers are taken for rather passive actors, not for proactive change agents. In sum, consumers are increasingly believed to have a role to play, but it remains often unclear and rudimentary what their contribution to the transition process actually is or could be (see also Kirchherr et al., 2017). This does not mean to devalue the recent attempts to incorporate consumers and consumption in, particularly, the circular economy (Sijtsema et al., 2020).

2.2.2 Consumer perceptions and segmentation

In recent consumer studies in the field of bio-based economy it is concluded that **consumer perceptions** about bio-based economy generally and several concrete bio-based consumer goods are not clear, unambiguous nor stable (Onwezen et al., 2017; Pfau et al., 2017; Sijtsema et al., 2016). Such studies suggest that many consumers are unfamiliar with bioeconomy, misunderstand it or have vague doubts about it. All in all, research so far indicates that a gap exists between consumer perceptions and the bioeconomic shift. In this respect it seems that not much has been changed since an earlier study pointing to "lack of knowledge and adequate flow of information; and insufficient perception and acceptance" as prime non-technical challenges in the bio-based domain (Rösch & Kaltschmitt, 1999: 347). Given the current situation in which bioeconomy appears to be no main consumer concern, information and awareness raising are still preconditions for establishing consumer commitment. Information and involvement are necessary stepping stones for consumers to possibly become actual enablers of the bioeconomy.

It is expected that consumers differ in their engagement and enthusiasm to support the greening of the economy. People are often reluctant to changes and prefer things as they are (see e.g. Kahneman & Tversky, 1979 or Samuelson & Zeckhauser, 1988 for earlier studies). This so-called **status quo bias** is understandable enough when it is realised that changes may imply more uncertainties, unpredictabilities, risks, costs and efforts.

In contrast to this natural negative perception, changes can be also related to **positive perceptions** such as attractiveness, excitement, improvement and worth. Consumers are also curious for novelties and believe in progress. In this respect, the categories of adopters by Rogers (1962) are still instructive. Five categories were distinguished ranging from innovators and early adopters, to early majority and late majority, and, finally, laggards. The first are receptive to innovations. Innovators and early adopters are willing and able to cope with uncertainties and to take the risks accompanying innovations. In contrast to these avant-garde leaders, the late majority's and the laggards' engagement and support to innovations is low and slow. A further distinction can be made between innate innovativeness, which can be defined as a personality trait that reflects an individual's innate tendency to seek out new experiences (Hirschman, 1980), and domain-specific innovativeness, which captures an individual's predisposition to certain domains of interest and reflects the tendency to quickly adopt new products or ideas from this domain (Bartels & Reinders, 2011; Goldsmith & Hofacker, 1991). Domain-specific innovativeness is often closely related to involvement in and knowledge about a certain product domain. For instance, some individuals are very much interested in technological gadgets whereas others show interest in food, cars or household appliances, just to name a few.

Both inclinations can be regarded as two fundamental human tendencies: **neophobia** (i.e. the fear for novelty) and **neophilia** (i.e. the urge towards novelty). As a result, people are alternating between acceptance and avoidance of innovations. Such alternation can cause ambivalent feelings affecting, for instance, people's sensitivity to the perceived risks or unnaturalness of innovative production processes or influencing their intention to purchase and consume end-products produced by technology-driven innovations. This directly refers to another aspect of consumers' opinions and reactions to innovations.

Next to neophobic reluctance and neophilic receptiveness to innovations, it could be relevant to make a distinction between **innovative production processes** and **innovation embodied in new consumer goods**. The latter will generally be more concrete to consumers and give them the opportunity to buy and use these products. Innovations concerning production process technologies will generally be more abstract to consumers and/or give them the impression that the role they could play is less influential. With respect to consumer engagement and acceptance of retrofitting, it seems important to keep this difference in mind too. Retrofitting, after all, concerns primarily innovation of production processes rather than consumer products. In principle, this alienates consumers from retrofitting initiatives.

The broader goal of retrofitting is sustainability and thus, consumer engagement needs to be seen from the viewpoint of **sustainable consumption**. This blossoming field of research has resulted in ample evidence that consumer choice is not only driven by egocentric, price-conscious or convenience-focused motives, but that consumers are often aware of possible harmful consequences their behavioural choices could have, take consciously environmental or societal concerns into account, and try to adopt a corresponding “green” consumption style.

It has been found that consumer commitment to sustainability differs and various consumer segments can be distinguished. An environmental segmentation study by Defra (2008), for instance, finds seven clusters with distinct beliefs about environmental issues and behaviours towards the environment. The segments cover *Positive greens* and *Concerned consumers* on the “green” side and *Cautious participants* or *Honestly disengaged* on the low potential and unwilling “non-green” side of the spectrum.

2.2.3 Investigating the role of consumers in retrofitting

This section describes how to investigate consumer interest and support for greening the economy, and, more specifically, for efforts in bioenergy retrofitting. The approach is based on people’s preferences and priorities on sustainability, technological innovation and industries’ responsibility for greening the economy. It is important to investigate what consumers consider important and valuable personally (How “green” are consumers themselves?), and on what consumers expect industries to do as well as whether they trust companies social responsibility business policies (How responsible and reliable do consumers want companies to be in greening the economy?).

Consumer approval and acceptance can be investigated by assessing consumer trust and distrust and their perception towards “**greenwashing**“ of a company (Cho, 2006; Leonidou & Skarmeas, 2017). Consumers can be asked to respond to such statements as:

- Companies mislead (with words or visuals) about the environmental features of their production practices or end products.
- Companies provide vague or seemingly unprovable environmental claims for their production methods.
- Companies overstate or exaggerate the environmental features of their production processes.
- Companies leave out or hide important information about the real environmental features of their production processes.
- Companies promote consumers‘ benefits as well as their own.
- Companies operate their business in responsible and reliable manners.

This can be further investigated by taking the framework of Mazutis & Slawinksi (2015) into account in which the two dimensions of authenticity of CSR activities, distinctiveness and social connectedness, are defined (Figure 2). They describe the stakeholder perceptions on Corporate Social Responsibility (CSR).

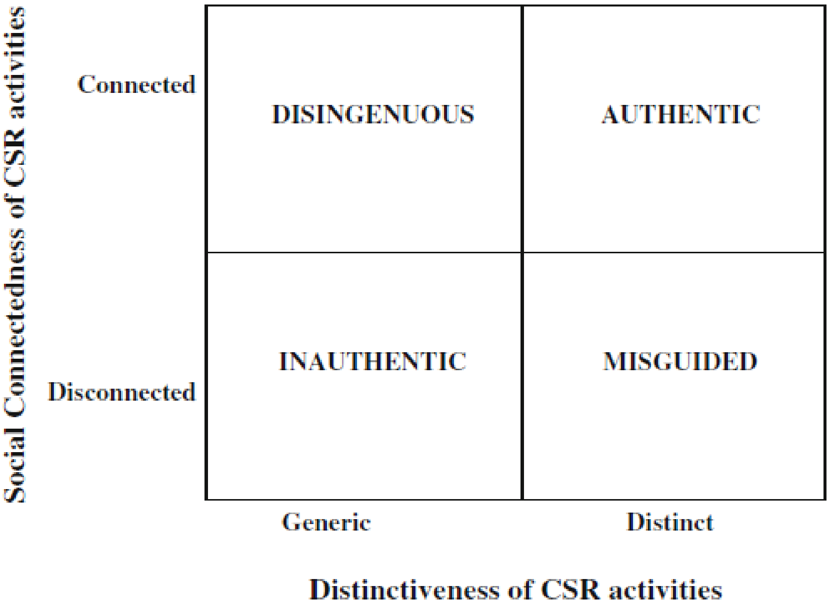

Figure 2. Perceptions of authenticity of CSR efforts (Mazutis and Slawinski, 2015: 144)

Although this conceptualisation is generally developed for CSR efforts, it can be helpful to use in the specific case of bioenergy retrofitting efforts. For **public acceptance** and consumer engagement it seems to be of significant importance whether or not an industry **communicates** – and proves in practice – clearly that its retrofitting activities are part of an industry's social responsibility and taken beyond its own business interest alone. On the other hand, it is not hard to imagine that consumer sympathy and support for retrofitting efforts of an industry is facilitated by a business strategy that is explicit about its commitment and connectedness to help solving societal challenges. From this perspective, an industry will be perceived being truer if corporate social responsibilities are part of a company's identity and expressed in business decisions (authentic). Bioenergy retrofitting initiatives without public communication could lead to cynicism and suspicion among consumers (disingenuous). Business activities which are not fair, just, transparent or sustainable in the social context are regarded as dishonest if they belong to the core values and purpose of a company (misguided). A company that associates itself explicitly with CSR, without taking this seriously in business practice, apart from taking isolated decisions to safeguard its reputation or "philantropic nature", will be judged negatively by consumers in terms of greenwashing (inauthentic).

The perception of consumers also depends on the **anonymity** versus **familiarity** of an industry applying bioenergy retrofitting. Consumers who live in the vicinity and who are perhaps even economically dependent of an industrial plant in which bioenergy retrofitting has been implemented, may respond differently than those for whom retrofitting as an abstract and distant phenomenon. In addition, the perception of consumers depends on whether and to what extent consumer perceptions and priorities differ with respect to various industries involved. For instance, do consumers have higher expectations as pulp and paper industry is concerned, or do they believe that, for example, fossil refineries have an obligation to take a lead in greening the economy?

2.3 Motivation for retrofitting

The motivation of industries to invest in retrofitting can be manifold. Industries need to comply with legislation and need to be either economic profitable or at least should not make losses. Public companies are sometimes not allowed to make profits, whereas private companies usually want to make profits which are shared among the company owners or which are re-invested to let the business grow.

In addition, the following strategic goals can be important for company decisions to make bioenergy retrofitting:

- Long-term market growth
- Technology leadership
- Short-term profitability
- Financial returns for owners
- Security of local feedstock supply
- Environmental issues

2.3.1 Compliance with legislation

Since industries need to comply with legislation, any legal measure can be a very powerful tool to motivate industries to make bioenergy retrofitting. **In surveys, legislation was even mentioned to be the main reason for retrofitting** (Nuhoff-Isakhanyan et al., 2019). Legal aspects for bioenergy retrofitting are described in the BIOFIT report on “Framework conditions for retrofitting Europe’s industry with bioenergy” (Rutz et al., 2019).

If **externalities** are not considered, the use of fossil fuels are usually very cheap. In the past and even today, fossil energies are often supported, either directly, or indirectly by neglecting the externalities. Governments generally do have the mandate to ensure the inclusion of externalities in the final prices of the industrial services and products. Thus, they could enact suitable legislation that either bans fossil energies, includes external costs e.g. through CO_2 taxes, or that supports renewable energies. With the Paris Agreement on Climate Change Mitigation, several governments in Europe have recently developed such legislation to stepwise move towards a carbon neutral economy. In general, it is recognized that important steps towards more sustainability were usually associated with the introduction of suitable laws.

A concrete example for a suitable legislative tool could be to **tax CO_2 emissions**. Due to the lower emissions, prices of biomass could be lower compared to that of coal. Another example is the stepwise banning of fossil fuel use, such as the stepping out of coal, which is enforced by some European governments.

2.3.2 Economic issues

Direct economic benefits can be an important motivation for bioenergy retrofitting. This is the case if the capital expenditures (CAPEX) for the technology and the operational expenditures (OPEX) for the use of biomass is cheaper than the use of the existing technology during the whole technology lifetime. These economic benefits can be due to increased efficiency of new equipment or due to lower feedstock prices.

A barrier against bioenergy retrofitting is the relatively **high CAPEX** of the installations in comparison to fossil technologies. This can be mitigated through governmental incentives.

The OPEX depends on the fossil and renewable feedstock prices, which is difficult to predict. In a study (Nuhoff-Isakhanyan et al., 2019), several stakeholders mentioned that the lower tax on biomass compared to that of coal formed the opportunity to implement retrofitting. It was even mentioned in the study that some projects would not be feasible without a CO_2 tax

Indirect economic benefits are related to increased demand for sustainable products or a better image of the industry by the use of renewable energies. Thereby it is important to only use retrofits with large environmental improvements for marketing purposes, as it could otherwise considered as “greenwashing” which could have the opposite impact, creating a negative image on the industry.

2.3.3 Risk-mitigation strategies

Any change of technologies may bring additional risks, but could potentially also reduce risks. The following list describes a few risks that could be considered in any upgrading projects:

- **Fluctuating prices for biomass**: The more biomass is used for bioenergy purposes, the larger is the competition for the biomass. This could increase the prices for biomass in the future. On the other hand, the more biomass is used, the better is the logistical infrastructure which could lead to lower prices in biomass logistics.
- **Fluctuating prices for fossil energies**: Fossil resources (oil, gas, coal) are decreasing due to its use. Prices are expected to constantly increase in the long-term, but with the discovery of new reserves, short-term prices may stagnate or even decrease.
- **Security of biomass feedstock supply**: The supply of biomass feedstock should be secured with long-term contracts as much as possible.
- **Security of fossil energy supply**: Depleting fossil reserves may increase the supply risk of fossil fuels.
- **Technology sensibility and reliability**: Biomass technologies can be as reliable as fossil energy technologies, but this depends on the technology itself and should be assessed individually for each technology.
- **Back-up equipment**: For any energy installations, back-up systems may be required to mitigate the risk of break down.
- **Changes in safety**: Safety issues must get a high priority in any upgrading project. Depending on the replaced technology and on the new biomass technology, safety risks (e.g. explosion risk) may increase or decrease.
- **Dependencies on other industries**: Any dependencies on upstream or downstream industries of old or of the retrofitted technology may pose different risks.
- **Consideration of non-feedstock based other renewable energies**: Any other renewable energy technology that does not depend on materials as input, such as solar thermal, photovoltaics, wind energies or ambient energy, should be considered to complement biomass technologies.
- **Changing policies**: Policies are currently changing more in favour or renewable energies than in favour of fossil fuels. So, in general, retrofitting industries with biomass is currently a measure to reduce the risk of policy changes.

3 Bioenergy sourcing for industries

3.1 Biomass potential

In the EU28, **agriculture** is the biggest biomass[5] supply sector with a relative weight of approximately 65% (from 13% in Finland to 90% in Greece, Malta, Hungary and Cyprus), followed by forestry with 34% of the dry matter content (from 8% in Malta to 87% in Finland). The relative weight of the **fishery** sector is quite small (less than 1%). In agriculture, crops

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[5] including biomass for food, feed, products and energy

represent almost 62% of the biomass supply with collected crop residues (23%) and grazed biomass (15%) being closer in weight but representing much smaller portions. The dominant source of **forestry** biomass is primary woody biomass accounting for almost 70% of the total (Gurría et al. 2017). An estimation of the demand for biomass for energy in the EU27 countries is shown by Scott Bentsen & Felby (2012) in Figure 3.

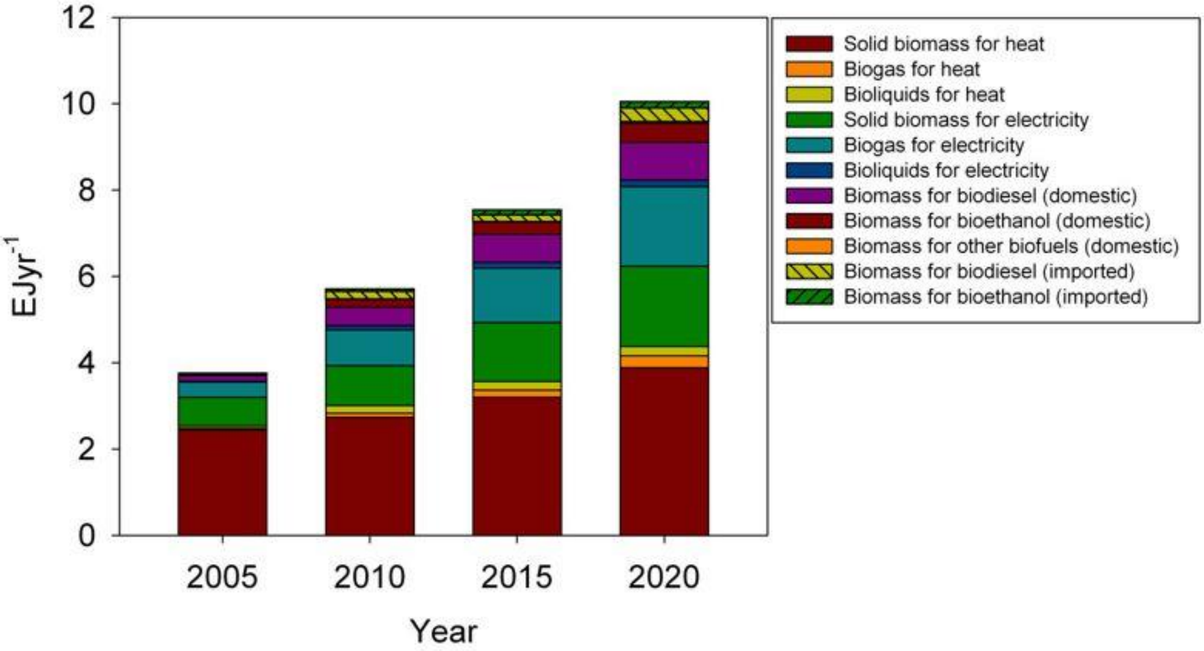


Figure 3: **Estimated demand for biomass for energy in the EU27 countries (Scott Bentsen & Felby, 2012)**

The European **agricultural biomass** total supply amounts to approximately 765 million tons of dry vegetal biomass equivalents, divided as follows (Gurría et al. 2017):

- The crop harvested production is estimated at 478 million tons of dry matter (t_{dm}) biomass in the EU-28 for the year 2013 (i.e. approximately 2 billion tons of fresh biomass).
- Collected crop residues provide additional 100 million t_{dm} of biomass.
- 19 million tons of biomass are derived from grazed pastures and meadows.
- Around 10 million additional tons of dry matter of crop residues could be collected without hampering the production of ecosystem services such as soil carbon conservation, fertility maintenance, water retention, etc.
- Around 67 million t_{dm} of vegetal biomass equivalents are imported, 53% in the form of crop products (non-manufactured), 25% in the form of food products and the rest in the form of biomaterial products (ca. 22%).

In agriculture, the main sources of primary residues come from arable crops in the form of straw and from maintenance of permanent crop plantations like fruit and berry trees, nuts, olives, vineyards, and citrus. **Straw** - as a by-product of grain production - is a potential raw material for energy production. Straw is usually left on the field as fertilizer or used as litter and then as fertilizer in terms of a circular economy. To leave the straw on the field offers many benefits among others nutrient supply and humus formation. However, when wheat is followed by rapeseed, the straw harvest could be beneficial since less plant material is left on the field to rot. Thus, it must be decided for each individual case, whether the use of straw makes sense.

Furthermore, the nutrient balance could be improved by straw-ash recirculation or fertilization with wood ash, if this is legally permissible (e.g. in Sweden).

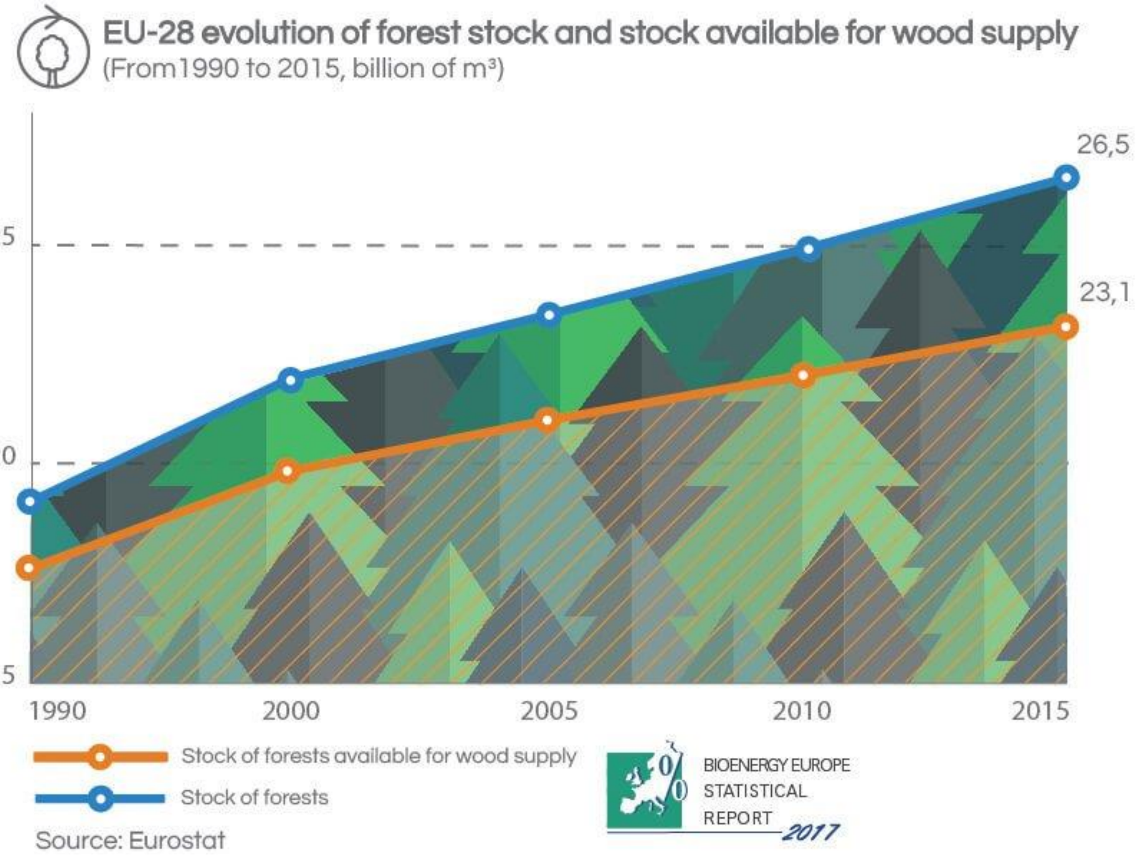
Figure 4: Short rotation coppice with poplar trees (Source: Rutz D.)

Furthermore, **short rotation coppice** (SRC) (Figure 4) and dedicated energy crops could be a promising raw material for bioenergy production. The management of SRC on arable land is an extensive form of land use due to the low demand of fertilizers and pesticides compared to other crops. Fast growing tree species (willows, poplar, paulownia, robinia, etc.), can be used as energy crop in multi-annual harvest cycles. The rotation time (period of the harvesting cycles) depends on the planting group, the intensity of use, the intended use of the raw material and the given site conditions. When the trees are ready for harvesting (after two to eight years), they will be cut, chipped and transported. Some species could be also used at marginal lands for the re-cultivation of former coal mines. For instance, robinia (*Robinia pseudoacacia*) is a very suitable tree species for dry soils with low carbon content.

Dedicated energy crops such as Miscanthus have also very low fertilizer requirements. Their cultivation and harvest can be similar to other agricultural crops. However, the area currently cultivated with dedicated perennial energy crops in the EU28 is limited to 117,401 ha, and includes mostly poplar, willow and miscanthus (Bioenergy Europe, 2019).

The **forest biomass** in the EU28 is estimated in total at almost 370 million t_{dm}. The total estimated removals from the forest of primary wood in EU28 add up to 252 million t_{dm}, while the net-import of roundwood is estimated to be about 6.8 million t_{dm}. Removals from forests were composed of 78.6% of industrial roundwood, and 21.4% of fuelwood. Fuelwood is estimated to be composed of 33% stemwood and 67% other wood components (branches, treetops, sub-merchantable stems). In addition to the removals classified as fuelwood, the total amount of woody biomass used for energy in the wood resource balance also includes secondary residues from wood processing, black liquor, removals from outside forests, imported secondary residues and wood pellets, post-consumer wood and actually also part of pulpwood classified as industrial roundwood. The net-import of by- and co- products (incl. wood pellets) is about 8 million tons dry matter, while net-import of wood pulp is 13 million tons (Gurría et al. 2017).

In 2015, the **forest and wooded area** in the EU28 amounts approximately to 181 million ha, corresponding to 42% of the total land area. This is roughly equivalent to the land area used for agriculture in the EU28. The forest area available for wood supply amounts to 134 million hectares. The following 7 of the EU28 Member States had at least half of their land area covered by forests and other wooded land in 2015: Portugal, Spain, Latvia, Estonia, Slovenia, Sweden and Finland. Over the last couple of decades the forest area in the EU28 hasincreased: Between 1990 and 2015, the area of forest cover and other wooded land increased by 5.2%. This is also shown by the volume increase of the forest stock in Figure 5. On average, only about 63% of the annual forest increment is used (Bioenergy Europe, 2019).



Source: Eurostat

Figure 5: **EU-28 evolution of forest stock and stock available for wood supply (Source: Bioenergy Europe, 2017)**

The **ownership structure** of the forest area differs in each country. EU28 forests are divided into small family holdings, state-owned forests, and large estates owned by companies. In total, around 60% of the EU28´s forests were privately owned in 2010. This percentage is highest (98.4%) in Portugal and lowest in Bulgaria (13.2%) (Bioenergy Europe, 2019).

Wood directly from forests accounts for about 38% of the solid biomass used for energy production in the EU28. Furthermore, the wood industry (industrial by-products and pellets) provides over 50% of solid biomass used for bioenergy (Bioenergy Europe, 2019). The woody biomass supply from the forest-based industry depends on the economic market situation. For instance, the more sawn timber is produced, the more by-products are available.

In addition, the **imports of solid biomass fuels** have increased over the last decade and amount to 8.5% of the total primary energy production from solid biofuels in 2016. Mainly pellets used as fuel in power plants are imported from outside of the EU28, particularly from the United States, Canada and Russia (Bioenergy Europe, 2019).

There is a clear **potential to intensify forest utilisation for energy** in the EU28 since, as mentioned before, only 60–70% of the annual increment of EU forests is harvested. At present, about 42% of the harvest is eventually used for energy; residues from higher value processing have a significant share. Recent projections for 2030 quantify the sustainably realisable potential of wood for energy from EU28 forests as high as 675 million cubic meters (146 million toe) per year, provided intensive wood mobilisation efforts are applied (European Commission, 2019).

Feed and food are the most important categories in terms of **biomass use**, adding up to over 60% of total biomass. Bioenergy accounts for about 19% of the total biomass in the EU-28. However, it is important to note that biogas and bioelectricity have not been considered in this. Biomaterials are the third biggest group (Gurría et al. 2017).

The biomass used for **feed and food** products is almost entirely of agricultural origin. 71% of the total agricultural biomass supply (expressed in dry matter) is used as food and feed: 69% is used as animal feed & bedding to produce animal-based food while the rest is directly consumed as plant-based food (Gurría et al. 2017).

Most of the biomass used in **bioenergy** is sourced from forestry products. In 2013, 178.7 t_{dm} of wood were estimated to have been used for energy, either directly or indirectly gathered from forest. Only 2% of the EU agricultural supply is processed into sustainable biofuels for transportation. The rest is either used as biomaterial or waste. Biofuels use in the EU transport sector in 2013 totalled 12.0 ktoe in energy terms. Common arable crops had the main contribution to the total biomass supplied to the transport sector, at more than 90% in 2013. Based on the available data, the volume of domestic common arable crops supplied to the transport sector is estimated at 15 million t_{dm} in year 2013. Germany was the main supplier with 12 million t_{dm} followed by Slovakia (668 thousand t_{dm}) and Romania (475 thousand t_{dm}) (Gurría et al. 2017).

Almost all of the **bio-materials** have an origin in forestry activities with the largest component being solid wood products. In 2013, 189.9 million tons of dry matter of wood were used for bio-materials. EU-28 is also a net exporter (14.3 million t_{dm}) of solid wood products.

The Biomass Energy Europe (BEE)[6] project compared more than 70 biomass potential assessments. It concluded that the estimates differ to a large extent due to different definitions of potential and due to different methods applied. Nevertheless, most of the studies agree that **biomass potentials from forestry and waste are relatively stable** over time. The significant uncertainty comes with the question, how much biomass for energy would EU agriculture be able to supply? Agriculture seems thus to be key for a genuine, large-scale expansion of biomass supply (European Commission, 2019).

