Interreg North-West Europe WOW!

European Regional Development Fund

REPORT

DATE: December 2020

NAME: Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH (WPT1 leader)

SUBJECT: WPT1 Designing value chains for carbon based elements from sewage

A2 MARKET POTENTIAL STUDY

WOW! is supported by the Interreg North-West Europe program.

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Content

1 Introduction

Sewage contains valuable substances that could be used as raw materials for biobased products. However, in North-West Europe (NWE) this potential is hardly exploited yet. This results in loss of valuable materials and increased CO_2-emmissions and use of natural resources.

There are market opportunities for raw materials from sewage, but for this, supply (sewage treatment plants (STPs)) and demand (from industry) need alignment. This calls for a transition: at STPs a shift is needed from treating sewage to producing valuable materials. Market parties need to regard sewage as a valuable source instead of 'dirty and unsafe water' and policies should better fit this new circular practice.

To capitalise on these opportunities and work towards a circular approach on sewage, WOW! will:

- Show the economic potential: by identifying the most promising carbon based value chains from sewage,
- Demonstrate the technical feasibility: in three pilots recovery and upcycling techniques for cellulose, lipids and polyhydroxyalkanoates (PHA) will be optimised, while tailoring the product specifications to market needs,
- Lower policy barriers: policy barriers for market uptake of recovered materials will be identified and action plans developed.

This market potential study is the deliverable 2.2 of the work package (WP) T1, Activity A2. The objective is to identify viable value chains for five carbon based products (CBE) from sewage: PHA-bioplastic, biodiesel, bio-oil, biochar, and acetic acid. In Figure 1-1 a simplified scheme of the recovery of the five CBEs is shown.

- For the production of biodiesel the sewage inflow is used to cultivate Microthrix p. and to enrich lipids. In a next step the lipids are extracted, processed and transformed to biodiesel.
- For the production of bio-oil, biochar and acetic acid the screenings of the fine sieves are used. In this first step cellulose is recovered, dewatered and then dried. In a thermal degradation process the cellulose is heated to a temperature of 400 - 600 ^{o}C in an oxygen free environment (pyrolysis). During the pyrolysis process volatile material is separated from the solid biomass and converted into biochar. With a condenser bio-oil and acetic acid with a concentration of 7% can be separated. The biochar is activated to activated carbon at a different site.
- For the production of PHA primary sludge is used. In a biological process PHA is enriched and extracted. Then the PHA is compounded and processed to an end product.

More details about the processes and an initial estimation of the quantities of the five CBEs which could be produced in future at STPs in NWE are summarized in (WOW! State of the art Report, 2019).

In the following market potential study, production quantities, collectable quantity at the sewage treatment plant, market price and market potential for the five CBEs are described.