Estimates for the **energy crops potential** ranges from 79 to 377 Mtoe (3.3 - 15.8 EJ). The actual potential depends on the land considered for production, on crop diversity and the selection of species as well as the intensity of agricultural management practices. Food security and the exclusion of areas of nature conservation have also been considered (Faaij, 2018).

The potential for **agricultural residues** range between 45 and 67 Mtoe (1.9 - 2.8 EJ) and depends on the type of residues used for energy (only straw and maize stover or cuttings and pruning residues), on the impact of weather and on soil protection measures (Faaij, 2018).

Regarding forest biomass, the estimates considering active sustainable forest management and a resource-efficient use of residues from wood working industries reach up to 174 Mtoe (7.3 EJ) (Faaij, 2018).

The availability of **biodegradable waste** strongly depends on how waste management practices are applied in the respective sectors; it ranges from 40 to 119 Mtoe (1.7 - 5 EJ) (Faaij, 2018).

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[6] http://www.eu-bee.eu/

3.2 Biomass commodities

Pellets

A wood pellet with or without additives is a compressed feedstock material, normally cylindrical with broken ends, with a length of typically 5-40 mm and a diameter of maximum 25 mm. The moisture content of wood pellets normally is less than 10% and they have an ash content of up to 3%. Pellets are usually produced in a pellet mill.

The advantages of pellets compared to log wood or wood chips are among others: the possibility to optimize the combustion because of the uniform fuel, the reduced costs for transportation because of the increased fuel bulk density and the improvement of thermal and combustion properties.

Common pellets are **made from woody biomass**, like sawdust, wood chips or forest residues, but there are a variety of raw materials which can be pelletized as shown in Figure 6. Some examples are paper products, waste biomass, corn, cotton seed, hemp, Miscanthus, reed canary grass, straw, cereal spillage, low grade hay etc. The fuel properties of pellets made from **alternative raw materials** differ from pellets made from woody biomass, usually exhibiting higher ash content. Certain fuel properties can be set by mixing different raw materials together in suitable amounts.

The International standard (ISO 17225-2:2014 "Solid biofuels – Fuel specifications and classes – Part 2: Graded wood pellets") defines the quality standards of wood pellets. There are three different classifications for pellets: A1, A2 and B. The differences are related to the used raw materials and their quality. Most small-scale (e.g. domestic) consumers use A1 wood pellets, while lower quality classes are used in larger installations, including power plants. Another International standard (ISO 17225-6:2014 "Solid biofuels — Fuel specifications and classes — Part 6: Graded non-woody pellets") defines quality classes for **agrobiomass pellets**.

The EU-28 is both the largest producer and consumer of wood pellets in the world. The situation per country differs. Italy, Germany and France consume wood pellets mostly in the residential heating market, Denmark and Sweden in CHP plants, while UK, Belgium and Netherlands mostly in converted coal power plants (see Section 7.6). North America (USA, Canada) is a net exporter of wood pellets to Europe, while it also interesting to note the rising demand in East Asia countries such as Japan and South Korea.

Figure 6: Examples of pellets made from different materials and processes (Source: DBFZ)

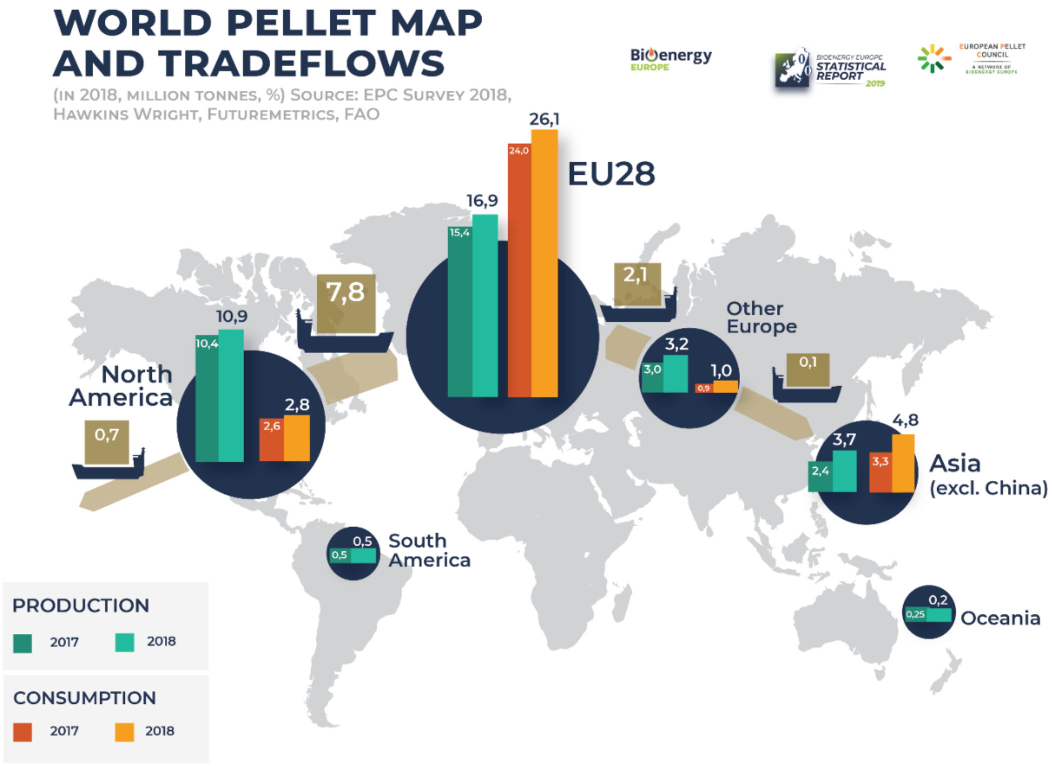

Figure 7: International wood pellets production and trade (Source: Bioenergy Europe)

Wood chips and hog fuel

In order to produce wood chips, woody biomass, with the intention of being burned afterwards, must be chopped. Because of the **chipping process**, wood chips are a relatively uniform fuel, which is able to flow and can be fed to a boiler automatically. The average dimension of a wood chip is from 16-45 mm. Because of the high surface area-to-volume ratio, they can be burned efficiently. However, compared to log wood, wood chips have a lower bulk energy density, which leads to a larger space requirement during transport and storage. The quality of the wood chips depends on the used raw material and the chipper.

Hog fuel is wood that has pieces of varying size and shape; unlike wood chips, hog fuel is produced by **crushing** with blunt tools such as rollers, hammers, or flails.

With respect to the raw material, wood chips can be divided into the following groups (ETIP Bioenergy, 2019):

- **Forest chips** (produced from logs, whole trees, logging residues, or stumps)
- **Wood residue chips** (produced from untreated wood residues, recycled wood, offcuts)
- **Sawing residue chips** (produced from sawmill residues)
- **Short rotation forestry chips**

An already published standard (ISO 17225-4:2014 “Solid biofuels — Fuel specifications and classes — Part 4: Graded wood chips”) covers wood chips specifications for small-scale systems (high quality fuel properties), while a standard currently under-development (ISO 17225-9) will cover fuel specifications and classes for wood chips and hog fuel intended for industrial use.

Figure 8: Left - wood chips from forest (Source: Rutz D.), Right – hog fuel from olive tree prunings (Source: Karampinis E.)

Thermally pre-treated biomass

The term "thermally pre-treated biomass" can be used to cover a different set of technologies aiming to increase the energy density of biomass and render it hydrophobic. The main aim is to produce a **coal-like material** that can be directly used to substitute coal in energy applications.

The most common technologies available for producing thermally pre-treated biomass are **torrefaction**, steam explosion and hydrothermal carbonization; further details are provided in Section 7.7 of this Handbook. Usually, thermally pre-treated biomass undergoes a pelletisation step in order to further improve its energy density and homegenize the final product.

There is an International technical specification (ISO/TS 17225-8:2016[7]) which defines the application and specification of thermally treated biomass pellets.

Despite the advantages that thermally pre-treated biomass pellets can offer and despite the fact that many technology developers have set up commercial-scale production plants, the market for these intermerdiate bioenergy carriers is not yet firmly established. The Horizon 2020 project MUSIC (Market Uptake Support for Intermediate Bioenergy Carriers)[8] intends to further expand the market for such upgraded biomass fractions, along with pyrolysis oil and microbial oil.

Figure 9: Thermally treated biomass pellets. Left: steam exploded Arbacore wood pellets (Source: Arbaflame). Right: torrefied wood pellets (Source: Yilkins)

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[7] DIN EN ISO 17225-8:2016 Solid biofuels – Fuel specifications and classes – Part 8: Graded thermally treated and densified biomass fuels

[8] www.music-h2020.eu

Bio-oil

A number of research and demonstration projects and companies are developing innovative processes to turn a wide range of biomass (forestry residues, crop residues, waste paper and organic waste) via pyrolysis / thermochemical conversion into stable, concentrated bio-oil (biocrude) or bio-slurry (oil with char) that is compatible with existing refinery technology and can be converted into advanced biofuels (ETIP Bioenergy, 2019). More info on the pyrolysis process is given in Chapter 5.

Figure 10: Bio-oil, bio-waste, straw bales (Source: Rutz D.)

Bio-Waste

Bio-waste is defined as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants. It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood. It also excludes those by-products of food production that never become waste. (European Commission, 2019c)

Any organic residues / biological waste materials can potentially be converted to advanced biofuels by thermochemical, biochemical or chemical processes. Increasingly, processing or manufacturing facilities that convert biomass to food, building materials, paper, and other bioproducts take a biorefinery approach - maximising the conversion of feedstocks and waste streams into valuable byproducts, energy and biofuels. But also municipal solid waste can be converted into liquid and gaseous biofuels for production of heat and power or be used as a transport fuel. Wood wastes and forestry residues are also promising feedstocks for advanced biofuels (ETIP Bioenergy, 2019).

Straw bales

Straw - as a by-product of grain production - is a potential raw material for energy production. Straw is usually left on the field as fertilizer or used as litter and then as fertilizer in terms of a circular economy. Both quality assurance and the minimization of supply costs require an optimization of the entire logistic chain from the field to the storage. Due to the bulkiness of straw, an appropriate level of compaction is particularly important to reduce the storage space requirements (=straw bales). With normal compaction systems, the density spectrum ranges from 80 to 160 kg m^{-3}.

Figure 11: Straw bale feeding system for a district heating grid in Denmark (Source: D.Rutz)

Plant oils

Oil crops are the base for biodiesel production. In Europe, rapeseed is the most common feedstock for biodiesel production. Vegetable oil is produced by pressing or extraction from oilseeds (oilseed rape, sunflower seeds, etc.), which can be used both raw and refined, but chemically unchanged as a fuel (ETIP Bioenergy, 2019).

Used cooking oils and waste fats

Used cooking oil, tallow, lard, yellow grease, chicken fat, trap grease and the by-products of the production of Omega-3 fatty acids from fish oil are increasingly used as biodiesel fuel feedstocks (ETIP Bioenergy, 2019).

Energy crops (cereals, sugar, ligno-cellulosic)

Starch-based feedstocks include grains, such as corn or wheat, and tubers such as (sweet) potatoes and cassava. These feedstocks contain long complex chains of sugar molecules. The starch can easily be converted to fermentable sugars. The sugar can then be converted to ethanol or drop-in fuels. The fibrous part of the plants (e.g. wheat straw or corn stover) can be converted to advanced biofuels. In Europe, wheat is currently the main starch crop for bioethanol production (ETIP Bioenergy, 2019).

Sugar crops, such as sugar cane, sugar beet and sweet sorghum, can be used as feedstocks for both conventional biofuels (ethanol via fermentation of sugar) and/or advanced biofuels. Residual beet pulp and bagasse (the fibrous material left after sugar extraction from cane or sorghum) can be used to produce cellulosic ethanol. Fermentable sugars can also be converted to 'drop-in' biofuels via biotechnology or chemical catalysis (ETIP Bioenergy, 2019).

Lignocellulosic biomass includes wood from forestry, short rotation forestry and lignocellulosic energy crops, such as energy grasses and reeds (e.g. Miscanthus). Lignocellulosic biomass can generally not be used as food or feed, which means that there is no or limited competition with food/feed end use. Lignocellulosic materials can be used as a feedstock for advanced diesel and drop-in biofuels (via thermochemical conversion) and for production of cellulosic ethanol (via biochemical conversion). Market penetration of these technologies is however so far relatively limited. Lignocellulosic crops generally have a higher

GHG efficiency than rotational arable crops since they have lower input requirements and the energy yield per hectare is much higher (ETIP Bioenergy, 2019).

3.3 Logistics and value chains

The logistics of biomass depends highly on the type of biomass and how it is pre-treated (in the case of e.g. oils, pellets, etc.). Biomass often has a **low bulk density** (e.g. wood chips, straw) and consequently high volumes are needed. A typical biomass for energy supply chain consists of the following process steps: planting, cultivation, harvesting, handling, storage, in-field/forest transportation, road transportation and utilization of the fuel at the power station/refinery. The activities required to supply biomass from its production point to a power station are the following (Rentizelas et al., 2009):

- **Harvesting**/collection of the biomass in the field/forest
- In-field/forest handling and **transport** to move the biomass to a point where road transport vehicles can be used
- **Storage**. Many types of biomass are characterized by seasonal availability, as they are harvested at a specific time of the year but are required on a year-round basis. The storage can be located in a farm/forest, at the processing station or at an intermediate site.
- **Transport** including loading and unloading: Considering the typical locations of biomass fuel sources (i.e. in farms or forests) the transport infrastructure is usually such that road transport is the only potential mode for collection and transportation in the first place. Other transportation means, such as ship or train may be considered when long distance biomass transport is examined.
- **Processing** biomass to improve its handling efficiency and the quantity that can be transported. This may involve increasing the bulk density of biomass (e.g. processing forest wood or coppice stems into wood chips) or unitising the biomass (e.g. processing straw or Miscanthus into bales). Processing can occur at any stage in the supply chain but will often precede road transport and is generally cheaper when integrated with the harvesting.

The biomass supply chain has several very specific characteristics in contrast to other supply chains. Agricultural biomass types are usually characterized by **seasonal availability**. Hence, there is a need to **store** very large amounts of biomass for a significant time period, if year-round bioenergy production is desired. Another characteristic of the biomass supply chain is that it must deal with **low-density materials**. As a result, there is increased need for transportation and handling equipment, as well as storage space. This problem is enhanced by the **low heating value**, which is partly due to the increased moisture of most agricultural biomass types. The low density of biomass increases further the cost of collection, handling, transport and storage stages of the supply chain (Rentizelas et al., 2009). These characteristics are **substantial barriers to a long-distance biomass feedstock supply** system. However, these challenges can be addressed by either (1) designing transportation, handling, and storage systems that accommodate the variety of types and formats of raw biomass or (2) formatting the biomass to be compatible with existing infrastructure (Searcy et al., 2014). The form in which the biomass will be procured often determines the investment and operational costs of the respective bioenergy exploitation system, as it affects the requirements and design of the biomass supply chain (Rentizelas et al., 2009).

Besides this typical value chain of harvested biomass, the logistics of biomass wastes is usually very different. For used cooking oil (UCO) or organic municipal solid waste (MSW), a core logistical challenge is the **waste management** and how to collect the waste. Thereby, industrial or private consumer awareness and behaviour plays an important role to facilitate the set-up of such a biomass value chain. Finally, also safety and hygienic aspects must be considered.

3.4 Sustainability and certification policies

The **first renewable energy directive** (2009/28/EC) established an overall policy for the production and promotion of energy from renewable sources in the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020. The Directive 2009/28/EC specifies national renewable energy targets for 2020 for each country, considering its starting point and overall potential for renewables. These targets range from a low target of 10% for Malta to a high of 49% for Sweden. EU countries set out how they plan to meet these 2020 targets and the general course of their renewable energy policy in national renewable energy action plans. Progress towards national targets is measured every two years when EU countries publish national renewable energy progress reports (European Commission, 2019b).

In December 2018, the **revised renewable energy directive** 2018/2001/EU came into force, as part of the Clean Energy for all Europeans Package, aimed at keeping the EU a global leader in renewables and, more broadly, helping the EU to meet its emissions reduction commitments under the Paris Agreement. The new directive established a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023 (European Commission, 2019b).

The RED II also defines a series of **sustainability and GHG emission criteria** that bioliquids used in transport must comply with. Some of these criteria are the same as in the original RED, while others are new or reformulated. Additionally, the RED II introduces sustainability and GHG emissions saving criteria for solid and gaseous biomass fuels, as well as specific requirements for electricity from biomass fuels (European Commission, 2019b).

Biofuels, bioliquids and biomass fuels from agricultural biomass must not be produced from raw materials originating from (European Commission, 2019b):

- **High biodiversity land** (as of January 2008), including primary forests; areas designated for nature protection or for the protection of rare and endangered ecosystems or species; and highly biodiverse grasslands;
- **High carbon stock land** that changed use after 2008 from wetlands, continuously forested land or other forested areas with trees higher than five meters and canopy cover between 10% and 30%;
- **Land that was peatland** in January 2008.

The sustainability criteria apply to plants with a total rated thermal input above 20 MW for installations producing power, heating, cooling or fuels from solid biomass fuels and to plants with total rated thermal input capacity equal to or exceeding 2 MW for installations using gaseous biomass fuels (European Commission, 2019b).

The RED II introduced new sustainability criteria for forestry feedstocks and mandates that harvesting takes place with legal permits, the harvesting level does not exceed the growth rate of the forest, and that forest regeneration takes place. In addition, biofuels and bioenergy from forest materials must comply with requirements which mirror the principles contained in the EU **Land Use, Land Use Change and Forestry** (LULUCF) Regulation. The "forestry" criteria applies either at the country level or at forest sourcing area level: the Commission will define implementation guidelines by 31 January 2021 (European Commission, 2019b).

Within the 14% transport sub-target, there is a dedicated target for advanced biofuels produced from specified feedstocks. These fuels must be supplied at a minimum of 0.2% of transport energy in 2022, 1% in 2025 and increasing to at least 3.5% by 2030. Biofuels and bioenergy produced from waste and residues only need to comply with the GHG emission sustainability criterion (European Commission, 2019b).

The maximum contribution of biofuels produced from food and feed crops will be frozen at 2020 consumption levels plus an additional 1% with a maximum cap of 7% of road and rail transport fuel in each Member State. If the total share of conventional biofuels is less than 1% by 2020 in any Member State, the cap for those countries will still be 2% in 2030. Further, if the cap on food and feed crops in a Member State is less than 7%, the country may reduce the transport target by the same amount (for example, a country with a food and feed crop cap of 5% could set a transport target as low as 12%). “Intermediate crops” such as catch and-cover crops are exempt from this cap. Fuels produced from feedstocks with “high indirect land-use change-risk” will be limited by a more restrictive cap at the 2019 consumption level, and will then be phased out to 0% by 2030 unless specific batches are certified as “low indirect land-use change-risk.” “Low indirect land-use change-risk” feedstocks include those that are produced on land that was not previously cultivated. Fuels used in the aviation and maritime sectors can opt in to contribute to the 14% transport target but are not subject to an obligation (European Commission, 2019b).

Furthermore, a number of other EU-level schemes (directives and regulations) indirectly affect the sustainability of a number of biomass types relevant for bioenergy production because they concern relevant areas such as forestry, agriculture, habitats protection, environmental conservation, etc. and thus form an overall framework. Among the most important schemes with relevance for national legislation are (ENERGY BARGE, 2017):

- Several regulations and directives under the **Common Agricultural Policy**. The Common Agricultural Policy (CAP) is the EU policy in the agricultural sector and was introduced in 1962. Since then it has been amended several times. Aims of the CAP are to increase the productivity in the agricultural sector and to ensure a fair standard of living for the farmers. Furthermore, it targets to stabilize the markets and to ensure the availability of supplies and reasonable prices for consumers. The CAP reform of 2013 aims to enhance the competitiveness of EU agriculture, provide more sustainability and improve its environmental performance.
- **EU habitats directive** (92/43/EC)
- **Protected area regulations**, especially NATURA 2000
- **EU biodiversity strategy 2020**
- **EU timber regulation** (995/2010/EC)

In terms of a **Forestry Policy**, in 2013 a new EU Forest Strategy for forests and the forest-based sector (COM(2013) 659) has been elaborated. Even though the EU contributes through its policies since a long time to the implementation of sustainably managed forests in the respective Member States, a uniform policy on EU level for forests and the forest sector does not exist. The need for a common policy framework has been determined to ensure and coordinate the coherence of forest-related policies in the EU. Therefore, a common framework on EU level shall guarantee, among other things, the sustainability of forest management, manage the increasing demand for raw material and renewable energy and protect forests and biodiversity (European Commission, 2013).

The **Fuel Quality Directive** (FQD) (2009) obliges the Member States to reduce GHG emissions related to the consumption of transport fuels by 10% by 2020 (European Commission, 2009).

In 2015, the **Directive to reduce indirect land use change for biofuels and bioliquids** ((EU)2015/1513) came into force. This so called iLUC Directive amended legislation on biofuels – specifically the RED and FQD – to reduce the risk of indirect land use change and to prepare the transition towards advanced fuels. Among others the Directive limits the share of biofuels from crops grown on agricultural land that can be counted towards the 2020 renewable energy targets to 7%, harmonises the list of feedstocks across the EU whose contribution would count double towards the 2020 target of 10% for renewable energy in transport and requires that biofuels produced in new installations emit at least 60% fewer greenhouse gases than fossil fuels.

The **Energy Efficiency Directive** (Directive 2012/27/EU) sets up a framework to increase the energy efficiency in the EU in order to achieve its 20% energy efficiency target by 2020. All Member States are required to utilize energy more efficiently at all stages of the energy chain, from production to final consumption.

In order to fulfil the requirements for different biomass feedstocks implemented by legislation, certification schemes are a useful tool. Biofuels and bioliquids used in the EU must fulfil the requirements of sustainability. To ensure this, companies can participate in **voluntary sustainability schemes** that verify the compliance with the sustainability criteria set by the EU. For the certification process, the whole production chain is reviewed by independent auditors. Most verification schemes are privately run but approved as valid by the European Commission. Recognitions can last for a period of five years (ENERGY Barge, 2017b). The Sustainable Biomass Program (SBP)[9] is an example of a sustainability certification scheme, mostly for wood pellets and wood chips used in industrial, large-scale energy generation. The SBP scheme aims to verify that such woody biomass fractions are sourced from sustainable and legal sources.

Fuel quality certification schemes aim to provide confidence on biomass fuel properties to small and medium scale consumers, who cannot undergo extensive monitoring of fuel properties themselves. The most well-known scheme is **EN*plus*®**[10], which aims to control wood pellets' quality along the entire supply chain, starting from the production up to the delivery to the end customer. Currently, **EN*plus*®** is the world-leading certification scheme for wood pellet quality, with an estimated 11.6 million tonnes of certified pellets produced in 2019. Other fuel quality certification schemes include **GoodChips®**[11] for wood chips and hog fuel and **BIOmasud®**[12], covering different types of Mediterranean solid biofuels (e.g. olive stones, nut shells, etc.).

4 Overview of biomass conversion pathways

Biomass conversion pathways are characterized by the type of the feedstock, the conversion technologies, and the final products. After harvest, biomass can be used either directly for conversion to energy or only if further processing is made. FAO (2019)[13] speaks about two major types (or forms) of biofuels: primary (unprocessed) biomass, and secondary (processed) biomass, whereas biofuels is not defined here.

- **Primary** (unprocessed) biomass are those where the organic material is used essentially in its natural form (as harvested; e.g. woodchips, logwood). Such biomass is directly combusted usually to generate energy for cooking, space heating, electricity supply, steam, and process heat.
- **Secondary** (processed) biomass in the form of solids (e.g. charcoal, torrefied biomass, pellets), liquids (e.g. ethanol, vegetable oil), or gases (e.g. biogas,

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[9] www.sbp-cert.org

[10] www.enplus-pellets.eu

[11] www.goodchips.eu

[12] www.biomasud.eu

[13] http://www.fao.org/3/j4504E/j4504e06.htm Whereas FAO is using the word „biofuels“ instead of „bioenergy“

biomethane, bio-H_2), can be used for a wider range of applications, including transport and high-temperature industrial processes.

In addition, a relatively new term for some secondary biomass was recently introduced, namely so-called **intermediate bioenergy carriers** (IBC). They are formed when biomass is processed to energetically denser, storable and transportable intermediary products analogous to coal, oil and gaseous fossil energy carriers. These IBCs can be further refined to final bioenergy or bio-based products or directly used for heat and power generation. Examples of IBC are pyrolysis oil or torrefied biomass. However, the term IBC is not defined officially and some biomass, such as e.g. pellets could be considered as IBC or not.

Biomass processing aims to provide biomass with clearly defined characteristics. This ensures a technically simple and environmentally sound conversion into useful energy. Standardised biomass can then be used with fewer problems to meet a supply task efficiently and comfortably. The conversion pathways can be categorized into three main conversion processes:

- **Thermo-chemical conversion** summarizes all conversion processes of biomass based on thermal energy: combustion, gasification, pyrolysis, torrefaction and carbonisation
- **Physical-chemical conversion** processes convert biomass based on physical (e.g. pressing, milling, etc.) and chemical processes (e.g. esterification, hydrothermal treatment). This includes e.g. the pressing of pellets, but also the pressing of oil seeds, including oil extraction and the transesterification of this oil to fatty acid methyl ester. Furthermore, several pre-treatment methods for converting lignocelluosic biomass into 2nd generation biofuels use
- **Bio-chemical conversion** summarizes conversion processes using biological processes that involve microorganisms. This can be anaerobic digestion for biogas production or fermentation for ethanol production.

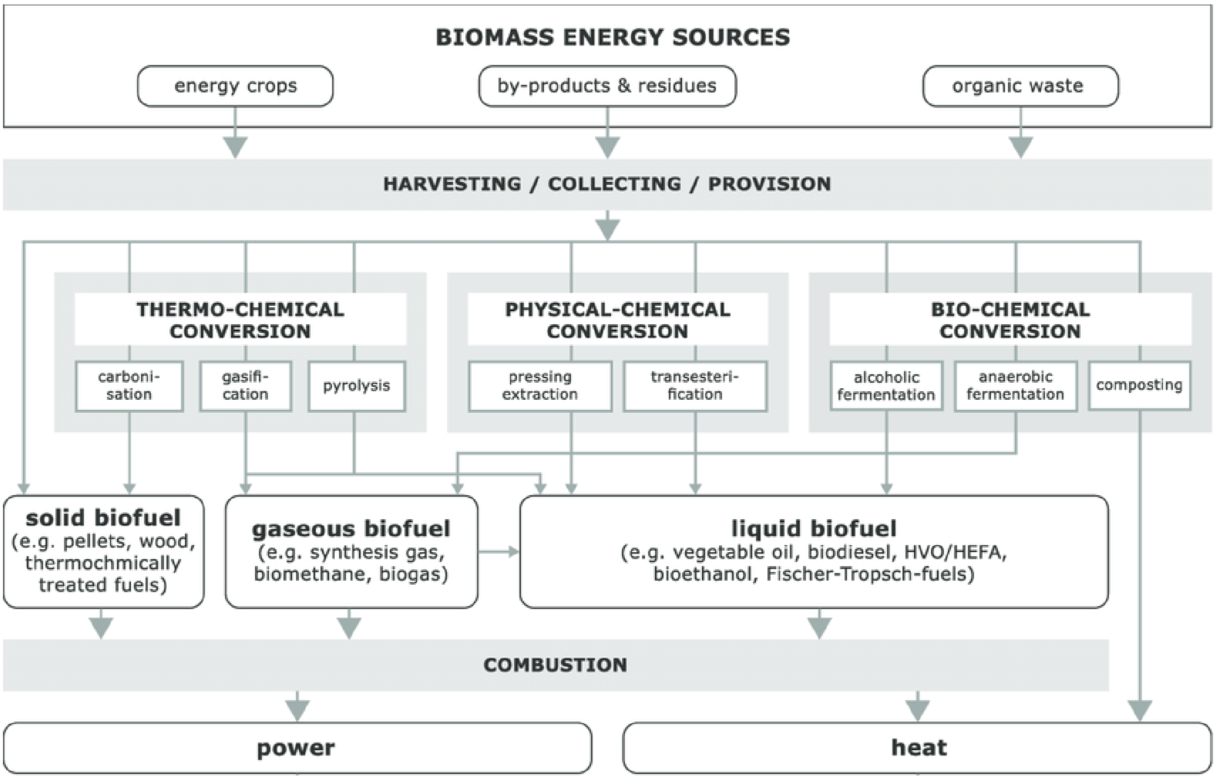

Figure 12: Biomass conversion pathways (Source: Thrän et al. 2015)

There are many reasons why a specific technology is preferable to others, but one main distinction is the moisture content of the biomass. When the biomass is 'dry', thermochemical technologies are generally preferable, since less water needs to be heated up. When the biomass is 'wet' – containing a lot of moisture – bio-chemical conversion technologies like anaerobic digestion or fermentation could be more suitable.

In the following chapters, the most important conversion technologies are presented, which are relevant for the BIOFIT industries.

5 Retrofitting first generation biofuel plants

5.1 Overview of the sector

The **first generation** (1G) biofuels sector in Europe involves the production of biodiesel (fatty acid methyl esters - FAME), hydrogenated vegetable oil (HVO) and bioethanol from various food crops. FAME and HVO are produced from oil bearing crops such as rapeseed. Bioethanol is produced from sugar or starch containing crops, such as sugar beet, grain and wheat. The main advantage of these fuels is that they can be blended with regular transport fuels.

For Europe, **biodiesel** production is more important than **bioethanol** production with a production of 11.5 million t/a of biodiesel in 2015, against 1.9 million m^3/a for bioethanol. These quantities are produced by numerous dedicated plants scattered across Europe. The production volume of biofuels, mainly biodiesel and bioethanol, has been stable in the last years in the European Union, after an increase in the years up to 2013. The support for biofuels from governments has decreased in recent years (e.g. Spain has decreased blending requirements). Uncertainties regarding the sustainability where addressed by the introduction of sustainability certification systems for biofuels, which can be seen as unprecedented models also for other sectors. However, uncertainties regarding the interactions of 1G biofuel production with the food production and land availability remain. A supplement and prospectively a replacement of 1G biofuels by 2G (**second generation**) biofuels is thus politically strongly desired, because the latter involve non-food crops such as lignocellulosic feedstocks and waste oils. In many cases, they have a better GHG balance, and are not subject to the cap on biofuels from food and feed crops to be imposed by the revised Renewable Energy Directive (RED II).

Besides the overall target on renewable energy in the transport sector, the RED II has also updated a set of sustainability criteria to ensure that the biofuels used do indeed reduce carbon intensity. New in the RED II is that there are also sustainability criteria for forest biomass and that there are GHG criteria for biomass fuels. For transport fuels, the minimum GHG reduction depends on the age of the biofuels production plants:

Table 3: Minimum GHG thresholds for biofuels in the RED II

Plant operation start date	GHG savings threshold in RED II
Before October 2015	50%
After October 2015	60%
After January 2021	65%
After January 2026	65%

Other important aspects of the RED II are:

- Prohibition of support for biofuels produced from certain **highly valued land types**, such as high biodiversity land, high carbon stock land and peat lands.
- A dedicated target for so-called **advanced biofuels**, which are biofuels produced from (defined) residues. This target increases from 0.2% of transport energy in 2022 to 1% in 2025 and finally at least 3.5% by 2030

For the EU, the RED II package is aimed at maintaining the role of the EU a global leader in renewables, while also helping the EU to meet its emissions reduction commitments under the Paris Agreement[14].

Opportunities for retrofitting are the conversion of 1G biofuels plants to produce more or only 2G biofuels, by (e.g.) cellulosic ethanol add-ons, multi-feedstock biodiesel add-ons or biogas add-ons. Best practise examples are the retrofit of a biodiesel plant from vegetable oil to animal fats and cooking oil in Volos, Greece, commissioned by BDI from Austria and a biogas add-on to a sugar-beet based ethanol plant in Anklam, Germany by Suiker Unie. Other retrofit options include improving the GHG balance (e.g. by producing biogas from waste streams) or more advanced electro fuel enhancements.

5.2 Cellulosic ethanol add-on to first generation bioethanol

Bioethanol is produced by fermentation with yeast from biomass that contains sufficient amounts of sugars. From **sugar crops** like sugar beet and sugar cane, the fermentable sugar juices are easily extracted in a process that is very similar to the first steps of sugar production. It is also possible to obtain a fermentable sugar solution from **starch crops** like wheat or maize. Starch is a biopolymer formed by glucose molecules that can be broken down into fermentable sugars by a heat and enzyme treatment called saccharification. The kernels are milled to obtain a flour which is mixed with water and enzymes and treated at temperatures up to approximately 90°C. Figure 13 shows the production volume of bioethanol. Thereafter, bioethanol is produced today mainly from corn, sugar beets and grains (especially wheat).

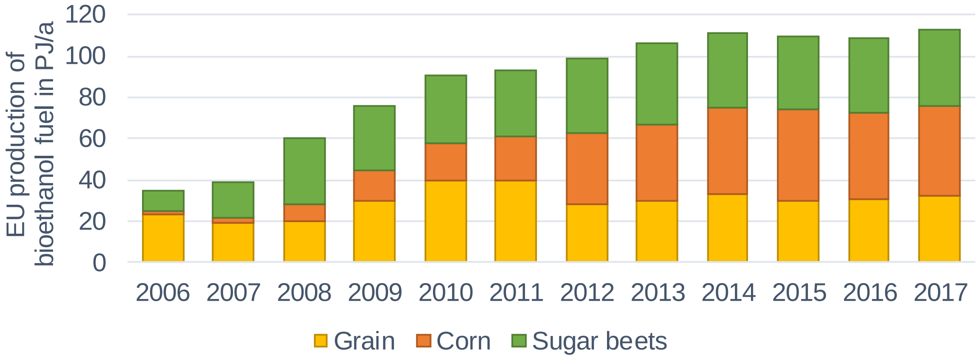

Figure 13: EU production of bioethanol fuel in PJ/a (Naumann et al., 2019)

The produced sugar solutions are fermented by yeast to obtain mash with 12-16% ethanol in a process that is similar to industrial brewing. To obtain pure ethanol (>99.5%) from the mash, distillation and other purification methods are applied. Apart from the ethanol, residues from the fermentations accrue. For processes using starch or sugar crops as feedstock, these residues are called stillage or vinasse, respectively. The water content of these by-products is usually reduced by evaporation or drying in order to increase the value as a fodder product. Especially stillage that is dried to **distillers dried grains and solubles** (DDGS) is an important by-product and gives extra revenue to first generation ethanol plants.

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[14] https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive

Further biomass potentials can be used for ethanol production with the 2G technologies that use **lignocellulosic feedstock** (Figure 14). Lignocellulosic biomass such as wood or straw mainly consist of cellulose, hemicellulose and lignin components. The cellulose is also a biopolymer based on glucose monomers. However, cellulose is more difficult to saccharify and obtain a fermentable sugar solution. Current technologies for 2G bioethanol production usually use a thermal pre-treatment process like steam explosion to destruct the lignin – cellulose – hemicellulose composite. This pre-treatment has the goal to facilitate subsequent enzymatic saccharification of the cellulose. Again, ethanol is fermented from the sugar solution and purified similar to the downstreaming process in 1G ethanol production value chains.

Since 2G ethanol technologies still suffer from uncertain economic viability, **add-on solutions** to 1G ethanol plants could result in synergies and cost savings (Macrelli et al. 2014, Watanabe et al. 2015). Different concepts for the integration of 2G ethanol into existing plants can be developed. Synergies could result from utilizing lignocellulosic parts of the starch crops (e.g. wheat bran), sharing parts of the downstreaming section, adapting the sugar contents of the fermentation by mixing of the mashes, sharing general infrastructure at the plant site or using lignin as a renewable fuel for heat provision.

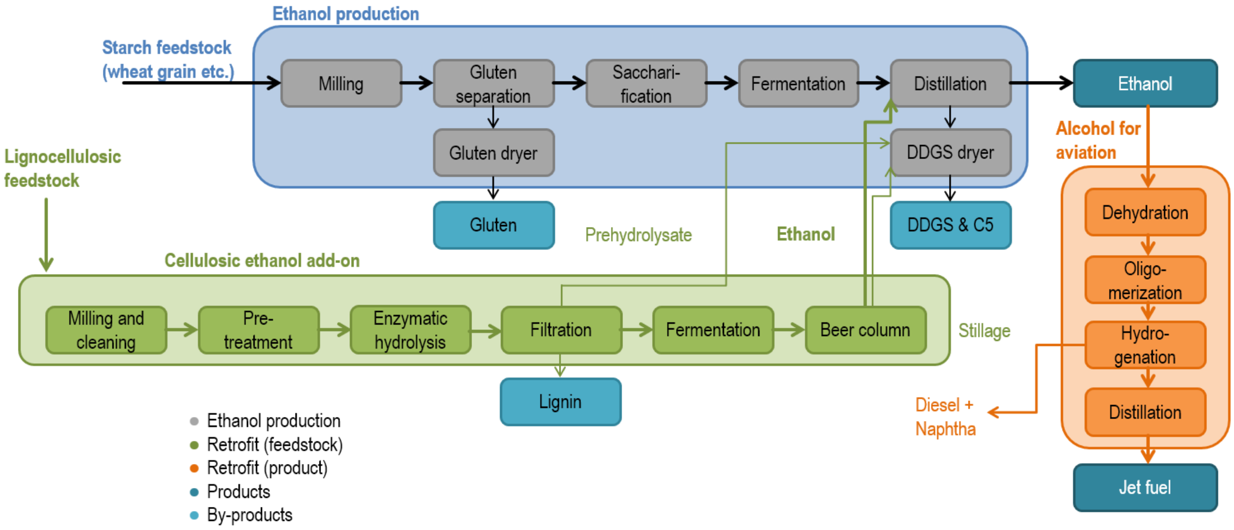

Figure 14: Exemplary concept of combined 1G and 2G ethanol production with additional jet-fuel production

The activities towards a **market launch** of lignocellulosic ethanol have recently taken place mainly in the USA and Brazil. The main focus was on the integration into existing production sites. For example, plans were developed to expand a Patriot Renewable Fuels site in Annawan, Illinois, (now CHS Inc.) with Inbicon lignocellulosic ethanol technology. The plant, which produces approximately 380,000 t/a of ethanol from grain, was expanded to produce additional 75,000 - 90,000 t/a of ethanol from corn straw (Lane, 2019). An existing POET biorefinery in Emmetsburg, Iowa, was also expanded by lignocellulosic ethanol plant in a joint venture between POET and Royal-DSM. The new part of the plant is designed to convert 300,000 t/a of corn straw into about 60,000 t/a of ethanol (DSM; 2013). Corn fibre to ethanol as a bolt-on solution has been added to the bioethanol plant of Quad County Corn Processors. The so-called “cellerate process” was employed here.

In Brazil, for example, Raízen, a joint venture between the sugar producer Cosan and the mineral oil group Royal Dutch Shell, commissioned the first of eight planned plant extensions in 2014. As a result of the expansion, an additional 32,000 t/a of ethanol can be produced from sugar cane bagasse and straw at the Piracicaba, São Paulo, site. Major plant areas (pretreatment, enzymatic hydrolysis and fermentation) were supplied by Iogen Energy. The main advantages of the integration with the existing sugar factory are access to low-cost bagasse and straw, lower investment costs due to the use of existing equipment and lower operating costs. A second plant extension with a production capacity of approximately 95,000 t/a ethanol was planned.

The concept is to use bagasse as feedstock for 2G ethanol and return the lignin residues to the on-site boiler for energy provision. Substantial integration opportunities are seen by co-locating with a sugarcane mill, which include:

- Access to bagasse at low cost, prepared for use and in steady supply
- Access to sugarcane straw currently left on the field
- Significant capital cost savings through use of existing equipment and other site infrastructure
- Operating costs savings due to sharing across the existing site.

Few studies are known to address cellulosic ethanol add-ons for the European ethanol industry. As part of the research project "Biorefinery2021 - Energy from Biomass - New Paths to the Integrated Biorefinery", various approaches to the optimisation of ethanol plants were investigated. Concepts were developed that consider both stand-alone and coupled production of lignocellulosic ethanol (Gröngröft et al., 2011). Initial plant concepts for the coupled processing of wheat and wheat straw were also developed. It was found that the specific investments for the construction of lignocellulose ethanol plants can be reduced by integrating them into existing plants (Gröngröft et al., 2011).

Studies on the integration of lignocellulosic ethanol into existing European production sites and their raw materials are therefore hardly to be found so far. In particular, the combination of lignocellulose ethanol with beet ethanol and sugar production has not yet been investigated.

Within the BIOFIT project, the project partners Biocarburantes de Castilla y Leon and CIEMAT investigate the integration of the production of 30 million litres/year of 2G ethanol from unutilised components of the current feedstocks into the existing cereal-based ethanol production facility in Babilafuente, Spain.

5.3 Alcohols for aviation

To add a further possibility of using bioethanol, aviation fuels can be produced from alcohol in a so-called **alcohol-to-jet** (ATJ) process (Figure 14). Within this process, short-chain alcohols (ethanol, propanol, or butanol) are converted to long-chain hydrocarbons and separated in various fuel fractions.

The ATJ process starts with the purified alcohols. Ethanol is produced as described above and other alcohols similarly, but with different microorganisms and downstreaming technologies. There are different processes for ATJ production, which vary slightly. The typical steps are illustrated in Figure 14. At high temperatures and under high pressure the OH groups of the alcohol molecules are dehydrated (removal of OH groups) and then converted into longer hydrocarbons (oligomerization). The resulting mixture of hydrocarbons of different lengths is distilled into desired fractions and remaining double bonds are saturated by using hydrogen. (Diederichs et al., 2016)

Depending on the processing parameters in the ATJ-process, kerosene fractions with and without aromatics can be produced. As by-products during distillation, biodiesel and naphtha fractions usually accrue.

The conversion of the alcohols to kerosene in the ATJ process is not yet commercial, but demonstration plants are currently operated and flight tests with resulting kerosene have been made. It can be expected that ATJ will be an important process for the future production of alternative aviation fuels. Within the BIOFIT project a case study is conducted by DBFZ and Swedish Biofuels on the benefits of integrating the ATJ technology with existing 1G bioethanol plants. An estimation predicts, that retrofitting of all ethanol plants worldwide with a subsequent

ATJ-process could produce around 20% of the aviation industries annual demand for aviation fuels (Reals, 2012).

An attractive alternative to using 1G ethanol for ATJ processes would be to use higher alcohols such as **isobutanol**, since those build up longer molecules in oligomerization more quickly. One possible manufacturing path is the production of isobutanol with the help of special yeasts as implemented by GEVO Inc. The challenge is to reach a stable fermentation process using the genetically modified yeasts. Other innovative alcohol production technologies are also discussed in connection to ATJ. For example, LanzaTech has developed a suitable fermentation process-based gas fermentation. Here ethanol can be produced from waste gases with the difficulty of dissolving enough gas in the liquid. (Geleynse, 2018)

5.4 Multi-feedstock biodiesel add-on

Until 2010, the EU production of biodiesel was based mainly on rapeseed. Since then the share of other oil crops such as soybean, sunflower and palm has increased. Nevertheless, total biodiesel production from oilseeds has not increased significantly since 2010. The increase of the production in the last years was mainly based on additional production of biodiesel from used cooking oil (UCO), animal fat and others. Figure 15 shows this trend for the production of biodiesel (FAME) and HVO in Europe since 2006. (Naumann et al. 2019)

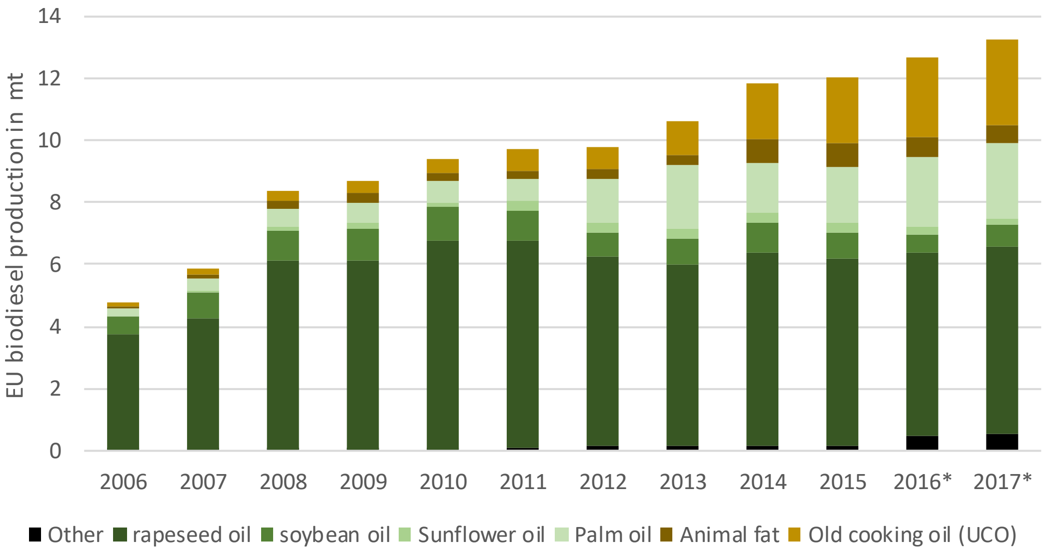

Figure 15 EU biodiesel production in million tons (*forecast) (Naumann et al., 2019, data: Flach et al., 2016)

Oils or fats are used as raw materials for biodiesel production, which can primarily be obtained from oil-containing plants. These are subdivided into oil fruits with oil-containing flesh (oil palm or olive tree) and oil seeds with oil-containing seeds (rape, sunflower, flax or soy).

The oil must first be extracted from the oilseed, which takes place in different types of oil mills. These can be classified into cold pressing, hot pressing and extraction pressing. During the processing of oilseeds, protein-containing press cake is produced, which is marketed as high-quality animal feed.

The subsequent **transesterification processes** of the oil differ primarily in terms of the catalysts used and the process conditions (T, p, t). After transesterification, the biodiesel must be washed and dried. The by-product glycerol is processed and, depending on the catalyst used, a salt is obtained. Methanol, which is added in excess, can be recovered by a rectification column.

Biodiesel plants built for processing vegetable oils can be retrofitted to **multi-feedstock biodiesel plants** that can also process **used cooking oil** (UCO) and **waste animal fats**. Compared to rapeseed oil, these feedstock types have a more inhomogeneous composition with varying levels of triglycerides, a higher proportion of free fatty acids (FFA), as well as increased levels of impurities like plastics, Phosphorous, Nitrogen and Sulfur components. For this reason, it is impossible to process UCO and waste animal fats in biodiesel plants which were built for plant oils without changing the components. Therefore, pre-treatment steps to separate impurities in these waste fat feedstock types must be added to the process (Figure 16). Furthermore, additional esterification reactors – e.g. with an acid catalyst like Sulfuric acid – decreasing the high content of FFA must be integrated in the biodiesel production system. After the esterification reaction, the separation of the raw biodiesel and the glycerol phase is carried out by sedimentation or centrifugation. The separated phases can then be integrated into the existing process. It might also be necessary to retrofit distillation columns for waste-based biodiesel to be able to meet the quality criteria of the EN14214 (European biodiesel fuel quality standard).

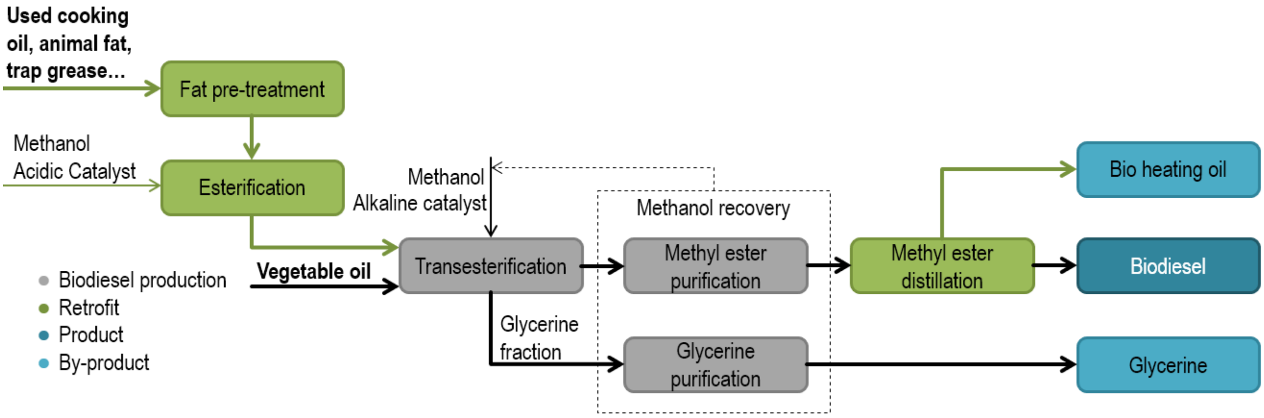

Figure 16: Process of multi-feedstock use in biodiesel production.

Another specific problem with UCOs and waste animal fats from the rendering process is **polymer contamination**. The reason for this is found in the case of UCO in the process of collection. UCO is usually collected in polyethylene or polypropylene containers. Parts of these polymers dissolve in the UCOs and cannot be removed by filtration. In the case of animal fat, plastics from e.g. ear marking tags of farm animals are contaminating the animal fat during the rendering process.

The result of these plastic contaminations is deposits on heat exchangers and column bottoms, as well as an increased content of polymers in the biodiesel or the glycerol phase. By various additional process engineering methods, such as the use of a hydrogel with subsequent filtration, the use of porous membranes or the addition of bleaching earth and activated carbon, the polymer concentration in the UCO and waste animal fat can be reduced. (Braune, 2016)

Figure 17: Biodiesel, biodiesel blend and fossil diesel (Source: DBFZ)

5.5 Glycerol reforming to methanol

Glycerol is a colourless, odourless and viscous liquid, which is present in all natural fats and fatty oils such as fatty acid esters (triglycerides). It is a by-product from the production of fatty acids or biodiesel and can be used versatilely, such as in the cosmetic industry, as a food additive and for producing plastics or biogas.[15]

Methanol is the simplest alcohol and a light, volatile, colourless and flammable liquid. Currently, most methanol is produced by the catalytic conversion of syngas from fossil sources. Using glycerol as feedstock enables the production of biomethanol.[16]

During the production process of biodiesel, glycerol is produced as a by-product in similar quantities as methanol is needed for the production. Due to the increasing demand of biodiesel, the production of glycerol as well as the demand for methanol will be increasing too. In order to address that issue, glycerol reforming to methanol is considered. (van Bennekom, Venderbosch, & Heeres, 2012)

Process description

There are different ways for glycerol reforming to create methanol. In the following paragraphs two of them are briefly described.

The production of methanol from glycerol has already been demonstrated on industrial scale by a company from The Netherlands, called **BioMCN**. In their process, the crude glycerol is purified and passed through steam reforming. The produced syngas is converted to methanol in a conventional packed bed methanol synthesis reactor. BioMCN markets and sells industrial quantities of biomethanol. However, the facility is no longer using glycerol as feedstock, but methane.

In the second pathway, the glycerol-to-methanol process (GtM), a wet biomass stream (glycerol) is converted into syngas by reforming in supercritical water (RSCW). Subsequently, it is further converted to methanol by a high-pressure methanol synthesis. The project **Supermethanol** investigated the GtM process and carried out several experiments with integration of a biodiesel plant (van Bennekom, Venderbosch, & Heeres, 2012). Figure 18 illustrates this GtM process with the relevant steps for the biodiesel production shown in grey, and the one for the GtM process shown in green. The methanol production is integrated with

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[15] https://www.chemie.de/lexikon/Glycerin.html
[16] http://www.etipbioenergy.eu/value-chains/products-end-use/products/methanol

the biodiesel plant in order to produce methanol from the crude glycerol by-product of biodiesel production and re-use it in the plant.

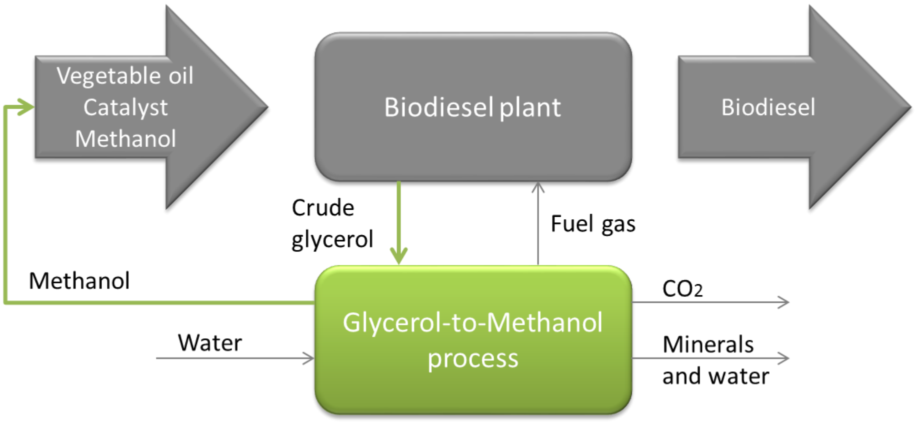

Figure 18: Glycerol-to-Methanol processadd

As mentioned above, one **application of methanol** is the production of biodiesel. Additionally, methanol is important for the chemical industry, for producing formaldehyde, acetic acid, polymers and paints. It can also be used as energy carrier or in small percentages in gasoline-blends. (van Bennekom, Venderbosch, & Heeres, 2012)

Methanol produced with a biomass feedstock has environmental benefits and may also lead to cost reductions in the long-term, if the oil price increases. An integration into a biodiesel plant could improve the energy balance, carbon performance, sustainability and overall economics of biodiesel production. Producers are less dependent on the methanol spot price, there is a (partial) security of methanol supply, and their by-product is used as a green, sustainable feedstock (van Bennekom, Venderbosch, & Heeres, 2012). The technology has been successfully tested on a pilot scale, but full-scale demonstration units have not been built yet.

As shown in Figure 18, existing biodiesel production facilities can be retrofitted by integration of a glycerol-to-methanol unit, hereby recycling most of the methanol back into the biodiesel process.

5.6 Biomethane as substitute for natural gas

Biogas can be produced by anaerobic digestion of digestible feedstock material. Biogas consists of roughly 50-60% methane (CH_4) and 40-50% carbon dioxide (CO_2) and small amounts of hydrogen sulfide (H_2S), water and siloxanes.

Through **biogas upgrading technologies**, most of the CO_2 can be removed. The obtained gas is called biomethane. This biomethane can be conditioned to the same standards as fossil natural gas and then be injected into the natural gas grid. It can be used as natural gas substitute for transport applications.

There are many different biogas upgrading technologies available on the market, including amine scrubbing, pressure swing absorption, water scrubbing, organic physical scrubbing, cryogenic distillation and membrane separation.

According to the European Biogas Association (2019), there were 17,783 biogas plants and 540 biomethane plants in operation in Europe by the end of 2017. The total Installed Electric Capacity (IEC) in Europe continued to increase in 2017, growing by 5% to reach a total of 10,532 MW, while the electricity produced from biogas amounted to a European total of 65,179 GWh. Biomethane production also rose to a total of 19,352 GWh or 1.94 bcm in 2017.

As FNR states, (2013), the upgrading of biogas into biomethane has significantly gained in relevance in recent years. In contrast to CHP generation on the production site, there are several advantages offered by upgrading biogas into biomethane, subsequently feeding it into natural gas grids, and then to use it wherever needed. Through the use of biomethane at a place with a high demand for heating, the upgrading of biogas into biomethane contributes to a significant increasing share of externally usable heat energy; this in turn leads to an increase in the overall efficiency of biogas use.

As upgrading technologies got cheaper in the last years, an opportunity for biogas plant operators could be to retrofit their biogas plants, by installing an upgrading facility that produces biomethane. Biomethane plants can also be regarded as retrofitting solutions for many other biobased industries (e.g. agriculture, food processing, pulp and paper), because they can be run on a large variety of wet biobased residues.