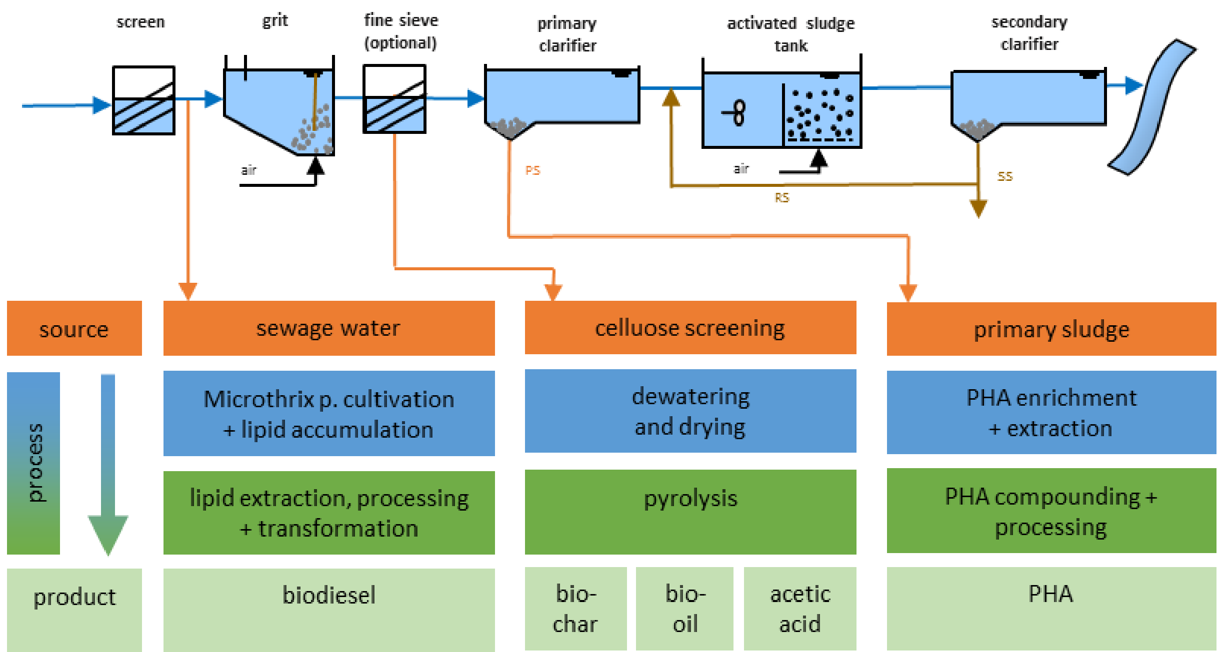

Figure 1-1: Recovery of CBEs from sewage

2 Approach

To get an insight into the market for the five CBE, surveys by questionnaires and end user meetings were conducted.

2.1 Survey by questionnaire

A questionnaire based on MS-excel was developed which could be used for all CBEs (see appendix, chapter 12.1). In the questionnaire market players were asked for customers / applications, quality requirements and drivers/barriers. For each country, a list of stakeholders for the five CBEs was compiled to which the questionnaire was sent by native speakers, being responsible as first contact and being able to answer possible questions.

2.2 End user meetings

To get more detailed information, end user meetings were carried out. The aim was to analyse with industry representatives/experts the market potential for recovered PHA, lipids, bio-oil, biochar and acetic acid from sewage. The results were summarized in a short report (see appendix, chapter 12.2).

2.3 Evaluation of Survey and end user meeting

The number of responses to the survey questionnaires were relatively low. A total of 7 questionnaires on PHA, biodiesel and biochar were evaluated. Due to the small number of responses, the focus was placed on eleven end user meetings. The distribution of the market participants in Europe is shown in Figure 2-1. The end user meetings in particular gave a deeper insight into the market requirements. Contacts to market participants in the field of acetic acid could not be established. The results of the surveys, together with literature studies, were used anonymously in the assessment of the market potential of the five CBEs.