5.7 Electrofuels

Electrofuels are fuels produced with **hydrogen** that is obtained from the electrolysis of water. Other terms used for this type of fuels and for the conversion paths are power-to-gas (PtG), power-to-liquid (PtL), **power-to-x** (PtX), and e-fuels. The hydrogen produced by electrolysis is then either used as such or used for the reaction with CO or CO_2 to form gaseous or liquid hydrocarbons. Electrofuels are similar to those produced by other conversion pathways that do not involve electrolysis. Table 4 shows different kinds of electrofuels. (Philibert, 2018)

Table 4: Overview of electrofuels

	Without carbon	**Containing carbon (carbon based electrofuels)**
Gaseous	Hydrogen (H_2)	Methane (CH_4)
Liquid	n.a.	Methanol (CH_3OH) FT-fuels (C_xH_y)

The sustainability of such electrofuels is determined by the origin of the used electricity, whether it is renewable or not. Furthermore, the GHG emissions of the carbon based electrofuels depend on the origin of carbon:

- Carbon is recycled from fossil fuel burning or process emissions. In that case, CO_2, which otherwise would have been emitted, is captured and re-used. This kind of electrofuels is called **electrofuels from non-biogenic CO_2**.
- Carbon is captured from a plant that processes biomass and produces CO_2 as part of the product or as by-product. This kind of electrofuels is considered carbon-neutral and they are called **biomass-based electrofuels**.
- Carbon is directly captured from the air (**direct air capture - DAC**). This process requires electricity and heat and is, due to the low CO_2 atmospheric concentration, more energy intensive than carbon capture from plant emissions. This kind of electrofuels is considered carbon neutral. (Philibert, 2018)

The extent to which electrofuels can be counted as renewable fuels with respect to the Renewable Energy Directive (RED-II) depends on the share of renewable energy sources utilized in the production of the electricity used for hydrogen production. Unless there is a direct connection from a fully renewable electricity generation to the electrofuel production plant, the national electricity mix is taken into account.

To produce carbon based electrofuels, electricity and carbon dioxide are needed. Figure 19 shows the conversion pathways for carbon based electrofuels. During the electrolysis, electricity is used to split water into oxygen and hydrogen. The hydrogen can be used as electrofuel or it can be combined with captured carbon dioxide in order to further convert the hydrogen to hydrocarbons through synthesis processes. Depending on the desired product, these synthesis processes use different catalysts to produce methane, methanol, or Fischer-Tropsch liquids.

Another option for producing methane is to use gas mixtures as source of the carbon dioxide. If syngas is used and hydrogen is added, the fuel output (methane, methanol, FT-liquids) is higher. If raw biogas is used and hydrogen is added, the microorganisms from the biogas process (hydrogenotrophic methanogens) perform biological methanation and produce more methane.

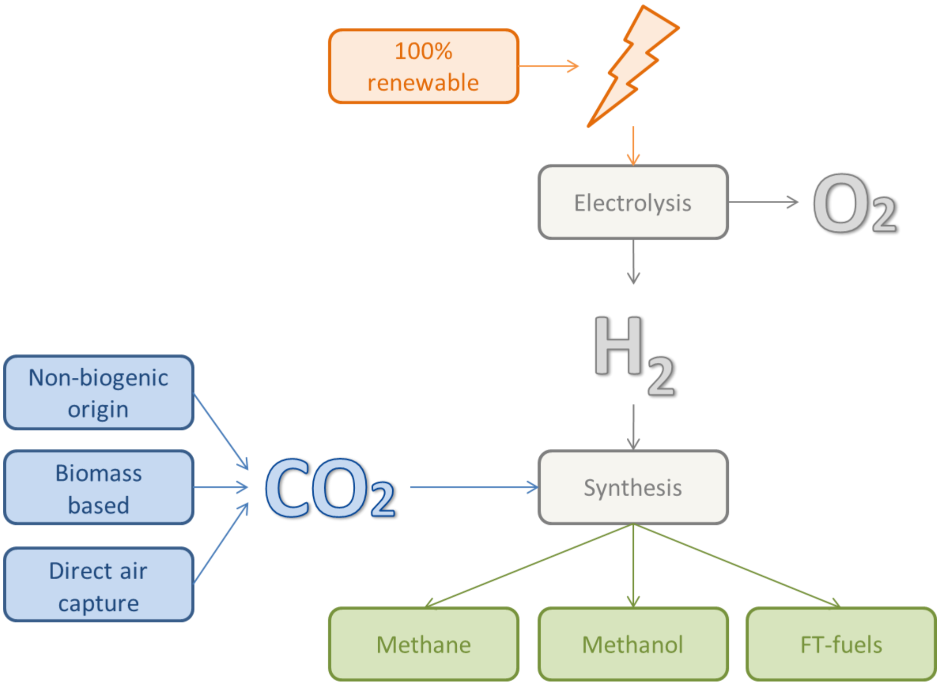

Figure 19: Electrofuels pathways

Since the term “electrofuels” includes different kinds of fuels, the possibilities for the **end use** are versatile. Some end use applications are:

- In order to complement other renewable electricity generation technologies, using electrofuels (hydrogen) is often considered in islanded systems (e.g. Japan) with high costs of fossil fuel delivery.
- To facilitate the use of hydrogen in smaller industries and buildings, it can be injected to the gas grid by mixing with natural gas or methane. There is also the possibility to use pure hydrogen in gas grids, but this still faces some difficulties, like high costs or efficiency issues.
- Using electrofuels in transportation (road, marine, aviation) enables almost zero-emissions mobility. For road vehicles there are several options, such as the use of FT-fuels as drop-in fuel in conventional vehicles, the use of methane or methanol in adapted vehicles, or the use of hydrogen in fuel cell vehicles. In the maritime sector hydrogen is considered for shorter trips but not for long haul ocean-going ships. For aviation FT-fuels can be used in blends of up to 50%.

Electrofuels are both liquid and gaseous fuels and therefore the application is versatile. **Advantages** of electrofuels are, among others, the possibility of long-term storage, their potentially low GHG-intensity, and their applicability in conventional vehicles. However, high conversion losses and high transportation and distribution costs make electrofuels quite expensive. (Philibert, 2018)

Opportunities for retrofitting

Existing installations for the production of ethanol or biogas can be retrofitted (extended) by **capturing CO_2** from the fermentation process and combining this CO_2 with hydrogen produced by an electrolyser. The subsequent synthesis produces methane, methanol, or FT-liquids.

Existing biomass gasification units can be retrofitted by **adding hydrogen to the raw syngas**, hereby altering the hydrogen to carbon monoxide ratio and partly or entirely replacing the water gas shift reaction. As a result, more fuels can be produced from the carbon in the biomass.

Existing biogas facilities can be retrofitted with a second reactor fed with hydrogen and biogas. **Biological methanation** is capable of converting most of the carbon dioxide in the raw biogas to additional methane.

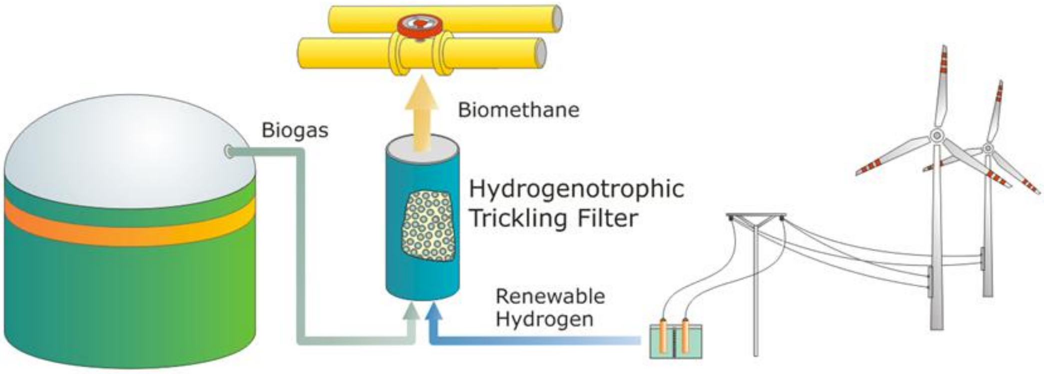

Figure 20: Biological methanation (Source: Rachbauer et al. 2016)

5.8 Concluding remarks

When comparing the goals for emission reductions in the transport sector with the development of sustainable alternatives it becomes clear that much production capacity has to be build up. While doing this, retrofitting could mainly make sense when additional fuel is produced or when the efficiency of the processes can be increased. Changing from one biobased feedstock (1G) to another biobased feedstock (2G) may lead to the production of a biofuel that is considered more sustainable but does not contribute significantly to the reduction of fossil fuels in the transport sector.

In general, the European biofuel installations are fairly new, since most of them have been built after 2005. Therefore, costly investments in retrofitting measures in the existing infrastructure may seem early from a plant operator's view.

Some other recommendations are more specific:

- The biofuels sector is heavily influenced by **regulations**. These regulations also have a great influence on the economy of investments in retrofitting. Changes in the regulations should thus be made with caution in order to keep up the plant operator's trust in their business plans. The risk of change of regulations seems to be considered very high, which apparently hinders investments in the biofuel sector.
- In order to make use of biomethane as a renewable transport fuel, the build-up of **infrastructure** for its utilisation should be promoted and supported. A larger share of

CNG fuelled vehicles would allow to make use of biomethane from thousands of biogas plants, many of which can use biobased residues as feedstock.

- Biofuel producers currently do not have a direct **access to the customers** and little possibilities to advertise the benefits of their products. Therefor dedicated biofuel products at the pump could offer a possibility to the customer to choose sustainable fuels.
- The **CO_2 emissions** of the different fuels, (fossil and biofuels) should be visible to the customer at the pump.

6 Retrofitting fossil refineries

6.1 Overview of the sector

Fossil fuel refineries convert crude oils into finished products by breaking them down and processing them to new products such as fuels for transport.

Crude oil is extracted from the earth. There are many types of crude oils, with many different components. Most of these components are hydrocarbons (molecules consisting of the elements carbon and hydrogen). Other components in crude oils consist of a combination of hydrocarbons and small amounts of other elements, such as sulphur, nitrogen and metals.

Refineries are large and capital-intensive installations that convert crude oil into **final products**. In European refineries about 65% of the products are transport fuels, such as diesel, gasoline, kerosene, heavy oil and liquid gas. 25% of the products are made for other applications, such as bitumen, lubricants, heating oil and oil coke. 10% of the products are petrochemical feedstock used in chemicals, synthetic rubber, and a variety of plastics.

Figure 21: Fossil refineries are large industrial complexes where a variety of fossil transport fuels and other products are produced. (Source: Thessaloniki Refinery of Hellenic

Petroleum)

Core processes in a refinery are 1) the separation of the crude oil in various fractions, and 2) processing these fractions into various products. In Figure 22, some basic processes of a typical refinery are shown. The 'heart' of any refinery is the atmospheric distillation. In this distillation column the crude oil is heated up, and separation is carried out based on boiling point. Gaseous products (with the lowest boiling points) leave the column from the top, and the heavy fractions (with high boiling points) are leaving the column from the bottom.

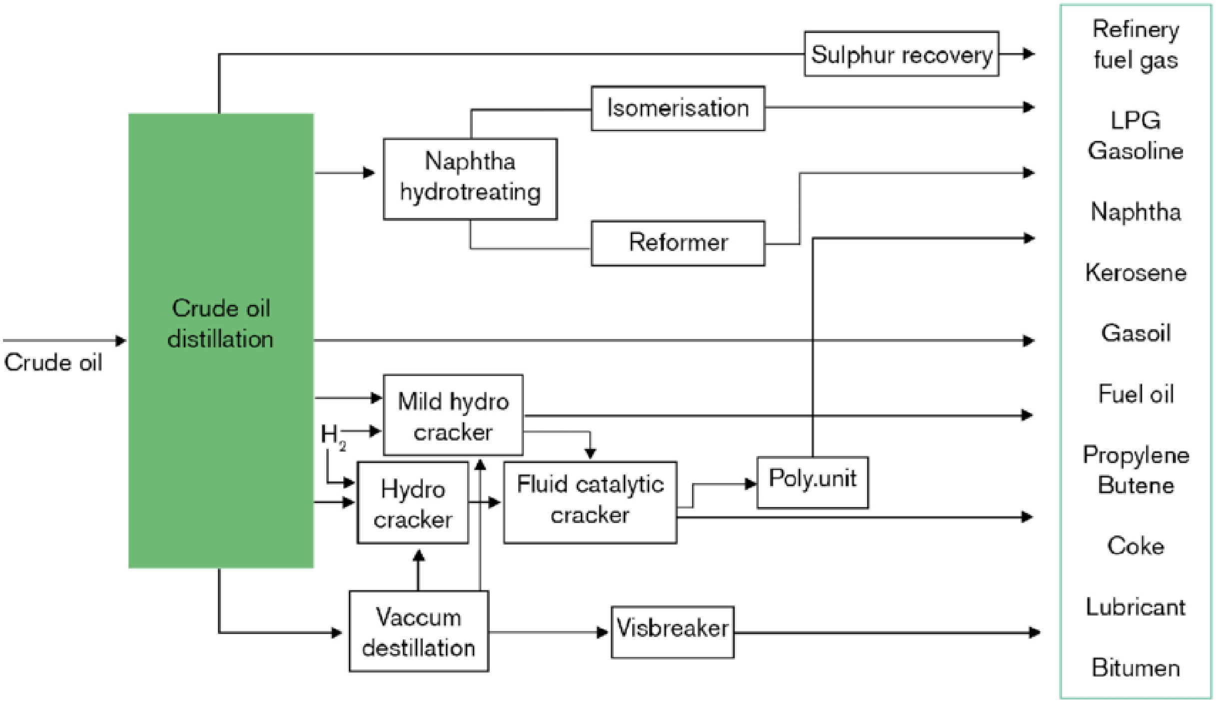

Figure 22: Basic processes in a refinery

Each refinery is unique, because of the differences in geographical location, crude oil specifications, markets, product specifications, etc. Refineries produce a variety of products, based on their input and market needs. Refineries can and do change their product compositions and quantities continuously based on factors within the physical limitations of their refinery processes. Because of the complexity of their operations and the interconnections between the various processes, mathematical models are used to adjust the refinery parameters so that products in the right quantities and specifications can be produced.

Refineries can be classified by the **Nelson complexity index**. This is a numerical value that denotes how many downstream processing units a refinery possesses after the crude distillation unit, which has a complexity of 1. These can be divided into the following categories:

Table 5: Nelson complexity index categorisation of fossil fuel refineries

Configuration	Type of processes
Simple and base	No conversion units beyond the crude oil distillation
Configuration 1 (complexity <2), also called **topping refineries**	Simplest type of oil refinery, consisting of a distillation unit, a naphtha reformer and some necessary treatment
Configuration 2 (complexity 2 – 6), also called **Hydro skimming refinery**	As configuration 1, but with a vacuum distillate unit and a catalytic cracker

Configuration 3 (complexity 6 – 12) also called **Conversion refineries**	Equipped with a hydro cracker, maximising the production of gasoline and middle distillates
Configuration 4 (complexity >12, also called **Deep Conversion refineries**	Includes both hydrocracking and catalytic cracking units and coking units to convert the heaviest crude oil fractions to lighter products

Many refineries in the EU have a relatively low complexity (configuration 1 and 2), while many refineries in the USA, India and the Persian Gulf have far higher complexities. A higher complexity means higher capital costs, but also more flexibility and the possibility to make higher valued products.

With a crude refining capacity of about 13.2 million barrels per day[17], representing 13% of total global capacity[18], the EU is the second largest producer of petroleum products in the world after the United States[19]. In the EU's 90 refineries, direct employment is provided to 120,000 persons, and indirectly to 1.2 million people. The transport sector in the EU is currently for 95% fuelled by liquid (fossil) fuels[20], and is responsible for more than 25% of GHG emissions in the EU[21].

In the last decade – roughly from 2007 onwards – the EU refining sector has seen a market contraction, due to changing market demand and competition from more modern refineries outside Europe. In total about 20 refineries have been either closed, or converted to biorefineries, and several have also reduced their capacities. This has resulted in a decrease in the number of refineries from 110 to 90.

Starting in 2015, margins have increased, slowing down the closures of European refineries. The modernisation of European refineries has allowed them to process heavier and more contaminated crudes.

6.2 Carbon reduction in fossil refineries

Due to the need to reduce carbon emissions in the environment, as agreed in the Paris Agreement of 2016, the EU has sought to develop renewable alternatives to fossil transport fuels, such as biofuels. Biofuels are liquid or gaseous transport fuels such as biodiesel and bioethanol which are made from biomass. They serve as a renewable alternative to fossil fuels in the EU's transport sector, helping to reduce greenhouse gas emissions and improve the EU's security of supply.

In the Renewable Energy Directive (RED) (2009/28/EC), it was stipulated that by 2020, the EU would have 10% of the transport fuel of every EU country come from renewable sources such as biofuels. Fuel suppliers are also required to reduce the greenhouse gas intensity of the EU fuel mix by 6% by 2020 in comparison to 2010.

The original RED was updated in 2018 to the Revised Renewable Energy Directive (RED II) (2018/2001/EU)[22], which was published as part of the Clean Energy for all Europeans package. In this RED II it is stipulated that each Member State should set an obligation on fuel suppliers

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[17] https://www.concawe.eu/refineries-map/
[18] https://www.eni.com/docs/it_IT/eni-com/azienda/fuel-cafe/WORLD-OIL-REVIEW-2018-Volume-1.pdf
[19] https://ec.europa.eu/energy/en/topics/oil-gas-and-coal/oil-refining
[20] www.fuelseurope.eu

[21] https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-10
[22] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

to ensure that the share of renewable energy within the final consumption of energy in the transport sector is at least 14% by 2030.

It is – also within the sector itself - accepted that a **main challenge of the refining sector** is how to manage the transition to a low-carbon economy[23]. The European platform organisation of refineries, FuelsEurope, has issued its own vision document "Vision 2050"[24] in 2018, in which they lay out their vision for a low-carbon future for the refining industry. The main points of this vision are:

- The EU refining industry states that they are committed to contribute to the EU objective to lead the world in addressing the global climate change challenge by continuing to reduce its CO_2 emissions and providing the economy and citizens with low-carbon fuels and other products that society needs.
- In the longer term they expect that renewable hydrocarbon will remain essential for chemical feedstocks, marine, aviation and a part of the heavy-duty vehicles
- They foresee the increased use of new feedstocks, such as renewables, waste and captured CO_2 in a very efficient manufacturing centre in synergy with other sectors, such as chemicals, district-heating
- Many technologies will be needed to produce low-carbon liquids with the potential to deliver low-emission mobility across lifecycle in all the transport segments, such as sustainable biofuels, CCS/CCU, renewable hydrogen and power-to-liquids
- They expect that in 2050, low-carbon liquid fuels can reduce net GHG emissions from passenger cars and vans by 87% compared to 2015.

From these main points, it is clear that the European refining sector wants to reduce its carbon emissions substantially, and that bioenergy and biofuels are seen as part of this solution.

Opportunities for retrofitting

As recognised by the refineries sector, bioenergy retrofitting is a way to increase the production of renewable transport fuels in their sector. The main technology for achieving this goal is the **hydroprocessing** of renewable liquid oils, such as palm oil and used cooking oil and upgrade these to renewable transport fuels in refineries. These 'green biofuels' are also called HVO (Hydrogenated Vegetable Oils). There are already several refineries retrofitted to produce HVOs.

Other technologies are less well-developed. The main pathways for converting lignocellulosic materials into fuels include various forms of thermochemical transformations such as, thermal pyrolysis, catalytic pyrolysis, hydropyrolysis, hydrothermal liquefaction and liquefaction in hydrocarbon solvents (Perkins et al. 2019). One of the more promising ways to increase the share of renewable fuels is the **co-feeding of a renewable bioliquid pyrolysis oil** in refineries.

These technologies are explained in the next chapters and are shown in Figure 23.

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[23] https://ec.europa.eu/energy/sites/ener/files/documents/Highlights%20%26%20summary%20of%20the%206th%20EU%20Refining%20Forum%20FINAL.pdf

[24] https://www.fuelseurope.eu/vision-2050/

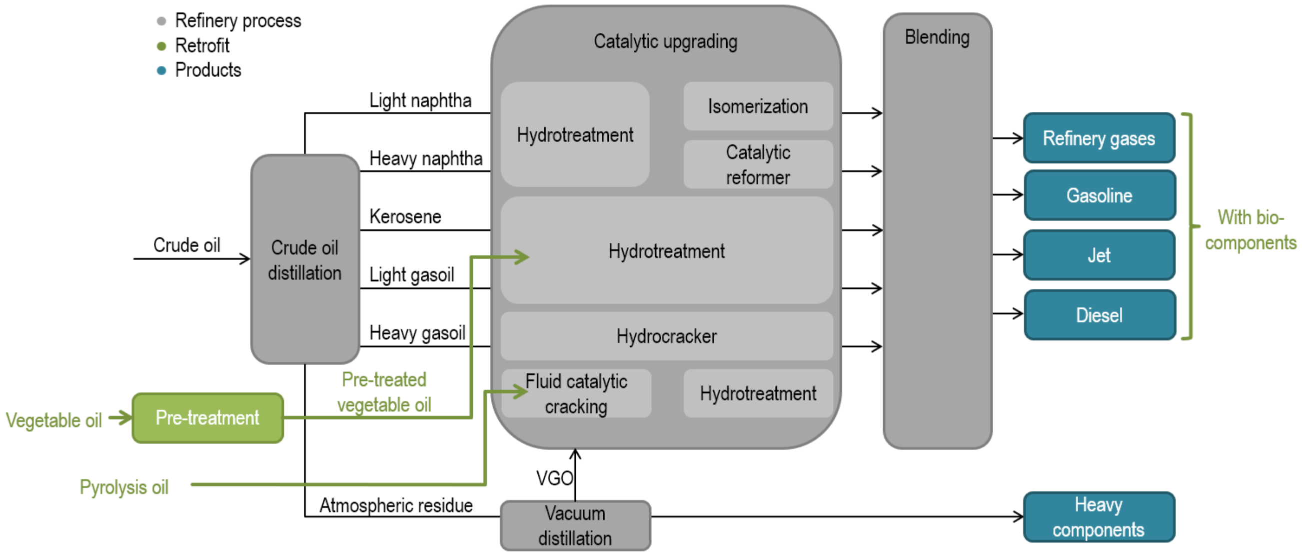

Figure 23: Integration of vegetable oil and pyrolysis oil in a refinery process.

6.3 HVO integration

A synonym for **HVO** (Hydrogenated Vegetable Oils) is **HEFA** (hydroprocessed esters and fatty acids). HVO/HEFA are produced differently than 'traditional biodiesel', which is also called **FAME** (Fatty Acid Methyl Esters). The traditional biodiesel production process involves a chemical reaction (transesterification) of fats or oils with methanol in dedicated biodiesel production plants. This transesterification results in biodiesel (the FAME) and a by-product – glycerol.

The simplified production process of HVO is shown in Figure 24. Raw materials are vegetable oils, used cooking oils or other used oils and fats. After a pre-treatment to remove impurities, the HVO production takes place in two **process steps**[25].

In the first step (Figure 25) – called **hydroprocessing** – the oils and fats are converted to paraffins. Paraffins are straight hydrocarbon chains, also called alkanes. Alkanes are relatively simple molecules, consisting of saturated carbon and hydrogen molecules, hence the name hydrocarbons. This process takes place at reaction temperatures 300°C and 390°C. Hydrogen is added to the oils and fats – here depicted as triglyceride – to get rid of the double bonds. Subsequently, hydrogen is used to split the molecule into a straight chain, with propane (also called bioLPG) as a by-product. Oxygen is then removed as water (deoxygenation) or as CO_2 (decarboxylation).

In the second step – called **isomerisation** – the paraffins are cracked and isomerised so that the green diesel (main product) meets the required cold property requirements. By-products are green naphtha and green jet fuel. HVOs are far more similar to the diesel fraction in crude oil distillation than FAME (fatty acid methyl ester). HVO contain no oxygen, no double bonds, no aromatics and no sulphur (Forschungszentrum Jülich, 2019). It was shown, that feedstocks with a high degree of saturation are more favorable, because it will require lesser amount of hydrogen during hydrogenation. (Mittelbach, 2015)

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[25] http://www.etipbioenergy.eu/value-chains/conversion-technologies/conventional-technologies/hydrotreatment-to-hvo

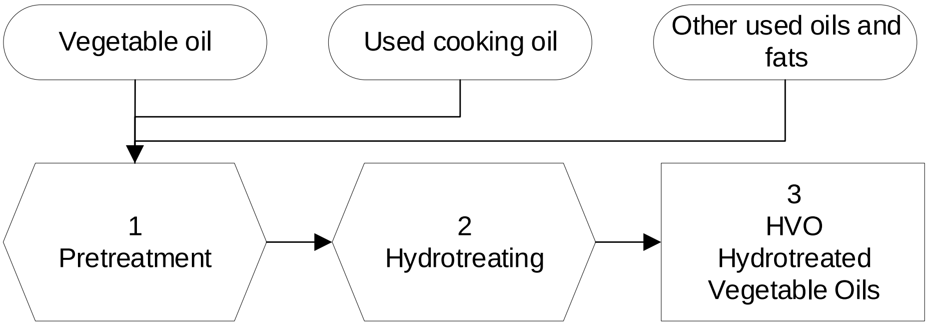

Figure 24: Simplified block flow diagrams of the HVO process

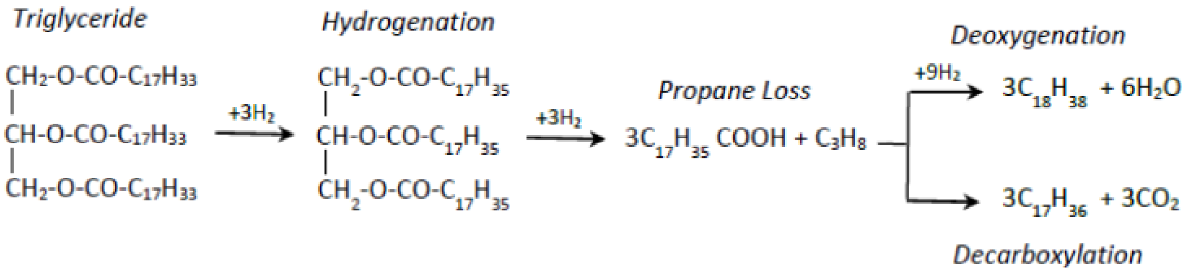

Figure 25: Hydroprocessing of oils and fats; step one of the two-step process to produce HVO.

The production of HVO is commercially proven, and there are several companies which license the technology[26], such as Axens IFP (Vegan), Honeywell UOP (Green Diesel), Neste (NextBTL), Haldor Topsoe (Hydroflex) and ENI (Ecofining).

A wide range of oils and fats can be used to produce HVO:

- Plant oils, including oil from food crops like rapeseed, sunflower soy bean, palm oil, but also inedible oils like jatropha and tobacco oil
- Animal fats, such as tallow, white grease and poultry fat
- Waste oils, like Used Cooking Oil (UCO) and yellow grease
- Microbial oils

Most of these feedstocks are tryglycerides, which means that HVO production yields bioLPG as a by-product. Some feedstocks, such as palm fatty acid distillate (PFAD) and tall oil are straight fatty acids, and do not yield bioLPG as by-product[27].