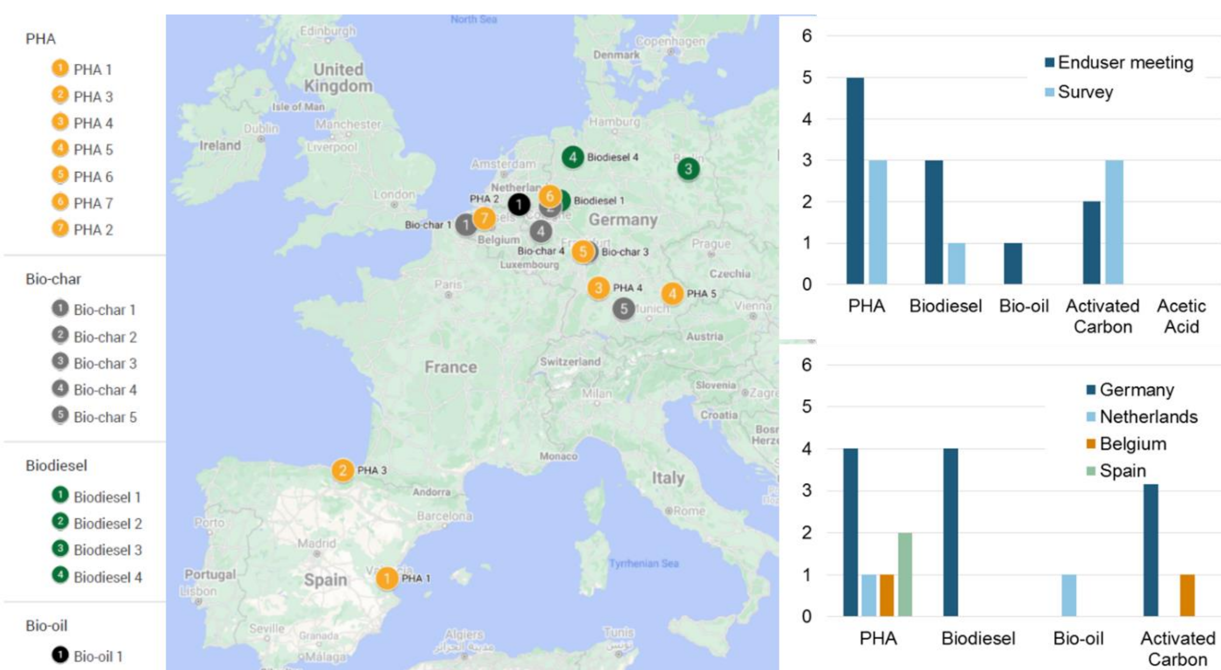

Figure 2-1: Location and numbers of surveys and end user meetings in Europe

3 Material flow balancing STP

The recovery of the five CBEs has an impact on the purification performance and the COD balance of the STP. In order to quantify the influence, calculations were carried out with the simulation programme Simba Classroom for a STP with a capacity of 250,000 population equivalents (PE), a specific influent flow of 130 L/(PE d) and a specific COD load of 120 g/(PE d) (Abels, 2019). In the simulation model, a sewage treatment plant with primary treatment, biological stage with nitrogen elimination and anaerobic sludge stabilisation was considered.

The purification capacity and the COD flow balance were calculated for the integration of the following processes at a conventional STP:

- PHA enrichment and extraction with further use for PHA
- Lipid accumulation with further use for biodiesel
- Cellulose production with further use for pyrolysis

Table 3-1 shows the effluent quality of the model STP for the parameter nitrogen. The integration of PHA recovery installation leads to a slight decrease in the nitrate effluent concentration. By using the primary sludge for PHA production, less sludge is stabilised anaerobically and thus the rejection water from the digester is reduced. When cellulose is removed with a fine screen, more COD is removed from the system compared to a primary clarifier and the carbon to nitrogen ratio shifts to an unfavourable range. At the same time, less sludge is anaerobically stabilised, thus reducing the amount of reject water. Overall, this leads to only a small change in the effluent values. If lipids are recovered, the ratio of carbon to nitrogen decreases in the influent of the biological treatment. This results in a higher nitrate effluent concentration. When integrating this process, it must therefore be checked whether the nitrogen monitoring values in the effluent of the STP are still ensured.

Table 3-1: Effluent concentration of a conventional STP in comparison *with CBE productions (Abels, 2019)*

		conventional STP	PHA	cellulose	lipids
N_{total}	[mg/L]	9.7	8.8	9.9	12.7
NO_3-N	[mg/L]	7.5	6.6	7.7	10.3
NH_4-N	[mg/L]	1.5	1.4	1.6	1.7

In Table 3-2 the influence of resource recovery at a conventional STP with anaerobic sludge stabilisation is shown. In a conventional STP, 36% of the carbon are respirated, 33% are converted to digester gas, 24% are disposed with the sludge and 7% are discharged into the receiving water body (see Figure 3-1).

Table 3-2: COD flow balance of conventional *STP in comparison with CBE productions in percent (Abels, 2019)*

	inflow		effluent	respiration	CBE-product	digester gas	sludge
conventional	100		7	36	-	33	24
PHA	100		6.2	36.6	9.5	24.4	23.3
cellulose	100		6	26	50	8	10
lipids	100		6.4	30.2	8.9	31	23.4

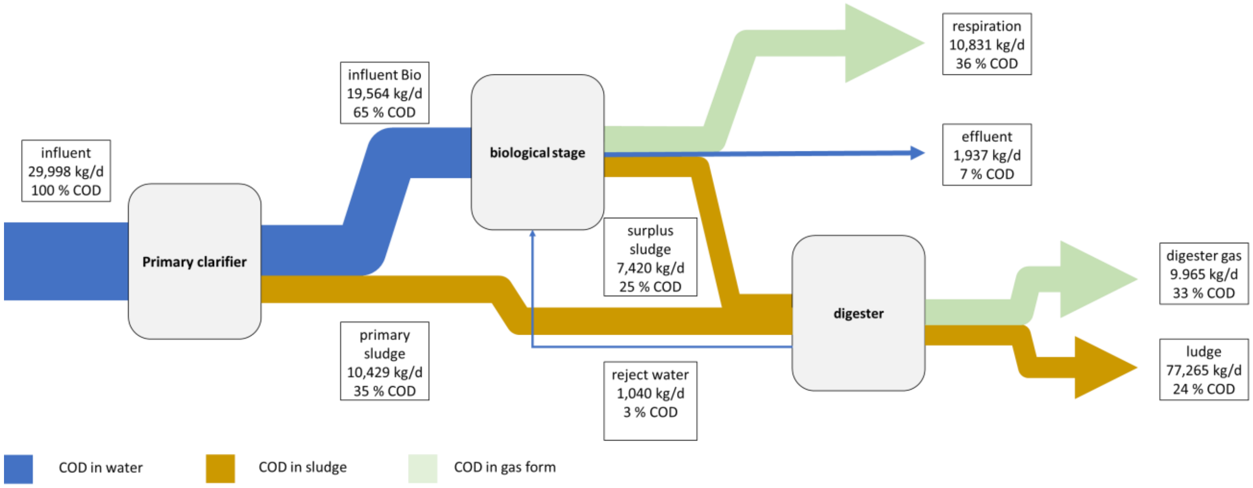

Figure 3-1: Example for a COD flow balancing of a STP with anaerobic digestion for 250,000 PE (Abels, 2019)