HVO production can be carried out stand-alone, or retrofitted fossil refineries. Table 6 provides an overview on current and planned projects for HVO production[28]:

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[26] https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel_handbook.pdf

[27] https://www.mdpi.com/1996-1073/12/2/250/pdf

[28] Argus, HVO production and outlook 2019 map, https://www.argusmedia.com/en/bioenergy/argus-biofuels

Table 6: Current and planned HVO production in Europe

Operator	Location	Type	Status	Capacity (t/year)
PREEM	Gothenburg (Sweden)	stand-alone	Operational	100,000
ST1	Gothenburg (Sweden)	stand-alone	Planning	100,000
Sunpine	Pitea (Sweden)	stand-alone	Operational	100,000
UPM	Lappeenranta	stand-alone	Operational	100,000
UPM	Kotka (Finland)	stand-alone	planning	500,000
Neste	Porvoo (Finland)	stand-alone	Operational	580,000
Neste	Rotterdam (Netherlands)	stand-alone	Operational	1,000,000
Galp	Sines (Portugal)	stand-alone	Operational	72,000
Total operational stand-alone production				**1,952,000**
BP	Castellon (Spain)	Retrofit	Operational	80,000
Repsol	various (Spain)	Retrofit	Operational	200,000
Cepsa	La Rabida (Spain)	Retrofit	Operational	43,000
Cepsa	San Roque (Spain	Retrofit	Operational	43,000
ENI	Venice (Italy)	Retrofit	Operational	300,000
ENI	Gela (Italy)	Retrofit	planning	600,000
Total	La Mede (France)	Retrofit	planning	500,000
Total operational production in refineries				**666,000**
Total operational capacity				**2,618,000**
Total operational and planned capacity				**4,318,000**

HVO properties can be influenced by upgrading reactions using different types of catalysts and modifying the reaction conditions, such as temperature and pressure. Therefore, the **properties of HVO** can be adapted to meet various industrial needs, so it is possible to obtain fuels which meet the specifications of aviation fuels.

FAME and HVO have **different material properties**. Because FAME is an ester, its chemical composition is different from fossil diesel, which means in practice that its use is limited to a maximum percentage of 7% in the EU (the "blend wall'). This maximum has been established because of possible problems in engines such as damage to specific parts, carbon build-up in the engine and absorption of water, which would lead to growth of microbes in the fuel tank. Other issues with FAME are its relatively high freezing point. HVO does not have these issues since it is very similar to fossil diesel.

HVO can be used for both **road transport** and well as **aviation**. The use of HVO for the aviation sector has been proven by various tests with different aircrafts and companies. HVO is already certified since 2011 by the international ASTM standard D7566. According to this standard, a blending rate of 50% is possible (Isfort et al., 2012). Although the technologies are available, so far HVO for aviation is produced only in batches for dedicated tests. An example is the test of Neste Renewable Aviation Fuel in a larger scale with 1,187 flights from Lufthansa between Frankfurt and Hamburg and one intercontinental flight to Washington DC in 2011. Within these tests, no complications occurred and the commercial use in the future has been proven (Neste Oil, 2012).

Due to the lack of other alternatives, sustainable **aviation fuels** will be necessary for climate friendly air traffic in the future (Zech et al., 2014). Kerosene-like alternative fuels with drop-in characteristics are sought, because they require little to no modification to the fuel infrastructure and aircrafts. Drop-in biobased aviation fuels also allow a blending of fossil-based kerosene with alternative fuels. Figure 26 shows the Jet fuel demand of all flights departing in Germany (grey bars) and the associated emissions of CO_2 (blue line). To reduce

CO_2 emissions with increasing jet fuel demand, it is necessary to fly with sustainable aviation fuels. This will require a large amount of sustainable aviation fuels in the future for reaching the ambitious targets of the International Air Transport Association (IATA, green line) and the climate protection plan of the German government (red line).

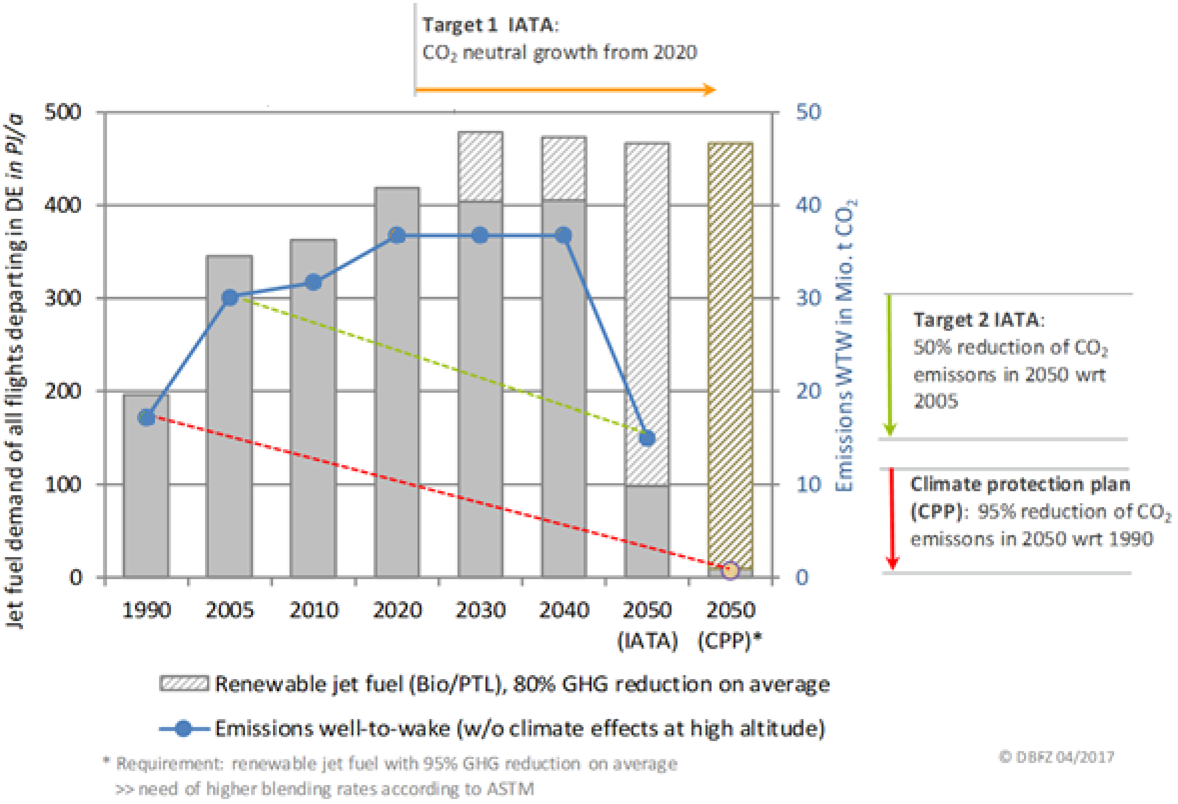

Figure 26 Jet fuel demand of all flights departing in Germany (Dietrich et al., 2017)

Costs for HVO production has been estimated in the framework of a wider study on the costs of biofuels[29]. In this study it was determined that production costs of HVO fuels are between 600 – 1,100 €/t, or 14 – 25 €/GJ. The dominating costs – 60% to 80% - are the costs for the feedstock. The costs for HVO are at the lower end of the spectrum when compared with costs for other biofuels. Costs for biofuels from biomethane could be lower (11 – 34 €/GJ), but all other biofuels – such as cellulosic ethanol, FT liquids, etc. - show higher cost ranges.

A significant expansion of production can be expected in the next years. Reasons for this are the low freezing point of HVO, no 'blend wall' and the opportunities to use HVO as aviation fuel. The equipment needed for HVO production is similar to that used for desulfurization of fossil crude oil. Therefore, this technology is suitable for the retrofitting of fossil refineries.

Currently, the share of HVO of the biodiesel production in the EU (2018) is 17%. Table 6 shows that, while operational capacity in refineries is currently a lot smaller than stand-alone capacity, the refinery capacity will increase markedly in the near future.

One **HVO project example** is the Total refinery La Mède (France). Since 2015 Total has transformed the fossil fuel refinery into a biorefinery. Today it has a capacity of 500,000 tonnes of HVO-type biodiesel. The start of the production was in July 2019. In the future aviation fuel can be produced as well (Total, 2019). Another example is the project of Eni in Gela (Italy). Outside Europe, HVO production volumes are smaller. In North America, 1,155,000 tons are

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[29] EU DG Mobility and Transport, „Building up the future – Cost of Biofuels" (2018) https://publications.europa.eu/en/publication-detail/-/publication/13e27082-67a2-11e8-ab9c-01aa75ed71a1/language-en/format-PDF

to be produced in 2020, a similar amount to Asia. In Asia the biggest volume (800,000 tons/year) is produced in the Neste NExBTL plant in Singapore[30].

The sourcing of feedstocks will however be challenging, since the RED II caps first generation crop-based biofuels, and in addition several Member States – notably France and Norway – are to stop considering palm oil-based fuels as biofuels from 2020 onward. Waste-based second-generation feedstocks are not in large supply and high collecting countries outside Europe (China, US, India) may increase their local consumption of waste-based biodiesel.

A more general challenge is the changing fuel mix in Europe. While kerosene consumption is set to grow in the next 10 years, diesel use is going to decline steadily, from 53% now to 33% in 2050[31].

6.4 Pyrolysis oil integration into refineries

Pyrolysis is a process in which biomass is heated in the absence of air/oxygen. Under these conditions the organic material decomposes, forming vapours, permanent gases and charcoal. The vapours can be condensed to form the main product: pyrolysis liquid. In order to maximize the liquid production, the biomass heating, as well as the vapor condensing needs to be done quickly. Hence the name fast pyrolysis. Alternatively, the biomass conversion can be directed at producing charcoal. In this case heating is less rapid and the process is called slow pyrolysis or carbonisation. The latter is usually carried out at temperatures below 400°C.

Figure 27: Pyrolysis oil

Fast pyrolysis is meant to convert the biomass to a maximum quantity of liquid of around 60 to 70 wt.% of the feedstock. Beneficially, a more uniform, stable and cleaner-burning product is obtained, that could serve as an intermediate energy carrier and feedstock for subsequent processing. The **essential process conditions** of fast pyrolysis for the production of pyrolysis liquids are:

- a very fast heating of relatively small biomass particles (in order of seconds),
- controlling the pyrolysis reactor temperature at a level around 500 degrees centigrade,
- a short vapour residence time to avoid further cracking to permanent gases,
- rapid cooling of all the vapours to form the desired pyrolysis liquid.

Various different **reactor types** have been tested in European and American laboratories. Amongst them are the vortex reactor, rotating blades reactor, rotating cone reactor, cyclone reactor, transported bed reactor, vacuum reactor, and the fluid bed reactor. Many pilot plants were set up during the 80s and 90s. However, for various reasons, most pilot plants are not in operation anymore. On the other hand, a few successful examples emerged as well. Amongst them are Ensyn's circulating fluid bed process that has been used for many years to produce "liquid smoke". The alliance of Ensyn and UOP resulted in the start of Envergent, which aims

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[30] https://www.chemicals-technology.com/projects/neste-oil-plant/

[31] Greenea Conference presentation, May 2019, Denver, USA, https://www.greenea.com/en/publications/

at the production of biofuels. Another successful example is the process developed at BTG using a rotating cone (Figure 28).

The technology based on the rotating cone has been successfully implemented in Malaysia on the pyrolysis on empty fruit bunches, as well as in the Netherlands on the pyrolysis of residual woody biomass (EMPYRO). The EMPYRO plant was commissioned in 2015, with the bulk of the pyrolysis oil being shipped to Friesland Campina for generating industrial heat. After three years of successful start-up time, the EMPYRO plant is now running at full capacity and has been acquired by Twence.

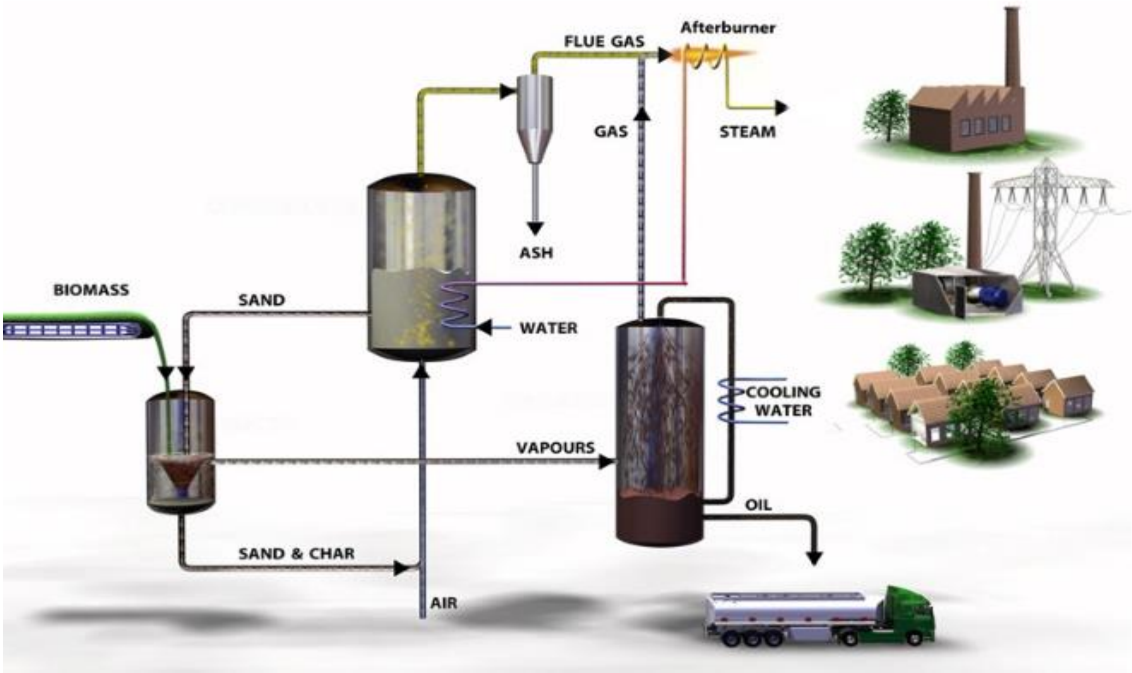

Figure 28: Artist impression of the pyrolysis process based on the rotating cone technique (Source: BTG)

Pyrolysis offers the possibility of de-coupling the fuel production from the handling of the biomass in terms of time, place and scale, easy handling of the liquids, and a more consistent quality compared to any solid biomass. With fast pyrolysis a clean liquid (Figure 27) is produced as an intermediate suitable for a wide variety of applications, one of which is co-feeding it in refineries.

The **properties of pyrolysis oil** (Table 7) are quite distinct from mineral oil. The oil usually contains a low amount of ash, and a significant amount of water (it is an emulsion). The volumetric energy density is 5 to 20 times higher than the initial biomass from which it is produced. The density is higher than fuel oil, and significantly higher than biomass. The HHV of pyrolysis oil is 16-23 MJ/l, which is a lot lower than fuel oil which has a typical heating value of 37 MJ/l. Pyrolysis oil is acidic, with a pH of 3. It is a reddish/brown liquid with an odour resembling a barbecue flavour. Due to large amounts of oxygenated components present, the oil has a polar nature and does not mix readily with hydrocarbons.

Table 7: Properties of a batch of pyrolysis oil (Source: BTG)

Property	Unit	Value
C	wt%	46
H	wt%	7
N	wt%	<0.01
O (Balance)	wt%	47
Water content	wt%	25
Ash content	wt%	0.02
Solids content	wt%	0.04
Density	kg/l	1.2
LHV	MJ/kg	16
LHV	MJ/l	19
pH	-	2.9
Kinematic viscosity (40°C)	cSt	13

By-products in the form of char and non-condensable gases are produced as well. In an industrial process, these two by-products (both 10 to 20 wt.%) would be used primarily as a fuel for the generation of the required process heat (including feedstock drying). But sometimes the char is also proposed to be applied as a biochar soil improver or as a substitute for metallurgic coke in the steel industry. Alternatively, for specific purposes (and reasons), it can be recombined with the fast pyrolysis oil to form **a char-oil slurry**.

The gaseous by-product essentially is a mixture of CO and CO_2. Apart from flue gas emissions and ash resulting from the char combustion, there are no waste streams. The biomass ash will be largely concentrated in the char by-product. It is separated when the char is combusted in the process, viz. to generate the heat for drying and heating of the biomass feedstock.

Almost all types of biomass are suitable as **feedstock** for pyrolysis. The main requirements for the fast pyrolysis process is that the biomass is relatively dry (less than 6-8% moisture content) and a relatively small size (a few millimetres).

Wood and wood residues are very well suited for pyrolysis, but many other types of biomass such as rice husk, bagasse, sludge, tobacco, energy crops, palm-oil residues, straw, olive stone residues, chicken manure and many more could be used as well. The type of biomass/residue influences the pyrolysis oil yield and quality. Typically, woody biomass gives the highest yields.

Since few types of biomass meet the two criteria – size and moisture content - when harvested commercial pyrolysis oil production plants require a biomass pre-treatment section. This pre-treatment section can be powered using the excess heat and power from the pyrolysis installation as long as the moisture content does not exceed a certain limit (about 55-60 wt.%).

The production of pyrolysis oil is currently being carried out at several locations in Europe:

- The EMPYRO pyrolysis plant in Hengelo, the Netherlands converts 5 tonne per hour of dry woody biomass to pyrolysis oil. The plant was completed in 2015 and has reached full production – 24,000 tonne of pyrolysis oil per year – in 2018. The pyrolysis oil is currently co-combusted with natural gas for the production of steam at the nearby dairy plant of FrieslandCampina in Borculo (the Netherlands). Currently (2019) the consortium behind the Empyro plant – a cooperation between the companies BTG-BTL and TechnipFMC[32] - is constructing a second full-scale plant in Finland[33].

- Fortum and Valmet have implemented a 50,000 tons of pyrolysis oil production plant, integrated with the Joensuu CHP plant in Finland. The pyrolysis plant was commissioned in 2013. The bio-oil raw materials include forest residues and other wood-based biomass types. Trade name of Fortum's pyrolysis oil is Fortum Otso[34].

Besides these two plants there are several plants operational outside of Europe, based on the Ensyn/Honeywell UOP platform. Three pyrolysis plants dedicated to the production of renewable fuels have been constructed, namely Ontario (Canada), the Red Arrow Products pyrolysis plant in Wisconsin (USA), and the recent AE Cote-Nord project in Montreal (Canada).

Figure 29: The Empyro pyrolysis plant in Hengelo, The Netherlands

Opportunities for retrofitting

Pyrolysis oil is a relatively homogeneous bioliquid that can be produced from a variety of solid biomass types. Hence it is in principle suitable for co-feeding in refineries, because refineries are used to liquids, and because refineries are large scale facilities that require large quantities of input. For normal bulky biomass this imposes logistical challenges, but the pyrolysis oil energy density is such that transport over larger distances becomes economical.

An important technical barrier with respect to co-feeding of pyrolysis oil is the oxygen content. Since pyrolysis oil is produced by a relatively simple thermal degradation of biomass, a lot of the oxygen present in the biomass is also present in the pyrolysis oil. This oxygen needs to be removed wholly or partially to be able to produce transport fuels.

There are several ways to co-feed pyrolysis oil in a refinery.

- The pyrolysis oil can be fed into the FCC (Fluid Catalytic Cracker) of the refinery as it is. This has been carried out on a pilot scale by Petrobras in Brazil. In the paragraph ‘current status’ this work is explained in more detail
- Pre-treat the pyrolysis oil so that part of the oxygen is already removed in by way of a hydrodeoxygenation step carried out in a catalytic hydrotreatment process. This way, an upgraded form of pyrolysis oil is available that can readily be utilised in a refinery. Because full deoxygenation requires quite some hydrogen, an alternative approach is to just partially de-oxygenate the pyrolysis oil and finish the conversion to transportation fuel in an existing refinery unit crude oil refinery.

The proof of concept for feeding partially upgraded pyrolysis liquids to an FCC, was demonstrated first in the EU FP6 project BIOCOUP that was concluded in 2010. This was further developed in the EU FP7 project FASTCARD, which aimed at a more efficient conversion of biomass to biofuels by improving catalysts. It has been concluded already that

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[32] https://www.btg-btl.com/en/technology

[33] https://bioenergyinternational.com/biofuels-oils/finland-first-for-dutch-pyrolysis-technology-developers

[34] https://www.fortum.com/products-and-services/power-plant-services/fortum-otso-bio-oil

'co-FCC of upgraded pyrolysis oil is technically possible. Currently (2019) the co-feeding of pyrolysis oil in refineries is further investigated in the H2020 project 4refinery[35].

Regarding the FCC product spectrum, no unexpected deviations occur. It merely depends on the degree to which the pyrolysis oil has been upgraded and the co-feeding ratio. Typically, coke and gas yields are getting higher. Regarding the severity (pressure, temperature, space time) at which the pyrolysis liquids have been pre-processed in a prior hydrotreatment step, three types of pyrolysis derived feedstocks can be distinguished: (1) fully deoxygenated, (2) partially deoxygenated, and (3) untreated pyrolysis liquids. Fully deoxygenated liquids should behave similarly to the usual feed for FCC (vacuum gas oil or VGO), while untreated pyrolysis liquids yield more coke and gas compared to VGO. Obviously, also the feed ratio of VGO over pyrolysis liquids will have a strong effect on the final result.

Costs of biofuel production from pyrolysis oil co-feeding have been recently estimated[29]. In this study, it was estimated that production costs of biofuels from pyrolysis oil are between 16 – 29 euro/GJ. It should be noted that since the co-feeding of pyrolysis oil in refineries is not commercially applied yet, there is considerable uncertainty about the costs. Feedstock costs are lower compared to the feedstock costs for HVO because pyrolysis oil can be produced from lignocellulosic residues.

The costs for biofuels produced from pyrolysis oil are at the lower end of the spectrum when compared with costs for other biofuels. Costs for biofuels from biomethane and costs for HVO (see previous paragraph) could be lower, but all other biofuels show higher cost ranges.

Pyrolysis oil integration in fossil refineries is not fully commercial yet. However, there have been developments to commercialise this option:

- **Co-feeding of pyrolysis oil in the Petrobras pilot plant**[36]*:* In this work, untreated pyrolysis oil, produced from pine woodchips, was co-processed with standard Brazilian vacuum gasoil (VGO) and tested in a 200 kg/hr fluid catalytic cracking (FCC) demonstration-scale unit while using a commercial FCC catalyst. Co-feeding ratios of 5% and 10% were used. It was shown that the co-processing of pyrolysis oil in an FCC was technically feasible. Both the VGO and the pyrolysis oil were cracked into transportation fuels such as gasoline and diesel. Oxygen was removed as water and CO. Carbon efficiency was 30%. Via C14 isotope analysis the presence of renewable carbon was confirmed.
- **Co-feeding of pyrolysis oil at the PREEM refinery in Lysekil**[37]*:* The first full-scale co-feeding of pyrolysis oil in a refinery in Europe has been announced by the companies Preem and Setra. Together they have established a joint venture – Pyrocell AB - to invest in a pyrolysis oil plant at Setra's Kastet sawmill outside Gävle, Sweden. First announced in June 2018, the new pyrolysis plant will be producing pyrolysis oil using sawdust as feedstock. The plant is expected to be operational by the end of 2021. The pyrolysis oil will be used as a renewable biocrude feedstock in the production of biofuels at Preem's refinery in Lysekil.

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[35] https://www.sintef.no/projectweb/4refinery/

[36] „Fast pyrolysis oil from pinewood chips co-processing with vacuum gas oil in an FCC unit for second generation fuel production", Andrea de Rezende Pinho, Marlon B.B. de Almeida, Fabio Leal Mendes, Luiz Carlos Casavechia, Michael S. Talmadge, Christopher M. Kinchi, Helena L. Chumc, http://dx.doi.org/10.1016/j.fuel.2016.10.032

[37] https://bioenergyinternational.com/biofuels-oils/setra-and-preem-first-in-europe-with-renewable-fuel-from-sawdust

6.5 Concluding remarks

Refineries are showing more and more interest in decarbonising their products by using biomass as inputs. Production of HVO in existing refineries is an example. Sustainability is a serious point of attention, since refineries are large scale enterprises and invariably need significant amounts of feedstock to produce biofuels.

The 'blend wall' becomes less and less of a problem because it is now possible to produce biofuels with equal or even better characteristics as compared to the fossil alternative.

Intermediate bioenergy carriers can play a significant role in providing sufficient feedstock to refineries, since transportation is more feasible and because of their homogeneity. Some value chains are already on the market, like co-feeding of pyrolysis oil; others are still in a developing stage. Support at pilot, demo scale, as well as stimulating the market uptake is recommended.

Work still needs to be done to determine the sustainability aspects of co-feeding biomass in a refinery. The current (C14) methods may not always work to determine the renewable carbon quantities in 'green' refinery products

Since refineries operate in a global environment, it is important that a level playing field is assured. Sustainability requirements for renewable biofuels should be maintained for all biofuels – both for inside and outside of the EU - that are put on the EU market, and these should be vigorously maintained.

7 Retrofitting fossil fired power and CHP plants

7.1 Overview of the sector

Fossil fuels contributed to 65.1% of the world's gross electricity production in 2016; coal alone amounted to 38.3% of the total amount (IEA, 2019). Mostly due to the huge growth in China and India, the installed capacity of coal fired power plants has exceeded 2,000 GW, more than double than the capacity in 2000 (CarbonBrief, 2019).

Thanks to a set of policies pushing for wide **decarbonization** of the energy sector, the situation in Europe is quite different from the global perspective. Still, 19.2% of power production in EU-28 is coming from hard coal and lignite (Agora Energiewende and Sandbag, 2019). As for 2018, the installed power capacity of operating coal-fired power plants in the EU-28 was almost 155 GW (CarbonBrief, 2019); the largest coal power plant fleet is located in Germany (48 GW), followed by Poland (30 GW). Several EU member states – Austria, Denmark, Finland, France, Greece, Hungary, Ireland, Italy, Netherlands, Portugal, Slovakia, Sweden, UK– have pledged a coal phase-out till 2030 or earlier. The decarbonization efforts are going to be more challenging however in several European countries in which coal contributes to more than 40% of the total power production. From the EU, these countries are Germany (41%), Bulgaria (45%), Greece (46%), Czech (53%), and Poland (80%); similar is the situation for most of the non-EU member states in South East Europe: Montenegro (45%), Bosnia & Herzegovina (63%), Serbia (65%), North Macedonia (70%) and Kosovo (97%) (EURACOAL, 2017).

The coal industry has already a lot of experience with co-firing of biomass, because of relatively low CAPEX requirements, scalable solutions and various options to co-fire. The IEA Bioenergy Task 32 database[38] lists hundreds of industrial co-firing cases from Europe and around the world. Figure 32 shows different concepts of co-firing.

Occasionally, the **incentive** to co-fire biomass in a coal power plant may be a temporary one and purely economic: biomass fuels may be available in sufficiently large quantities and prices

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[38] http://task32.ieabioenergy.com/database-biomass-cofiring-initiatives/

that are competitive to coal (on an energy basis). One of the oldest commercial co-firing cases in Europe, the Gelderland power plant (Netherlands), in which co-firing with waste wood at a 3 – 4% heat input was demonstrated in 1992, was based in such a principle (Koppejan and van Loo, 2012). The evolution of EU policies however has created a more structural set of principles based on which bioenergy retrofitting in coal fired power plants can be adopted. These include the stricter emission limits imposed on coal power plants, the Emission Trading Scheme (ETS) which limits the competitiveness of coal power by setting a price for CO_2 emissions generated, and the support schemes adopted for biopower. All these have created positive or negative incentives for utilities to switch from coal power to biopower. A pertinent example is the Drax power station (UK); probably the largest biomass power plant in the world (2.6 GW), that came about from converting four of its six coal-fired units to 100% biomass firing.

Such bioenergy retrofitting cases come with their own non-technical challenges, primarily ensuring adequate and sustainable biomass supply for operation. This handbook focuses on the technical challenges and options for bioenergy retrofitting of coal power plants: co-firing and biomass repowering. The technology options that will be presented have – for the most part - reached commercial status; it should be noted however that there are a few options that still need further research and demonstration efforts to be widely applied at industrial scale.

Combined Heat and Power (CHP) plants produce both heat and electricity at the same time, thereby reaching higher total efficiencies and exhibiting a better use of energy resources compared to heat-only or electricity-only installations due to primary energy savings. In EU-28, only 26% of the electricity from conventional thermal sources (coal, gas, oil, nuclear, etc.) was generated in CHP plants, while this value reached 60% for bioelectricity (Bioenergy Europe, 2019).

In several Nordic EU countries – Sweden, Denmark, Lithuania – extensive retrofitting of fossil-fuel fired CHPs to (solid) biomass CHPs is (or has) taking place. For example, the main fuel in Swedish CHP systems is biomass, and Lithuania is expected to follow in a few years. Other opportunities for retrofitting are the replacement of fossil oil with liquid biofuels. An example is the Lantmannen Reppe (Sweden) retrofit. On a small scale, the Organic Rankine Cycle (ORC) technology helps to convert heat-only systems into CHP. An example is Ronneby Miljöteknik (Sweden) retrofit[39].

7.2 Technologies used in the sector

In fossil solid fuel (and biomass) power and CHP plants, the primary process is **combustion**, through which the chemical energy stored in the fuel is transformed into heat. The heat produced is transferred to a heating medium, usually water, which turns into steam. Steam is used to move a turbine, connected to an electrical generator. From the bioenergy retrofitting point of view, it is the combustion process that mainly dictates how biomass can be integrated in the generation process. Hence, this section focusses on the main commercial technologies used for combusting solid fuels: pulverized fuel combustion, fluidized bed and grate combustion.

A key difference between combustion systems using solid fuels and systems using oil or natural gas comes from the higher ash content of the fuels. This has an impact on the design of the furnace (which has to be larger in case of more ash) and requires installation of sub-systems for handling the fuel ash as well as for controlling particulate emissions.

Pulverized Fuel (PF) combustion refers to the firing of a suspension of very fine fuel particles, created through grinding / pulverization in mills. Combustion takes place at temperatures ranging from 1,300 to 1,700°C, while the particle residence time in the furnace is less than 5

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[39] http://energikontorsydost.se/sorbyverket-i-ronneby

seconds; the requirement for fine particle size is needed to ensure adequate fuel conversion during this time.

Power production units with pulverized coal use specially designed boilers, dedicated for this fuel. The solid fuel in powdered form will be burned as easily as gaseous fuel, maximizing the combustion efficiency. At first, the milling system is fed with the raw coal, where it is pulverized. Then, the powdered fuel is injected pneumatically into the boiler through a burner, where it is mixed with pre-heated air. Depending on the design fuel properties, there are different variants of the technology as regards the arrangements of the firing system (front firing vs. tangential firing), ash removal (dry bottom vs. slag tap furnaces) or other parameters. The produced flue gas transports its heat through the tube walls of the boiler and a series of heat exchangers to steam, which is driving the steam turbines. The electrical efficiency reached by PF plants is determined by the temperature and pressure; three categories can be defined – in the order of increased steam pressure/temperature: subcritical, supercritical and ultra-supercritical. The efficiency of these categories ranges from 35% to 45% (Massachusetts Institute of Technology, 2007).

The PF technology has been successfully applied for practically all coal types, accounting for 90% or more of the installed coal-fired capacity in the world (IEA Clean Coal Centre, 2018). The technology is generally applied in large scale installations; the largest examples have an installed capacity of more than 1,000 MW_e.

PF systems are not widely used for new biomass power plants for two main reasons. First, being large in size, these require large volumes of biomass to operate continuously, which may not be locally available. Secondly, grinding biomass to fine dust is more difficult and energy-consuming than coal. There are some few exceptions, e.g. some specialized systems applied for burning of sawdust. However, since the technology is the most widespread in coal combustion, most bioenergy retrofits of coal-fired power plants are PF systems. PF systems have been successfully employed for burning of solid biofuels, either through partially substituting coal (co-firing) or through fully replacing it, usually with wood pellets.

Fluidized Bed (FB) combustion has been commercially applied since the early 1980's; following significant technological advancements, it is currently considered as a "state-of-the-art" technology for solid fuels combustion.

The technology gets its name from its primary characteristic: fuel, along with an appropriate non-combustible solid material, such as sand, is supplied in a furnace, while air is supplied from the bottom with appropriate velocity to lift-up the particles but not enough to carry them away. This ends up in the creation of a "fluidized bed", in which the mixture of particles and air behaves as in a fluid phase. The creation of the FB ensures an intense mixing of the fuel and combustion air, hence the very high conversion efficiencies even at much lower combustion temperatures than the PF technology (around 800°C). Due to the low temperatures, reduced NO_x emissions compared to other technologies are generated; additionally, by using an appropriate bed material – such as limestone or dolomite – the released SO_2 can be captured before its release in the atmosphere. As a result, FB systems exhibit an improved emission performance and there is no need to install additional de-SO_x or de-NO_x systems (Johnsson, 2007).

Another advantage of FB systems is that they have less strict requirements in terms of particle size compared to PF systems. For all the reasons mentioned above, FB technologies are quite popular for the utilization of "difficult" fuels, such as some low-rank coals and waste wood.

An operational issue with FB systems is the loss of the fluidization; this can happen for example if the ash formed by fuel combustion has a low melting temperature, which can lead to bed material particles sticking together and reaching a size which is not suitable for the formation of a fluidized bed (so called agglomeration issue). This is a well-known phenomenon of the FB technology.

Two dominant fluidized bed varieties can be found in the market: **Bubbling Fluidized Bed (BFB)** and **Circulating Fluidized Bed (CFB)**. The BFB systems are simpler in design and are often used in smaller scale installations, using high moisture / low heating value fuels and larger particle sizes. A characteristic of BFB systems is the lower fluidization air velocity, which makes the fluidised bed stay 'stationary' at the bottom of the furnace. On the other hand, CFB boilers use higher fluidization velocities and have a system for re-circulating the bed material that gets carried away. CFB boilers have more complex designs, but surpass the BFB variants in terms of sulphur removal, scale and combustion efficiency (Koornneef et al., 2006). A schematic drawing of a CFB system is presented below, in Figure 30.

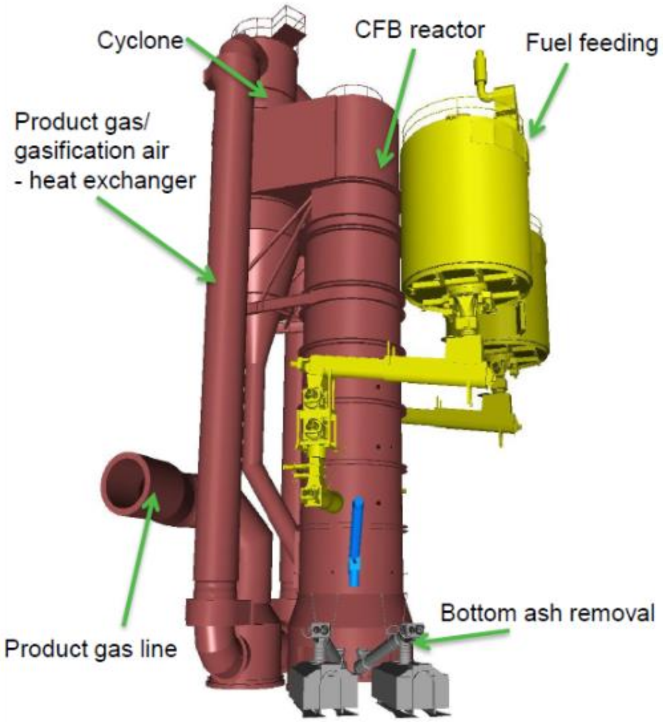

Figure 30: CFB produced by Valmet (Louhimo, 2019)

A **grate boiler combustion** uses, as the name indicates, a grate. The fuel is located on the grate and air, so called primary air, is supplied to the bed from below the grate. The grate can either consist of a flat surface, with the disadvantage that the ash needs to be removed manually. However, the most common grate boiler has a number of stages. The fuel is pushed into the grate on the top of the construction and passes various stages in the combustion process and mainly ash is reaching the very last stage. Every second stage is normally movable and pushes the fuel in one certain direction. This type of grate is also called a traveling grate or a moving grate. The grate can be cooled by water if the fuel is dry. Parameters which influence the operation of the boiler are e.g. the flow of fuel pushed into the grate, the velocity of the movable stages, the flow of primary air and the moisture content. Air is supplied to the boiler also in other ways, e.g. from the walls of the boiler over the grate. This influences the combustion process.

The most important parameter of burning efficiency for a grate furnace is the fuel fraction size, and its variation. The fractions of the fuel have to exceed a certain size in order to stay on the grate during the burning phase. They have to be quite coarse. Sawdust is one example of an inappropriate fuel for a grate boiler. A wide variation of fraction sizes and of moisture content are examples of parameters where a FB system is more appropriate in comparison to a grate furnace.

Grate boilers are widely applied for biomass combustion in the range from a few MW to about 100 MW in terms of fuel input. However, most biofuel boilers in the energy sector are in the range of up to 15 – 20 MW. If the fuel is appropriate and fulfils certain criteria, grate boilers are appreciated for their robustness, price and simple construction.

Biomass co-firing can be defined as the partial substitution of fossil fuels, usually coal, in power & CHP plants. **Repowering** on the other hand refers to an almost full replacement of the main fossil fuel by biomass.

A wide range of biomass materials can be considered for co-firing applications: wood-based (wood chips, wood pellets, forest residues, etc.), herbaceous (straw, miscanthus and other fast-growing energy crops, etc.), agro-industrial residues (exhausted olive cake, palm shells, spend coffee grounds, etc.) and various waste-derived fractions (e.g. waste wood, demolition wood, Refuse Derived Fuel / RDF, Solid Recovered Fuel / SRF, Tire Derived Fuel / TDF, etc.). Compared to hard coal, most biomass fuels considered for co-firing are characterized by higher moisture and lower heating value, lower ash content (but increased in problematic components such as alkalis), higher chlorine content, lower sulphur content and lower energy density. Taking into account the aforementioned characteristics, the infrastructure of a unit supporting the co-firing of fossil fuels along with biomass should consider some technical constraints concerning the power plant type, the fuels employed, the biomass thermal share, the desired complexity and the cost of the infrastructure and its operation.

Generally, as the process complexity and investment cost rises, the biomass thermal share can be increased and more “difficult” biomass fuels can be co-fired. The co-firing technology options can be classified in three broad categories (Basu, Butler, & Leon, 2011): direct co-firing, parallel co-firing and indirect/gasification co-firing. Direct co-firing is the most common and economic solution. However, it poses several limitations on the range of fuels and thermal shares. Parallel and indirect co-firing schemes are more suitable for biomass fuels containing problematic compounds or when the ash quality is of importance for sub-sequent sale or disposal. Finally, repowering has been mostly employed for wood biomass fuels (e.g. pellets & chips). Different concepts of bioenergy retrofitting in a coal-fired power or CHP plant are shown in Figure 31 and Figure 32.

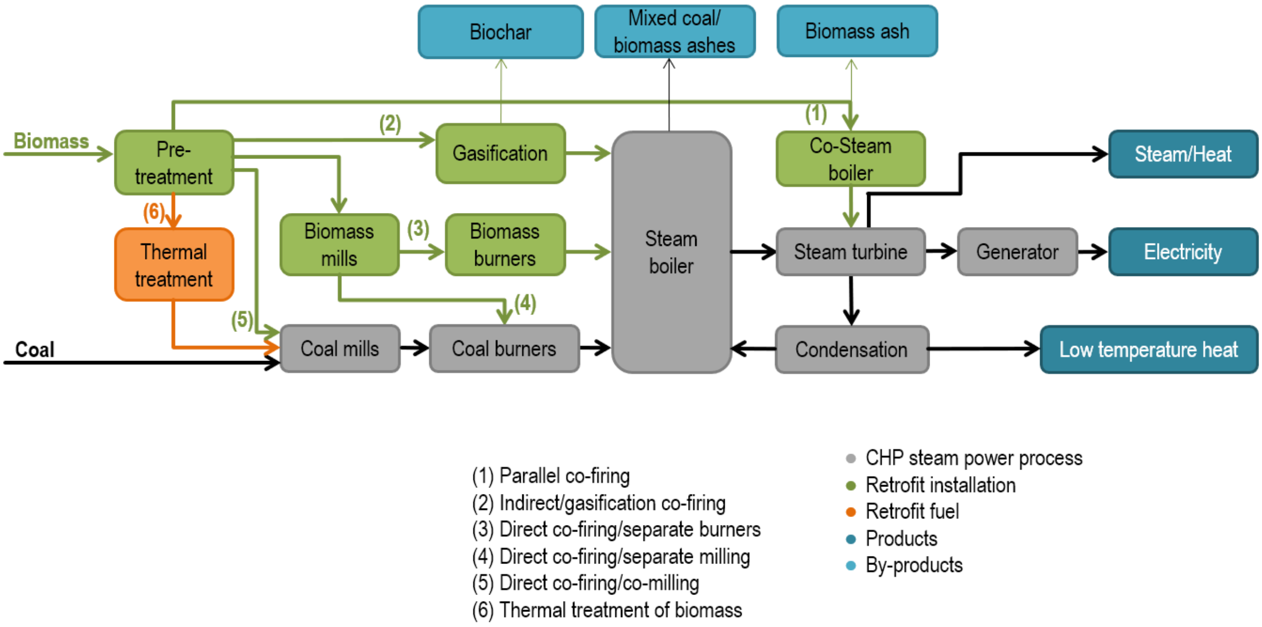

Figure 31: Different processes of biomass integration in coal power and CHP plants

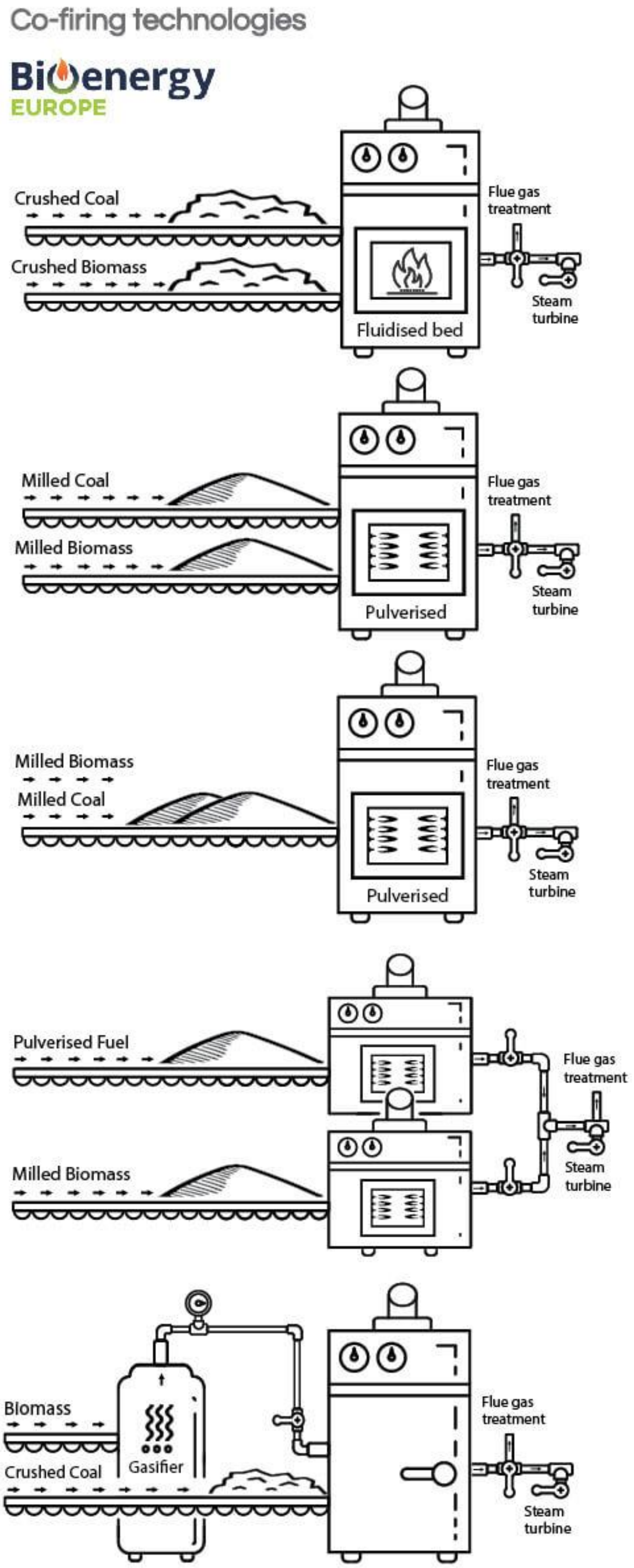

Figure 32: Concepts of Co-firing: co-feeding, co-fuelling, co-miling, parallel co-firing, indirect co-firing (Source: Bioenergy Europe)

7.3 Direct co-firing (partial bioenergy retrofitting)

The simplest and most cost-effective method to integrate bioenergy in an existing coal plant is the so-called direct co-firing concept, which is essentially the **co-combustion** of coal and biomass in the same furnace. This is the simplest solution to adopt co-firing, since the retrofitting measures can be kept to a minimum and the total investment can be kept at very low levels. On the other hand, the flexibility and control of such co-firing schemes is limited. Moreover, combustion results in a mixed coal / biomass ash, which may not have a commercial use (unlike coal ash). The maximum biomass share in direct co-firing schemes is usually in the range of 10% of the total fuel thermal input (Karampinis et al., 2014), but it depends also on the biomass type. Usually, higher shares can be achieved with woody biomass fractions, while lower shares with difficult agrobiomass or waste fractions. There are three main variants of the direct co-firing scheme, which are described below in order of increasing complexity (Karampinis et al., 2014):

- The first option, **co-milling**, involves the pre-blending of coal and biomass or their separate transport to the same milling system used for coal size reduction. It is the simplest option to implement. However, there is a higher risk that co-milling of fibrous biomass particles will also affect the coal particle size, while combustion conditions are not optimized.
- The second option is to install a **dedicated biomass pre-treatment / milling system** (or modify existing coal mills); however, the two fuels enter the furnace through the same, existing coal burners. This method offers much better control of the biomass particle size, but still the combustion conditions are not optimized. Its application may also be limited by space limitations near the boiler house.
- The third option is to install a **complete separate biomass line**, e.g. dedicated biomass pre-treatment / milling system and dedicated biomass burners. Understandably, this option comes with higher investment costs and higher degree of technological risk, but offers the possibility of increased control on combustion conditions and reduction of the biomass impact on the boiler. Biomass repowering (Section 7.6) is essentially the logical expansion of this retrofitting option, by replacing or modifying all coal mills / burners with biomass ones.

The BIOFIT project includes a case study that falls under the direct co-firing scheme: Tuzla unit 6 of Electropriveda BiH for which the co-firing of a wide range of local biomass resources (e.g. sawdust, agricultural residues, energy crops grown in reclaimed mining areas, etc.) will be investigated for a mass input basis of up to 30%.

7.4 Indirect co-firing (partial bioenergy retrofitting)

Indirect co-firing – also known as gasification co-firing – is a more sophisticated option compared to direct co-firing. A **biomass gasifier** is installed, replacing the need for biomass pre-treatment equipment. The syngas produced in the gasification process is sent to the furnace of the coal boiler for combustion. Through the use of indirect co-firing most of the negative impacts of biomass on coal combustion are avoided and the fuels are handled separately – allowing, among others the separate collection of ashes. The biomass syngas can be used for gas over-firing, thus contributing to NOx emissions reduction. Finally, since in many cases the syngas can be injected directly in the furnace, energy conversion loses and expensive syngas cleaning, both common issues in biomass gasification applications, can be avoided. Still, some amount of syngas cleaning might be required, depending on the presence of chlorine, alkalis and other elements in the biomass composition.

The capital investment for indirect co-firing is in the range of 300 to 1,100 €/kWe (IEA Bioenergy, 2017), higher than direct co-firing. This is a limiting factor for the further uptake of this technology. Examples of commercial implementation of indirect co-firing systems can be found in the table below.

Table 8: Commercial indirect co-firing plants (IEA Bioenergy, 2017)

Power plant	Country	Commissioning	Gasifier capacity (MW thermal)	Co-firing share (share of heat input to main boiler)	Fuels used
Amergas / Amer 9	Netherlands	2000	83	5 %	Waste wood
Kymijärvi II	Finland	2012	45 – 70	15 %	Recycled energy fuel (REF), sawdust, bark, wood chips, wood wastes
Vaskiluodon Voima	Finland	2012	140	Up to 40 % [1]	Forest residues (chips)
Ruien	Belgium	2003	40 – 80	10 % [2]	Wood chips, bark, hard and soft board residues
Sources: [1] Valmet; [2] Ryckmans, 2012					

7.5 Parallel co-firing (partial bioenergy retrofitting)

The final option for partial biomass retrofitting of fossil fired power units is the parallel co-firing of biomass and coal. Within this configuration, **two separate combustion plants and boilers** are used for the two fuels. The two units are connected on the steam side, which is used in the turbine for power generation. The handling, pre-treatment and combustion conversion of the two fuels to the boilers are totally independent. Moreover, due to the fact that biomass and coal are separately combusted, the produced ashes are separately gathered, like the case of indirect co-firing, and thus they can both be utilized with the best way possible. Another advantage of the separate firing is that the combustion process can be optimized for both cases, while the handling of relatively difficult fuels can now be achieved, which was not possible in all the cases presented so far (direct and indirect co-firing). Parallel co-firing can benefit from high steam parameters of modern, state-of-the-art coal-fired power plants, thus achieving much higher electrical efficiencies than stand-alone biomass power plants. However, the capital cost of the examined case is the highest among the co-firing solutions because totally new infrastructure (new feed-in installments, boilers, combustion chambers etc.) needs to be installed along with the current one.

This method allows high proportion of biomass utilization for the plant since there is no technical restriction regarding the amount of coal that can be swapped to biomass. The only issue that must be taken into consideration is the capacity of the installed steam turbine (Koppejan & van Loo, 2012). In terms of retrofitting a unit, it is not possible to suggest a steam turbine alteration, so the one that is currently installed must have the capacity to operate in the cumulative steam that imports from both biomass and coal boiler, otherwise it would not be a proper solution.

The most well-known parallel co-firing case in Unit 2 of the Avedøre power station in Copenhagen metropolitan area in which a 105 MW straw-fired boiler has been installed along with the main, 800 MW, ultra-supercritical boiler that uses a mixture of wood pellets, coal and natural gas; the plant has a reported total efficiency of 92% and electrical efficiency of 42%, rising to 49% if no district heating is provided (Sørensen, 2011).

7.6 Biomass repowering (full bioenergy retrofitting)

Biomass repowering is the evolution of direct co-firing to very high shares of biomass in the fuel mixture, often up to 100%. This option requires the change of the fuel feeding, milling and burning system to something suitable for biomass.

The reasons for a utility operator to adopt biomass repowering can be related to a wish to phase-out coal completely, while keeping existing assets operational. It can also be supported by policies that render co-firing with low biomass thermal shares ineligible for financial support, while accepting large-scale power production from biomass.

One of the earliest examples of a 100 % retrofit to biomass is Rodenhuize 4. The conversion was implemented with a series of successive steps, starting from installation of transport, storage, handling, and milling infrastructure for wood pellets and the conversion of a single burner row in 2005. The Advanced Green Project resulted in the switch of two coal burner rows to wood pellet firing and, finally, the Max Green project resulted in the complete switch from coal combustion to wood pellets, burner replacement, as well as other in the implementation of other retrofitting options, including the installation of a Selective Catalytic Reduction (SCR) unit for control of the NOx emissions (Savat, 2010).

There are several examples of coal-fired power or CHP plants that have been converted from coal to biomass; a summary is provided in Table 9. Most conversions have been implemented in pulverized fuel boilers, in which the retrofits where related to the milling and feeding system, along with the logistics infstracture for biomass sourcing (e.g. storage, port facilities, etc.). However, there are examples of more extensive retrofits, such as the Polaniec Green Unit in Poland, where the older pulverized fuel boiler was replaced with a state-of-the-art CFB boiler and the steam turbine was retrofitted as well.

A key challenge in such retrofits is biomass sourcing; the volumes required are very high and in most cases they have to be supplied from the global market. This is one of the main reasons why wood pellets are the most commonly used biomass fuel in such retrofits; their relatively high energy density and standardized properties allows them to be traded over large distances. Another reason for choosing wood pellets over other biomass fuels is their fuel properties; they have relatively low ash content (< 2-3 % weight on dry basis) and low concentrations of chlorine and alkalis which can create problems of corrosion and fouling in power production applications. Wood chips are also occasionally used.

Table 9: List of coal-to-biomass conversions

Power plant / Unit	Country	Finalization of retrofits	Installed Capacity (MW electrical)	Fuels used	Combustion technology
Les Awirs 4	Belgium	2005	80	Wood pellets	PF
Helsingborg	Sweden	2006	126	Wood pellets	PF
Västhamnsverket	Sweden	2006	69	Wood pellets	PF
Herning	Denmark	2009	75	44 % wood chips, 44 % wood pellets, 12 % top-gas	GF (chips) / PF (pellets)
Rodenhuize 4	Belgium	2011	180	Wood pellets	PF
Tilbury*	United Kingdom	2011	750	Wood pellets	PF

Power plant / Unit	Country	Finalization of retrofits	Installed Capacity (MW electrical)	Fuels used	Combustion technology
Ironbridge*	United Kingdom	2012	740	Wood pellets	PF
Drax 1	United Kingdom	2013	660	Wood pellets	PF
Polaniec Green Unit	Poland	2013	195	80 % wood chips, 20 % agrobiomass	CFB
Drax 2	United Kingdom	2014	645	Wood pellets	PF
Atikokan	Canada	2014	205	Wood pellets	PF
Drax 3	United Kingdom	2015	645	Wood pellets	PF
Thunder Bay 3*	Canada	2015	160	Arbacore wood pellets (steam explosion)	PF
Avedore 1	Denmark	2016	258	Wood pellets	PF
Studstrup 3	Denmark	2016	362	Wood pellets	PF
Yeongdong 1	South Korea	2017	125	Wood pellets	PF
Drax 4	United Kingdom	2018	645	Wood pellets	PF
Amer 9	Netherlands	2019	631	80 % wood pellets, 20 % coal	PF
Asnæs 6	Denmark	2019	25	Wood chips	BFB
Suzukawa	Japan	2020 (expected)	112	Wood pellets	PF
Uskmouth	United Kingdom	2021 (expected)	240	Subcoal® pellets (RDF pellets)	PF

* Unit no longer in operation

BFB: Bubbling Fluidized Bed, CFB: Circulating Fluidized Bed, GF: Grate Fired, PF: Pulverized Fuel

The Drax power plant (Figure 33) is currently the world's largest biomass consumer, using in its four biomass converted units more than 7 million tons of wood pellets in 2018, mostly from the USA (62.2 %) and Canada (17.3 %), with smaller volumes sourced from EU, Brazil and other European countries (Drax, 2019). The total biomass conversion cost for the first three Units at Drax has been given as 700,000,000 GBP (around 416 EUR/kWe); the cost of conversion of Unit 4 was only 30,000,000 GBP (around 54 EUR/kWe) due to the use of spare parts from the conversion of the previous units[40] as well as to the fact that no additional investments related to biomass fuel supply (e.g. port and rail infrastructure, storage, etc.) were implemented. The company management has also stated its ambition to become carbon

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[40] www.biomassmagazine.com/articles/15532/drax-completes-fourth-biomass-unit-conversion

negative by 2030 by integrating bioenergy carbon capture and storage (BECCS) technologies[41].

Figure 33: The Drax power station in Selby, UK; the biomass storage domes are visible (Source: Drax Group)

The BIOFIT project includes two industrial case studies that aim for a full biomass repowering of existing coal plants:

- Kakanj Unit 5 (118 MWe) CHP plant of Elektroprivreda BiH, which is considered for repowering using locally available woody biomass resources, e.g. wood chips, sawdust, etc.
- Fiume Santo Unit 4 (320 MWe) power plant of EP Produzione. The plant is located on the northwest of Sardinia; along with the BIOFIT project partners, the company is investigating its conversion into a biomass power plant using imported wood pellets as the main fuel.

7.7 Thermally treated biomass

Thermal upgrading is a process intended to transform biomass into a coal-like material that can be easily handled by existing coal-fired power plants. The main goals of biomass thermal upgrading are:

- To create an easily grind-able fuel, capable to be used in existing coal mills without major modifications, thus limiting the need for expensive retrofits.
- To increase the energy density of the biomass (usually be including a densification step, e.g. pelletization after the thermal upgrade), so that its transportation can be more economic over longer distances.
- To make biomass resistant to moisture uptake (hydrophobic), thus allowing it to be stored like coal, e.g. in open yards, and thus reducing its handling costs.

There are different technologies that have been developed for the thermal pre-treatment of biomass; the most well-known and advanced are the following:

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[41] www.drax.com/press_release/drax-sets-world-first-ambition-to-become-carbon-negative-by-2030/

- **Torrefaction** is is a thermal process whereby biomass is heated to a temperature of approx. 250-350°C, in the absence of oxygen or at low oxygen concentrations. Almost of the moisture, as well as most of the volatile fraction of biomass is released due to this process, which breaks down the fibrous structure of the biomass due to the dismantling of hemicellulose. The solid product is a black, charcoal-like material that can be further processed into pellets (Kofman, 2016). The gaseous products can be combusted to sustain the heat for the process; the net efficiency of the net efficiency of an integrated torrefaction process is approx. 70 – 98%, depending on the reactor technology, concept for heat integration and the biomass type[42].
- **Steam explosion** uses steam under pressure (1 to 3.5 MPa) and temperature (180 to 240°C) in a pressure vessel to impegrate biomass. The impregnation is followed by an explosive decompression, causing the fibre clusters to rupture and realizing the lignin in a pulp, which can be further compressed into pellets. The hydrolysis rate of hemicellulose can be further improved by using acidic gases (e.g. SO_2, H_2SO_4) as a catalyst during the pressurized phase. Steam explosion is also used as a biomass pre-treatment step during 2G bioethanol production (Kofman, 2016).
- **Hydrothermal Carbonization (HTC)** differs from the other two technologies since it allows the direct pre-treatment of wet biomass, without a previous drying step. In the HTC process, biomass is suspended in water and treated at elevated temperatures (180-300 °C). An elevated pressure (20 – 100 bar), above the respective vapour pressure of water, is applied in order to keep water in the liquid phase. Another advantage of the HTC process is that the water can leach elements such as alkalis and chlorine from the biomass, that would normally cause slagging, fouling and corrosion issues (Hansen et al., 2018).

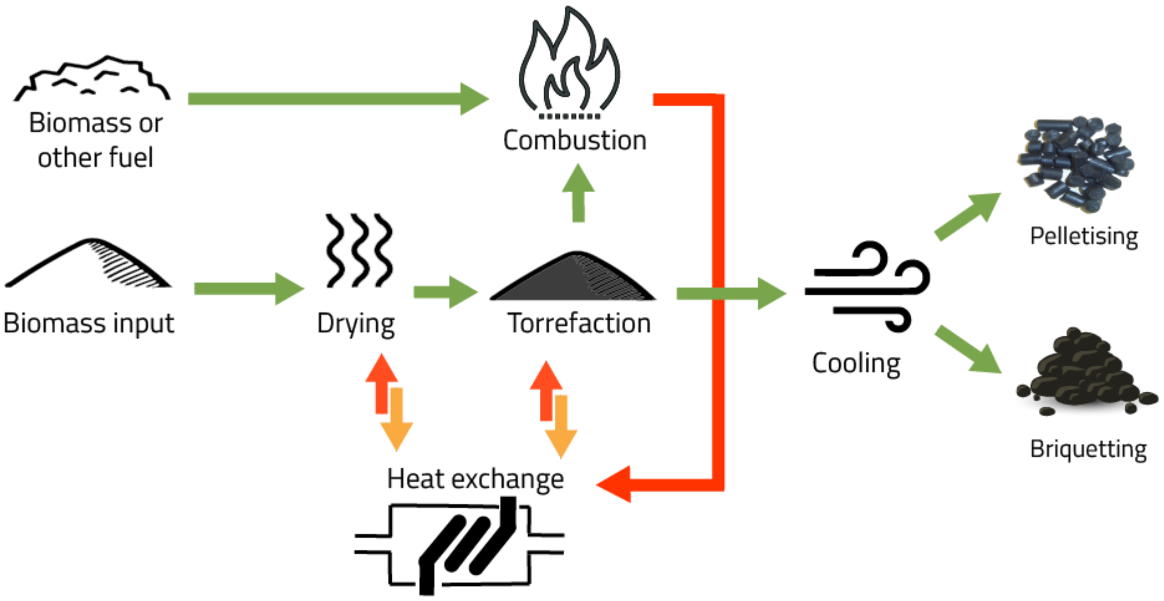

Figure 34: Overview of the torrefaction process (Source: IEA Bioenergy Task 32)

So far, the only commercial retrofit with thermally treated wood pellets is the conversion of Thunder Bay Generation Station, Unit 3 of Ontario Power Generation (OPG). The conversion started in 2014 and was completed ahead of schedule and under budget in 2015 with a capital expenditure of only 3 Million Canadian Dollars – approximately 2 Million EUR. Considering that the capacity of the Unit is 160 MWe, the conversion cost is approximately 12.50 €/kWe, much

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[42] https://ibtc.bioenergyeurope.org/torrefaction-basics/

lower than the costs stated for other conversion experiences with wood pellets[43]. The project was implemented using steam exploded pellets from Arbaflame.

Co-firing trials with torrefied and steam exploded biomass have been performed by various European utilities with generally positive results[44,45]. Moreover, the Horizon 2020 project ARBAHEAT[46] intends to transform the 731 MWe ultra-supercritical coal-fired power plant Maasvlakte 1 into a biomass CHP plant integrating the biomass steam treatment technology of Arbaflame.

7.8 Concluding remarks

There are several different options for retrofitting fossil fired – and in particular coal – power or CHP plants to biomass depending on the desired level of biomass integration in the facility.

The simplest option to implement is direct co-firing, but it is also the least ambitious, since the level of fossil fuel substitution with biomass is usually low and does not exceed 10 – 20 % on a fuel thermal input basis. As such, it implies the continued operation of a power or CHP plant with coal. Therefore, this option is no longer possible in the EU, although it may be relevant as a transitionary technique to countries that are maintaining or expanding their coal generation capacity.

Indirect co-firing and parallel co-firing are most sophisticated options, allowing for higher shares of biomass to be used. Again though, their application implies the continued operation of a power plant with a fossil fuel and only a partly decarbonization can be achieved.

Full biomass repowering, e.g. the complete conversion of a coal-fired power or CHP plant to biomass, has been demonstrated in several installations in Europe or beyond. Although there might be complications in specific cases, this option has already reached a sufficient level of technological maturity.

A key issue that needs to be considered in coal-to-biomass conversions is the biomass availability; the conversion of a large-scale coal-fired plant to biomass required huge volume of material and the logistics arrangements can be complicated, especially for plants that have not historically relied on external fuel supply. Such is the case with lignite-fired power plants located near lignite mines and far from sea ports (Karampinis et al., 2014).

It should also be noted that such repowering cases have been commercially demonstrated only with wood biomass fuels (mostly wood pellets). Agrobiomass may offer the possibility of a lower fuel cost compared to wood pellets, however its combustion comes with its own technical challenges – as well as mobilization and logistics issues – and still needs to be demonstrated in such large scale systems.

Finally, the use of thermally treated biomass has only been demonstrated in one commercial case and in several demonstration campaigns. Although it presents several advantages – most notably the very low CAPEX requirements for the conversion and the promise of a reduced fuel cost - one of the key challenges in the deployment of this solution is to develop the infrastructure needed to provide the volumes of thermally treated biomass that conversion projects require.

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[43] The plant was operated on average for only 2.5 days/year as a peak load unit and in May 2018, significant corrosion damage (not related to biomass firing) was found in the boiler. Since then, the unit was decommissioned.

[44] www.blackwood-technology.com/company/references/

[45] www.cegeneration.com/ceg-and-tse-trial-1000-tonnes-of-renewable-black-pellets-at-tses-naantali-power-station-in-finland/

[46] www.arbaheat.eu

Despite criticisms by some NGOs, the coal-to-biomass conversion projects is the only option currently available for large-scale dispatchable and renewable electricity generation. It should also be noted that in order to ensure the sustainable and effective use of biomass in power production, the EU has set a series of requirements in RED II, ranging from sustainability criteria for biomass sourcing, to a mimimum level of GHG emission savings achieved throughout the value chain, to a series of technical limitations (e.g. a mimimum level of 36 % net electrical efficiency for power-only installations with a rated thermal input above 100 MW). Moreover, such installations offer the possibility for integration of Carbon Capture and Storage (CCS) technologies, which together with biomass use, pave the way for negative emissions.

8 Retrofitting the pulp and paper industry

8.1 Overview of the sector

The number of paper and board mills as well as pulp mills in Europe[47] has steadily decreased since the 1990's. In 2018, 151 pulp mills and 746 paper and board mills existed. Nevertheless, the production of paper and board in Europe[47] has stayed relatively stable during the past decade, with 92 million tonnes produced in 2018. A similar trend is seen in the total pulp production (integrated and market pulp), which was 38 million tonnes in 2018. Notable, is that despite the stable total production, global market pulp production is an increasing trend (CEPI, 2019). Contrary to Europe, the markets for paper industry are growing in Asia due to increasing purchase power (Suhonen and Amberla, 2014).

Digitalisation has affected the end products from the paper industry; the graphic paper usage declines, but the need for packaging increases (Suhonen and Amberla, 2014). The pulp and paper industry in Europe has undergone some consolidation, while at the same time there is ample interest in high-valued bio-based products such as biofuels, bio-composites and bio-based plastics. Since many pulp mills are no longer integrated into paper mills, their own energy consumption has decreased, which opens up the opportunities for production of higher-valued bioenergy products from their residues.

The pulp and paper industry is the fourth largest industrial energy consumer in Europe (Chan and Kantamaneni, 2015). The industry has been able to reduce its carbon emissions by 26% since 2005 by using solid by-streams for energy purposes (CEPI, 2018a). The pulp and paper industry sector in Europe is already using renewable energy for nearly 60% of their total fuels consumption. The consumption of biomass for energy in the pulp and paper industry was 710 PJ in 2017 (CEPI, 2019). The rest of the fuel consumption is mainly covered by gas, which accounted for 390 PJ (CEPI, 2019). Countries where the paper industries use natural gas as a source of energy often only have a small forestry sector, which could feed the plants with forest residues. In these countries recycled fibres are by far the main source of domestic raw material for paper. Although the use of natural gas is not a precondition for paper recycling, natural gas is often used due to cost-efficiency, lack of viable alternatives and national energy policies. (CEPI, 2018a)

The main renewable energy source in the pulp and paper sector is bioenergy from wood handling residues such as sludge, bark and wood processing wastes. Opportunities for bioenergy retrofitting in the sector are the increased use of residues such as bark for energy generation, biogas production from pulp mill sludge and increasing the efficiency of bioenergy CHP production by high-efficiency equipment (higher steam pressures). Figure 35 shows a scheme for the retrofitting of the energy supply of a pulp and paper mill with biomass. Other

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[47] in CEPI member countries: Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy The Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom

important retrofit opportunities involve secondary fuels production for example by the upgrading of black liquor.

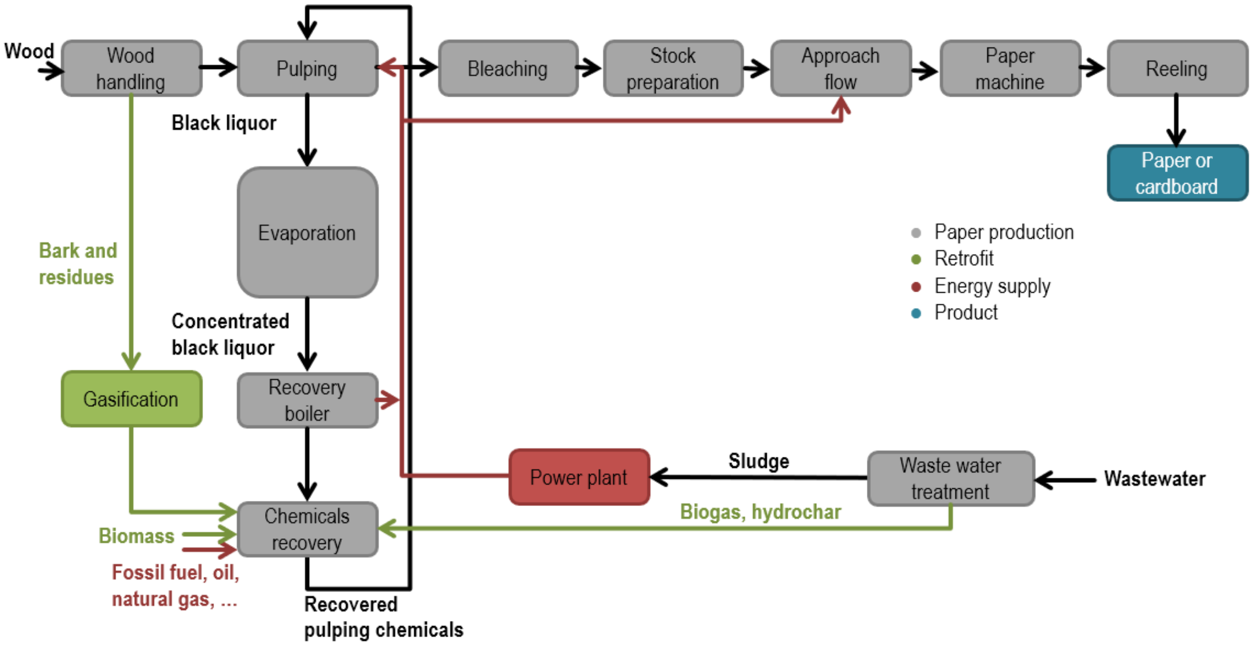


Figure 35: Scheme for the retrofitting of the energy supply of a pulp and paper mill with biomass

8.2 Pulping process and residues from pulp and paper industry

8.2.1 Fibre extraction

Pulp fibres can be extracted from the raw material (wood) mechanically or chemically.

In **mechanical pulping**, wood is treated with mechanical shear forces e.g. by grinding to soften the lignin binding fibres. Higher yields (up to 95%) of the pulp wood is obtained from mechanical pulping compared to chemical pulping since the whole log except the bark can be utilised (CEPI, 2018b). A notable drawback of mechanical pulping is the lower strength of the end-product compared to chemical pulping due to varying fibre length. In addition, the energy requirements in mechanical pulping can only be partly covered with energy input from the bark residues.

In **chemical pulping**, round logs are first de-barked and the wood is chipped. The left-over bark is typically sold or combusted to produce heat and power on-site. The pulping process is self-sufficient in energy, since combustion of by-products can cover the energy demand of the process. After debarking, the wood chips are cooked in an aqueous solution together with chemicals that dissolve the lignin. The solid residue that has a low lignin content is called pulp remains. It can be sold or further processed into cardboard or paper products. The yield of the pulp wood in chemical pulping is typically 45% (CEPI, 2018b).

In **semi-chemical pulping**, the woodchips are cooked with a small amount of chemicals, after which mechanical treatment of wood is still applied. For instance, in Neutral Sulphite Semi-chemical (NSSC) pulping, chemical pre-treatment with sulphite is conducted before defibration.

8.2.2 Cooking process

The common cooking processes include Kraft cooking and sulphite cooking. The type of cooking process significantly affects the valorisation of the side products.

The **Kraft process** (sulfate process) is the main process for producing paper. It converts wood into almost pure cellulose fibres. In this process sodium hydroxide (NaOH) and sodium sulphide (Na_2S) are used as chemicals to break bonds between lignin, hemicellulose, and cellulose (Figure 36). In the Kraft pulping process, the solution is alkaline and contains lignin and hemicellulose sugars. These degradation products are difficult to be converted into biofuels by yeasts or other micro-organisms.

After the cooking phase, the pulp is washed (Figure 37). During the washing, residual lignin is removed by oxygen in an aqueous solution. The pulp is often also bleached so that it becomes white and suitable for white paper products. The solution that contains the dissolved lignin residues is called **black liquor** and it is concentrated by evaporation. Pathways for using black liquor are shown in Figure 38.

In the **sulphite cooking** process, a sulphite-salt solution (magnesium-sulphite typically) is used. Dissolving the biomass components depends very much on the pH of the solution. The sulphite cooking process can be conducted at different pH levels, depending on the raw material. For example, the acid calcium bisulphite process is conducted at very acid conditions typically at a pH of 1-1.5 (Hanhikoski, 2014).

In acidic sulphite pulping, the so-called **brown liquor** contains lignin as lignosulphonates (water soluble lignin that can be sold as separate chemical) and sugars that can easily be fermented into ethanol or other biofuels. Pathways for using brown liquor are shown in Figure 39.

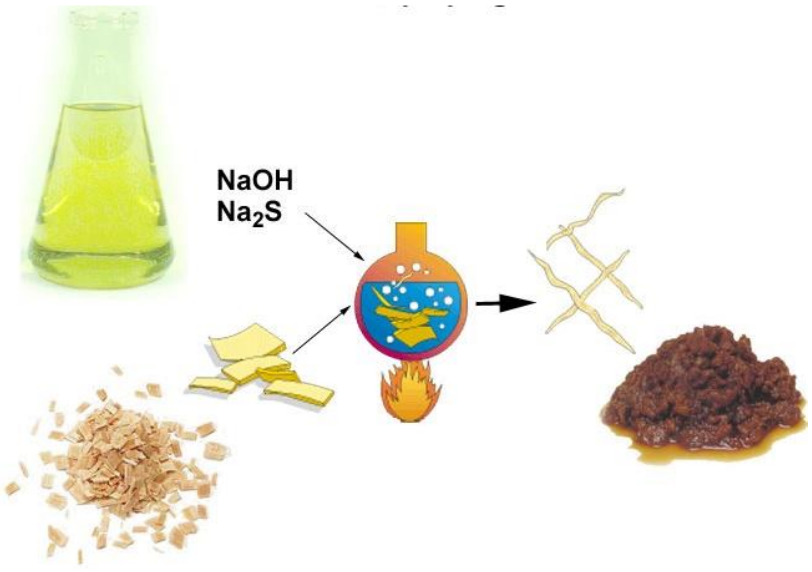


Figure 36: Schematic diagram of the Kraft cooking process (KnowPulp, 2019).

Figure 37: Washing of dirty pulp produces black liquor and washed pulp (KnowPulp, 2019)

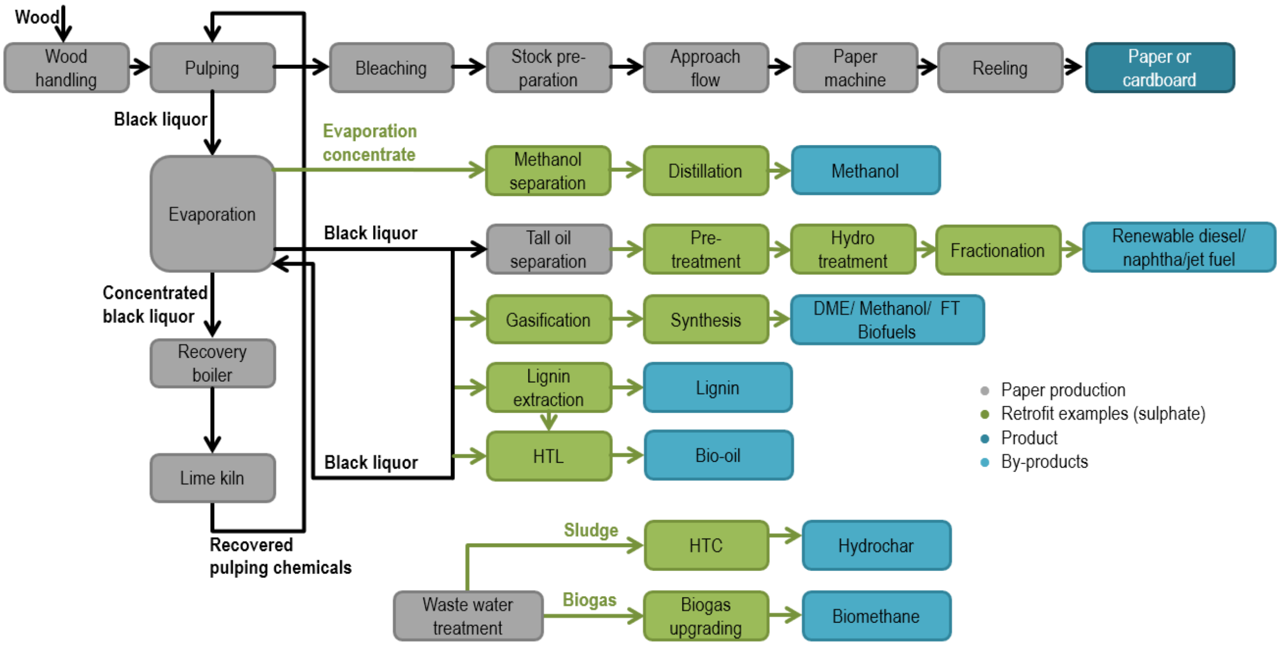


Figure 38: Methods for using black liquor

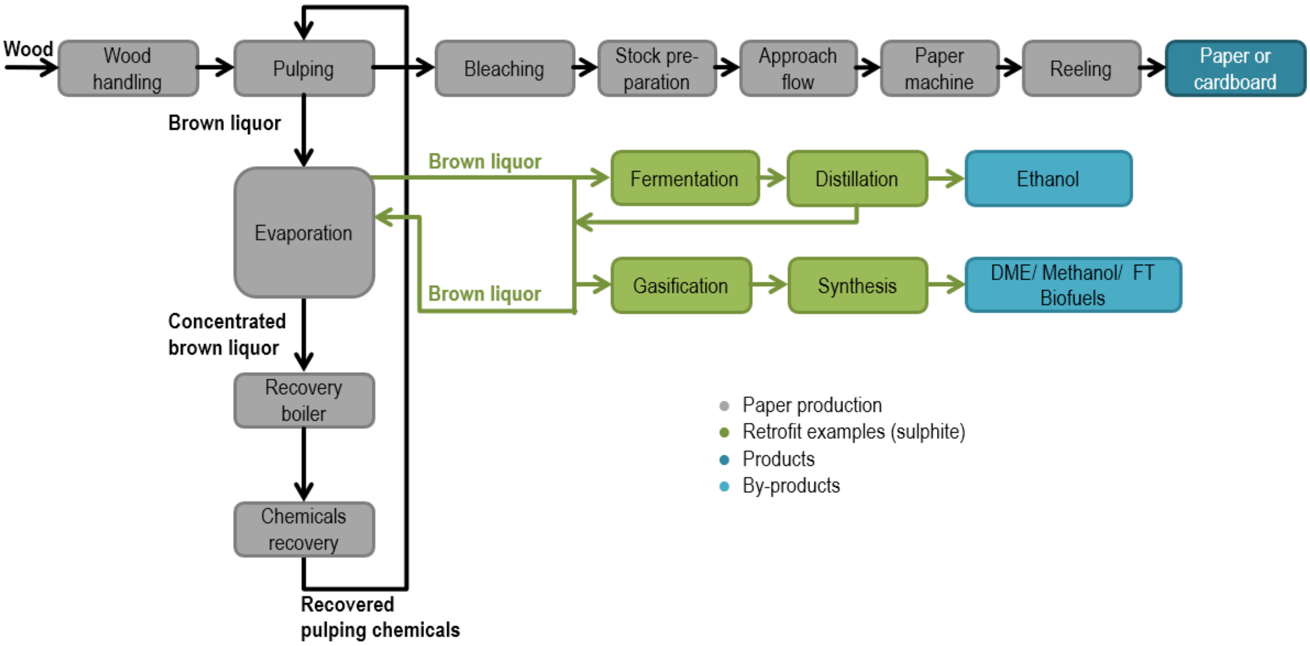


Figure 39: Pathways for using brown liquor

8.2.3 Black liquor evaporation

When black liquor from the Kraft pulping process is concentrated by evaporation, several fractions are separated (Figure 39). One of these fractions called "**soap**" is converted into crude tall oil by adding acid. Methanol and turpentine are instead separated from the condensate of evaporation. Methanol and crude tall oil can be purified and converted into biofuels or other products. This is further discussed in chapters 8.5 and 8.11.

Modern pulp mills are often **self-sufficient** in terms of heating and can also produce excess heat. The surplus heat is produced particularly, if there is not a paper plant at the same location that uses a significant part of the heat which is produced. Since not all organics need to be combusted to generate sufficient heat for pulp production, part of the organics in black liquor can be extracted for example in the form of lignin or other bio crude.

Recently, processes have also been developed to separate part of the **lignin** from Kraft black liquor. Lignin can be precipitated by adding CO_2 or acids such as sulphuric acid, since reducing black liquor pH level below nine leads to lignin precipitation. The produced lignin can be used as a solid fuel or converted into biofuels, chemicals or material products. However, lignin from the Kraft process contains sulphur which limits its use as a fuel.

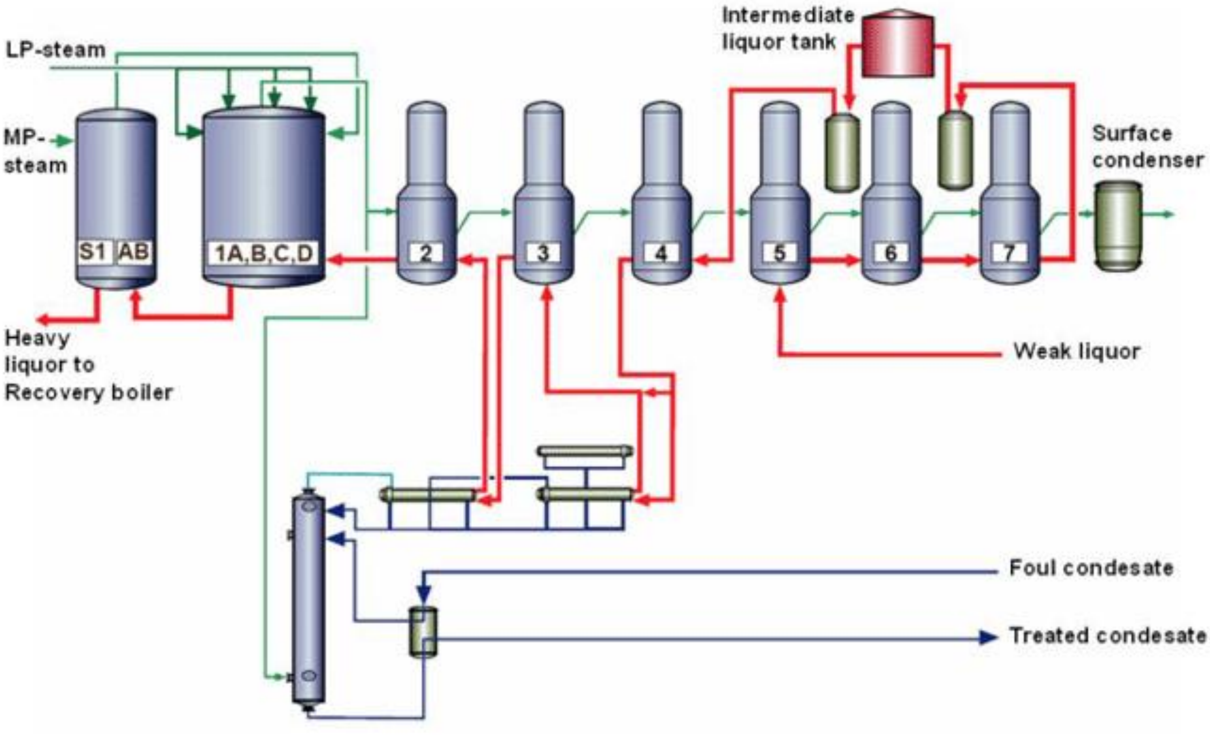


Figure 40: **Typical 7-stage black liquor evaporating plant equipped with super concentrator (KnowPulp, 2019)**

8.2.4 Recovery process

After evaporation, strong black liquor typically contains only 15-25% of water. It is combusted in the recovery boiler (Figures 41 and 42) to make full use of its energy content and to recover at the same time the cooking chemicals in the form of inorganic salts also called **green liquor**. In the Kraft process, these inorganic chemical residues are sodium carbonate and sodium sulphide. Sodium sulphide, which is required in the Kraft pulping process as a cooking chemical, is produced from sodium sulphate under high temperature and oxygen deficient conditions in the recovery boiler.

Before returning the chemicals back to the pulping stage, sodium carbonate must be turned into sodium hydroxide and this can be done in the recausticising process by adding calcium oxide. In the recausticising process, the reactive calcium oxide is turned into inactive calcium carbonate while sodium carbonate is converted into sodium hydroxide. The calcium carbonate has to be regenerated into calcium oxide by heating it to a high temperature in a separated lime kiln to liberate CO_2. In the lime kiln, fossil fuels such as natural gas and fuel oil have typically been used. However, lately biogas, lignin, sawdust, or gas from biomass gasification have also been used for this purpose.

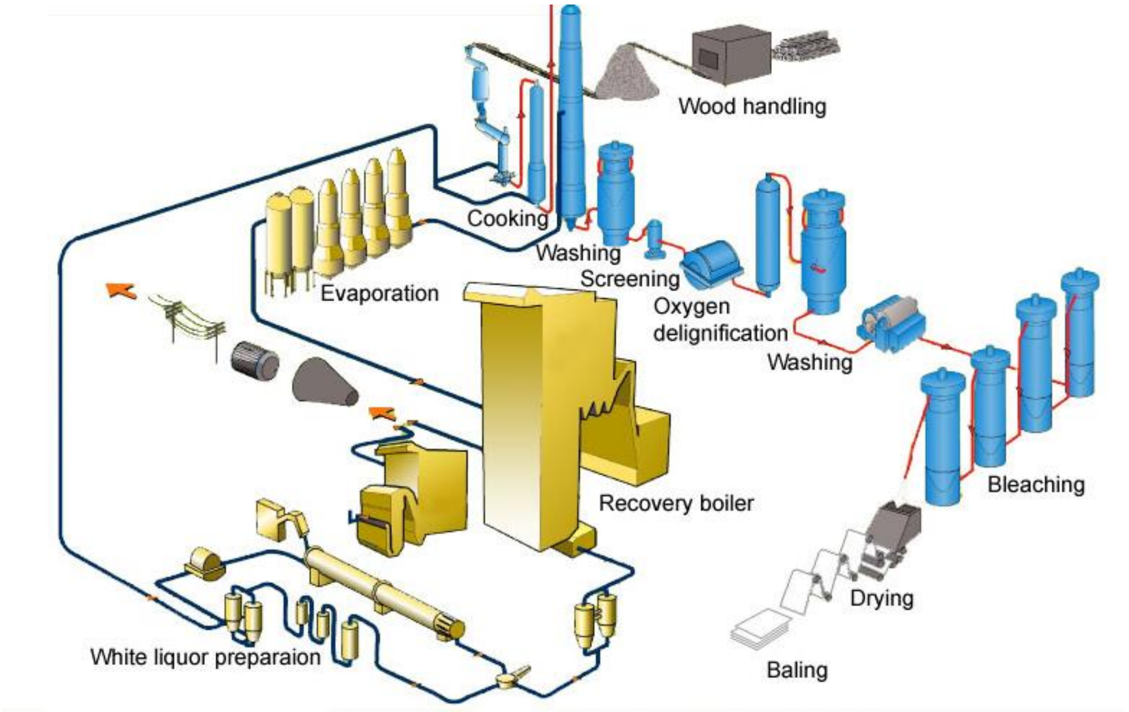


Figure 41: Principle of the chemical recovery in Kraft Process (KnowPulp, 2019)

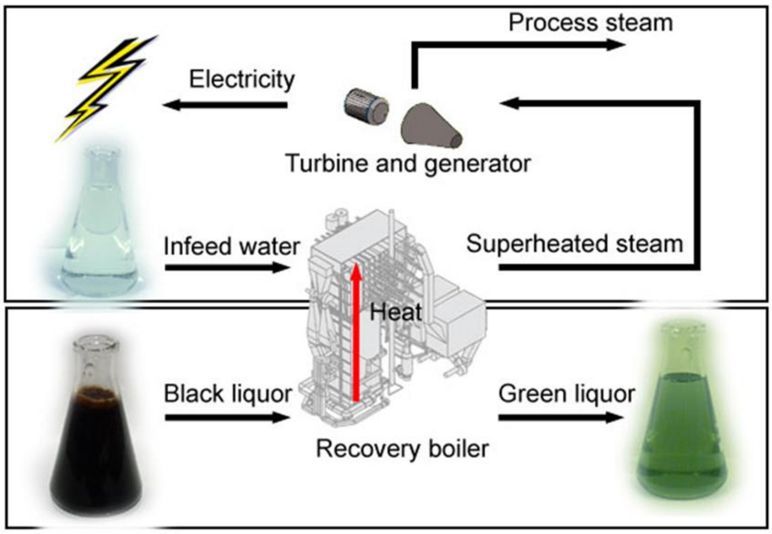


Figure 42: Recovery of chemicals and energy in the black liquor recovery boiler (Know Pulp, 2019)

8.2.5 Wastewater treatment

Wastewater from the pulping process and debarking of logs are typically treated in a mill wastewater treatment plant. The residual organic content in the wastewater would be harmful to the environment if it would be discharged without separation and treatment. In an activated sludge process, the organic content of wastewater is reduced by bacteria and sludge is produced. The challenge of this process is that large volumes of **wet sludge** are produced, which is difficult to handle. It is possible either to reduce the amount of sludge by digestion and produce biogas or to heat the water solution of sludge to more than 200°C in a so-called hydrothermal carbonisation process to convert the sludge to a coal like product with low water content and an aqueous phase.

Figure 43: Activated sludge process that removed organic components from wastewater (KnowPulp, 2019)

8.3 Black/brown liquor ethanol

In the **acidic sulphite pulping process**, in which pulping is done at a low pH level, the hemicellulose part from the wood is converted into simple sugars also called monomeric sugars. Monomeric sugars can be directly fermented into ethanol by yeast or digested to produce biogas. Currently, ethanol is produced in several old pulp mills that are based on sulphite pulping technology. The advantage of this approach is that sugars suitable for ethanol production can be obtained easily as a by-product of pulping from the hemicellulose part of wood. Certain types of sugars such as the 5-carbon atom containing sugars such as xylose are not efficiently converted into ethanol and, therefore, also biogas is often produced in addition. Unlike the production of ethanol from processes in which the cellulose part is utilised; no costly enzymatic hydrolysis step is needed that requires long reaction times. However, most pulp mills today employ **Kraft pulping process**, which limits the possibilities for ethanol production, since the approach can only be utilised in sulphite pulping.

Examples of sulphite mills that are in operation today and produce ethanol are the Domsjö plant in Örnsköldsvik (Sweden) and Borregaard in Sarpsborg (Norway). The Domsjö plant produces 20,000 tons of ethanol and 90 GWh of biogas annually from the side streams of utilisation of 1.4 million m^3 of timber wood raw material for speciality pulp (mainly for textile applications) and the lignin (used as concrete additives) production. (Domsjö, 2019) The plant uses a two-stage sodium sulphite pulping process (Hankikoski, 2007).

The Borregaard biorefinery in Sapsborg that produces speciality pulp, produces 20 million litres of ethanol per year, as well as specialty lignin and range of different products (Borregaard, 2017). The produced ethanol is used for chemical products or as solvents, but also sold to Statoil to be used in transport (European Biofuels Technology Platform, 2016).

8.4 Black liquor gasification to DME

A black liquor by-product from evaporation is a thick liquor that contains organic components, lignin, several tens of percent of residual water and approximately one third of inorganic salts. Black liquor can be gasified into synthesis gas (IEA, 2007). The synthesis gas can be further converted into biofuels suitable for transportation such as Fisher Tropsch (FT)-diesel, methanol or Dimethyl ether (DME). These products typically have a higher value than the heat and power obtained from the combustion of black liquor in a recovery boiler. In addition, during the gasification, cooking chemicals can be recovered since organics are gasified from black liquor. This way, sodium sulphate is converted back to sodium sulphide and can be used as cooking chemical in the pulp production.

DME is a substance that have similar properties as LPG. It can be liquefied at room temperature under pressure (Röj, 2017). It can also be produced directly or from methanol. The utilisation of DME as a new diesel fuel in cars and trucks was demonstrated by Volvo. DME has favourable fuel properties such as a cetane number similar to diesel fuels.

The challenge in black liquor gasification is the corrosive environment at high temperatures and molten alkali metal salts inside the gasifier (Navqi and Yan, 2010). In addition, when black liquor gasification is retrofitted to a pulp mill, the operation of the pulp mill becomes more difficult. In a conventional plant using a recovery boiler, all sulphur is recycled as Na_2S but in black liquor gasification hydrogen sulphide is also formed. Since additional sodium hydroxide is needed to convert hydrogen sulfide back to Na_2S a higher capacity of the causticization plant is required (Navqi and Yan, 2010).

LTU Green Fuels, former Chemrec, has operated a black liquor gasification plant in Luleå (Sweden) and they have demonstrated black liquor gasification to dimethyl ether (DME) on a scale of four metric tons /day. Black liquor is sprayed as a liquid in their gasifier design and the produced syngas is cooled fast by quenching (Landälv, 2016).

8.5 Methanol from pulp mills

During the evaporation of black liquor in the Kraft pulping process, a small amount of **methanol** (typically between 7-15 kg/ oven dry ton of pulp) is produced (Jensen et al., 2012). It can be separated in liquid form from foul condensates of black liquor evaporation with a condensate treatment system. That way, the substance that would otherwise be considered as waste stream to be disposed or treated with effluent system, can be stored and utilised (Valmet, 2018b). Methanol has been commonly used by combusting it in the recovery boiler and in the lime kiln. It is also useful as a solvent and in making chemicals such as acetic acid and formalin, and it can be used as vehicle fuel.

The methanol from pulping process contains sulphurous pungent impurities, which has hindered its use. Different purification systems have been developed. For example, Andritz has developed a purification process (Andritz, 2019a) and a plant that aims at producing 5,000 tons of methanol is under construction in Mörrum at Södra's pulp mill in Sweden (Andritz, 2019b).

Figure 44: Separation of methanol from pulp mill: storage tanks and foul condensate stripping system (KnowPulp, 2019)

8.6 Valorisation of pulp and paper slurry

In the pulp and paper mills' water treatment systems, slurries are produced that contain a high amount of water. They cannot be dried sufficiently just by mechanical pressing. Therefore, it has been a common practice to combust them together with other dried fuels, although it is economically not very attractive.

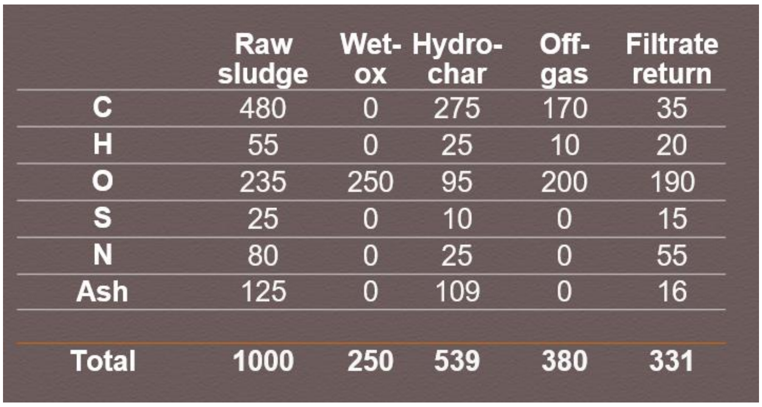
8.6.1 Hydrothermal Carbonisation (HTC)

Hydrothermal carbonisation (HTC) is a method to separate water and produce a coal like product (**hydrochar**) from the sludge. In hydrothermal carbonisation, the feedstock is heated in an aqueous solution to approximately 200-250°C so that a char-like product (Figure 45) is formed that separates from the aqueous phase water after cooling. Since the reactions in the process take place in the liquid phase, the pressure in the process is maintained high enough to keep the solution in liquid form at the operating temperature.

The major part of the energy content in the sludge is retained in the coal-like product, whereas only a small part of the organic matter is going to the aqueous phase. A small part is also released in gaseous phase, mainly as carbon dioxide. The typical composition of hydrochar from pulp and paper mill sludge is presented in Table 10.

Figure 45: Biocoal pellets and hydrochar produced with C-Green's HTC-process (Source: C-Green)

Table 10: Composition (kg per tonne DS in sludge) of hydrochar from C-Green's pilot HTC-plant trial (Source: C-Green)



	Raw sludge	Wet-ox	Hydro-char	Off-gas	Filtrate return
C	480	0	275	170	35
H	55	0	25	10	20
O	235	250	95	200	190
S	25	0	10	0	15
N	80	0	25	0	55
Ash	125	0	109	0	16
Total	**1000**	**250**	**539**	**380**	**331**

C-Green Technology and Stora Enso are building a HTC demonstration plant in Heinola (Finland) at the semi-chemical fluting mill. The planned HTC plant would convert 25,000 tonnes of mill sludge into biocoal. The amount would account for approximately 13 GWh of bioenergy and reduce 7,000 tonnes of equivalent CO_2 emissions. (Bioenergy International, 2018)

8.6.2 Anaerobic digestion (AD)

Another option is to treat slurry by anaerobic digestion (AD) so that biogas is produced and that the amount of sludge is reduced. These AD plants are characterized by the large volumes of feedstock from pulp and paper industry and the high organic content of the sludge. Furthermore, there is a lower risk in handling the material than sludge from communal wastewater treatment plants since pulp mill wastewater treatment sludge does not typically contain harmful microbes. However, a disadvantage is that the sludge may contain inhibitory components for digestion.

Figure 46: Sludge from pulp mill wastewater treatment (KnowPulp, 2019)

In Äänekoski (Finland), at the Metsä Fibre's Bioproduct Mill, a biogas plant treats the wastewater treatment sludge with anaerobic digestion producing biogas and pellets (Biokaasuyhdistys, 2016). In 2017, it was announced that part of the biogas from Metsä Fibre's digester will be upgraded to biomethane (Bioenergy, 2017).

Scandinavian Biogas has developed a co-digestion concept called Effisludge, in which wastewater sludge is digested with other complementary substrates. They demonstrate biogas production from pulp mill wastewater treatment sludge at Norske Skog's Skogn mill (Norway) (Scandinavian Biogas, 2019).

Biogas could also be produced from semi-mechanical pulp production condensates. This was examined in 10 days laboratory batch testes at Heinola fluting mill in Finland. Anaerobic treatment of condensates is expected to decrease wastewater treatment plant load and increase biogas production. (Lotti, 2013)

8.7 Lignin extraction

Lignin concentrated from black liquor is typically combusted in a recovery boiler. Lignin separated from the Kraft process can be used as energy product for example as fuel in the lime kiln or converted into more advanced biofuel by hydrothermal liquefaction. Lignin can be recovered from black liquor in the Kraft process by first lowering the pH to approximately 9-10 using CO_2 in order to precipitate it out of the black liquor solution and then leaching the impurities such as sodium in dilution wash with sulphuric acid (Andritz 2019c).

Valmet has developed a technology called LignoBoost (Valmet, 2018a) for lignin separation. In the Valmet's Lignoboost process it is possible to tailor the lignin into different qualities. The process has been demonstrated in full scale at Stora Enso Sunila mill (Finland) (lignin production 50,000 t/a) and by Domtar in the US as well as in pilot scale in Bäckhammar (Sweden).

Other Lignin separation processes under development are LignoForce by FPInnovations that is demonstrated at West Fracer pulp mill in Canada (Kouisni et al., 2016), in which a separate oxidation step is included that oxidises smelly and volatile sulphur components with oxygen into non smelly and non-volatile components, and Sequential Liquid Lignin Recovery and Purification (SLRP) process, in which lignin separates by gravity and does not have to be filtered as in the other processes (Velez & Thies, 2015).

Figure 47: Lignin separated from the Kraft process (KnowPulp, 2019)

8.8 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is an attractive process to increase the energy content of wet organic containing streams into a biocrude product without drying. The aqueous phase that is produced in HTL as a side product can also be treated at the pulp mill by evaporation and combustion in the recovery boiler.

Black liquor, lignin, sawdust sludge or other organic containing feedstock can be converted into a heavy oil like bio crude by HTL (Figure 48). The produced bio crude needs further upgrading in an oil refinery process in order to use it as transportation fuel. HTL is a process were the feedstock is treated in an aqueous solution at a high temperature typically between 270-370°C and elevated pressure of 5-30 MPa.

Examples of companies contributing to the liquefaction process development through HTL or similar processes include Renfuels, Suncarbon, SCA, Silva Green energy, Steeper Energy, and Licella.

Renfuel produces a biocrude product called Lignol via a catalyst process from lignin. They have demonstrated their technology in Bäckhammar (Sweden) near the LignoBoost demo plant and currently they are building a production plant in Vallvik (Sweden) in cooperation with the Rottneros pulp mill and the oil refinery company Preem. The plant’s opening is scheduled for the first quarter of 2021 (Renfuels, 2019).

Suncarbon is separating lignin by membrane separation and converting the separated lignin into depolymerised lignin via hydrothermal treatment (Suncarbon, 2019) SCA is also investigating production of fuels from black liquor presumably using HTL (Papnews, 2016).

Silva Green energy is building a demonstration plant in Tofte (Norway), in which forest residues are converted into biocrude with HTL (BiofuelsDigest, 2018).

Figure 48: HTL crude produced from black liquor (Source: VTT)

8.9 Replacing fossil fuels at paper mills' energy production

Existing paper mills in Central and Southern Europe are heavily dependent on natural gas. Natural gas accounts for more than 50% of fuels used for paper making in Italy, Netherlands, Spain, United Kingdom and Germany. (CEPI, 2018a) Mills in Germany, Poland, the Czech Republic and Hungary utilise also significant amounts of coal. A huge bioenergy retrofitting potential lies in increasing the share of bioenergy at the European paper mills.

Although further increasing the share of biomass is technically a viable option at paper mills, the mills have limited access to bio-based energy resources, lack in storage facilities and logistics constraints (CEPI, 2018a). Natural gas can be replaced with biogas from external sources and plants can more efficiently recover energy from sludge and rejects. CEPI (CEPI, 2018a) estimates that up to 10% of energy consumption at a paper mill site could be covered with biogas from anaerobic wastewater treatments.

Figure 49: Bark is a possible source of bioenergy at the pulp mill (Know Pulp, 2019)

8.10 Alternative fuels in the lime kiln and bark gasification

At pulp mills, black liquor is typically combusted in the recovery boiler to produce heat and power. Bark, as a side product from debarking, is also typically either combusted or gasified. In both cases, additional heat and power is produced. Some of the pulp mills sell part of the produced heat to a communal district heating system. Alternatively, bark can be sold to a separate energy company that produces heat and power both for the mill and/or a nearby community.

Most of the energy for pulp mills is produced from the feedstock itself i.e. pulpwood. The lime kiln has traditionally been one of the biggest consumer of fossil fuel at the pulp mill. The used fossil fuels include natural gas or oil. Other fuels such as biogas, lignin and saw dust have been also used in the lime kiln. Lately, the fossil fuels commonly used in lime kilns have been replaced by renewable ones.

In the fibre plant of Metsä in Joutseno (Finland), bark is gasified in an air operated gasifier and the produced gas is burned in the limekiln. At the Metsä's Bioproduct Mill in Äänekoski (Finland), bark is also gasified to produce fuelgas for the lime kiln. For an existing air gasifier that is retrofitted into a dual bed gasifier, producing also synthesis gas has been proposed as a future option to increase the output of bioenergy and high value products. The concept would enable production of transportation biofuels such as Fischer-Tropsch diesel with lower additional investment.

Figure 50: Components of a gasification plant (Know pulp, 2019)

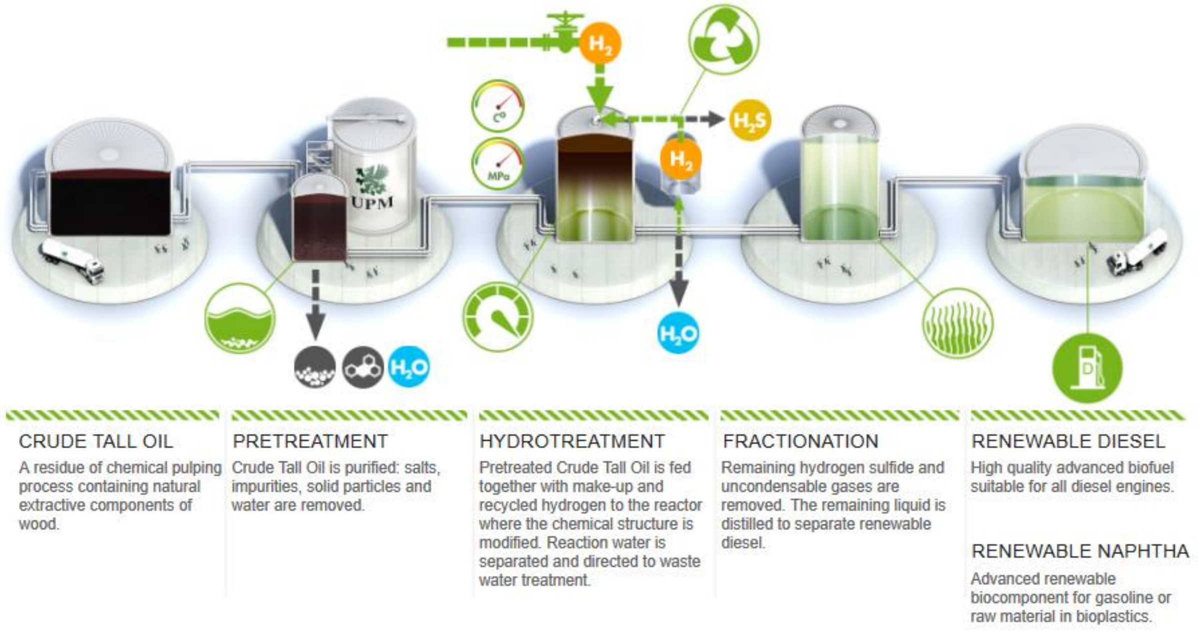
8.11 Renewable diesel from pulp mill residue tall oil

Tall oil (Figure 51) is an attractive feedstock for biofuels' production due to its low oxygen content. Thus, it requires less treatment compared to other feedstocks. Crude tall oil is obtained in separation of the soap in the Kraft pulp mill. The soap is acidified in order to separate out the crude tall oil. It can be further purified and refined into fractions with different boiling points.

Figure 51: **Samples of crude tall oil and bark at Metsä Group's Fibre's Pro Nemus Visiting Centre**

A drawback in utilising tall oil for biofuel production is that it is available in limited amounts and part of it could be used for more valuable chemicals than biofuels. For tall oil biofuels, supports schemes in Sweden favour production of biofuel instead of chemicals.

Sunpine in Northern Sweden esterifies tall oil with methyl ester and their product is further converted into transportation fuels at the Preem refinery in Piteå (Sweden) (Sunpine, 2019). UPM Biorefinery produces transportation biofuels in Lappeenranta (UPM, 2019). The capacity of the facility is 120 million litres of renewable diesel and naphtha per year. The UPM's enhanced biofuel production technology is presented in more detail in Figure 52.



CRUDE TALL OIL
A residue of chemical pulping process containing natural extractive components of wood.

PRETREATMENT
Crude Tall Oil is purified: salts, impurities, solid particles and water are removed.

HYDROTREATMENT
Pretreated Crude Tall Oil is fed together with make-up and recycled hydrogen to the reactor where the chemical structure is modified. Reaction water is separated and directed to waste water treatment.

FRACTIONATION
Remaining hydrogen sulfide and uncondensable gases are removed. The remaining liquid is distilled to separate renewable diesel.

RENEWABLE DIESEL
High quality advanced biofuel suitable for all diesel engines.

RENEWABLE NAPHTHA
Advanced renewable biocomponent for gasoline or raw material in bioplastics.

Figure 52: **Flowchart of UPM's renewable diesel production (Source: UPM[48])**

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[48] https://www.upmbiofuels.com/about-upm-biofuels/production/

8.12 Concluding remarks

Bioenergy retrofits in the pulp and paper industry can be used to replace fossil fuels used on-site for energy production (natural gas, coal and fuel oil) with renewable alternatives or to enable the production of renewable fuels from process side streams.

The possibilities related to fossil fuel replacements with bioenergy at paper and pulp mill sites depend highly on the site ecosystem. Pulp mills do have several exploitable side streams. Whether these side streams are enough to cover the mills energy consumption, depends on the used pulping technology. In Kraft pulping process, side streams can be effectively utilised, and mills often produce excess energy that can be sold, especially, if they are not integrated with a paper mill. In sulphite pulping, the sugars remaining in the black/brown liquor can be converted into biogas, whereas lignin, which is converted into lignosulphonates, is typically sold and not combusted. In the pulping industry, fossil fuels are commonly replaced with bark (residue from debarking) and biogas (from anaerobic digestion of sludge or liquid effluents from the mill's wastewater treatment). Solitary paper mills, those that are not co-located with a pulp mill, do not always have access to adequate feedstock for bioenergy production. Biogas and hydrochar produced from the wastewater treatment sludge could, however, increase the bioenergy share of these plants as well.

Besides replacing fossil fuels on-site, another option is to retrofit the facility to produce renewable fuels for external markets. Fuels that can be produced include biogas, lignin, bioethanol, renewable diesel or bio crudes. In the process of recovering the chemicals at Kraft pulp mills, more heat is produced than what is needed at the mill, even if only side streams were used at the site for energy production. This heat can be converted to power by a turbine and used on site or sold. However, converting the excess heat to power is not very energy efficient. Therefore, utilising part of the side streams and excess heat to produce bioenergy products such as lignin and liquid biofuels becomes an attractive option.

The feasibility of bioenergy retrofits depends significantly on the type of the pulping process which is used. In sulphite cooking process, valorisation of hemicellulose to bioethanol or biogas production is an option. However, in the Kraft process, valorisation of sugars after the cooking from black liquor is difficult, because they are degraded in the process. Only in a special case when the product is dissolving pulp for textile applications, a by-product stream of hemicelluloses can be utilised also in the Kraft process. Generally, in the Kraft process, lignin can be separated from black liquor and used as fuel directly in the lime kiln instead of fossil fuels. It can be also converted into biocrude by hydrothermal liquefaction. The biocrude product can be further refined into high quality transportation biofuels in an oil refinery. It is also possible to convert part of black liquor directly into biocrude by hydrothermal liquefaction.

In the Kraft process side streams are produced, such as methanol from black liquor evaporation and tall oil from soap separated in the evaporation of black liquor. Methanol can be cleaned from smelly impurities and used as biofuel or chemical. The tall oil or heavy fractions from further refining such as tall oil pitch can be further converted into renewable diesel and gasoline fuels. However, renewable fuels are not the only use for methanol and tall oil, but they can also be converted to more valuable products such as functional food (sterols) and paints (binders). For semi-chemical processes, such as near neutral sulphite pulping, acetic acid containing condensates can typically be used in biogas production.

In all of the pulping processes, bark which is a side product not used in the pulp production can be used to produce heat and power in a separate boiler or gasified into fuel gas. The fuel gas can be burned instead of fossil fuel in the lime production in the chemical recovery. Additionally, it can be sold or stored either as such or refined into a liquid form or converted into biomethane which can be fed to the gas grid.

Typically, mills also generate wastewater and sludge. These waste streams can be processed into biogas, although some streams such as water from debarking might contain substances that inhibit biogas production. Another possibility is to convert the sludge into coal type product (hydrochar) by hydrothermal carbonisation process. Hydrochar, which has a high energy content, can be used energetically.

The bioenergy retrofit options related to the pulp and paper industry are at different levels of technical maturity, which hinder the possibilities for exploitation. Replacing fossil fuels can be a technically viable option. Commercial processes exist related to side stream utilisation such as for bark combustion, bark gasification, biogas production from mill waste products, ethanol production from black liquor, tall oil conversion into transportation fuels and lignin separation from Kraft black liquor. Bark and black liquor conversion via gasification into biofuels, methanol purification, biocrude production from lignin and black liquor and hydrothermal carbonisation of mill sludge have been demonstrated in pilot units or demonstration plants connected to pulp mills.

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