Figure 3-2 shows the COD balance for a STP with PHA recovery. 34.8% of the COD in the inflow of the STP are used for PHA recovery. However, only 9.5% of this are removed from the system as PHA-containing biomass. 23.4% of the total COD from the PHA accumulation are charged to the digester. Due to the reduced COD load, the COD portion which is converted to biogas is reduced to 24.4%. This results also in a reduced energy production at the STP.

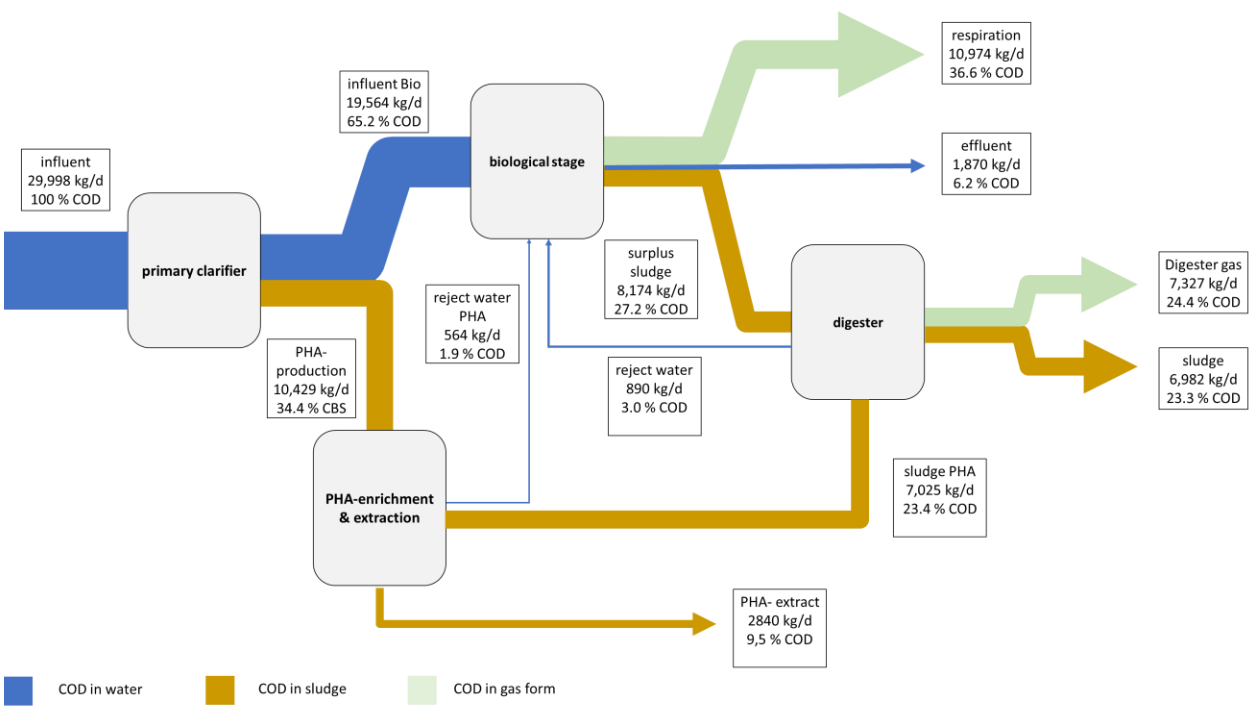

Figure 3-2: Example for a COD flow balancing of a STP with digestion and integration of a PHA production for 250,000 PE (Abels, 2019)

Figure 3-3 shows the COD balance for a STP with cellulose recovery. In contrast to a removal of 34% COD in a conventional primary clarifier, 50% of the COD in the influent of the STP are discharged through fine screening. This results in a COD reduction in the inflow of the biological stage, which means that less COD is respirated and less excess sludge is produced. The digester gas production of 8% COD is also much lower than in the conventional STP and results in a significant reduction in related energy production. Cellulose recovery is therefore more suitable for STPs without digestion.

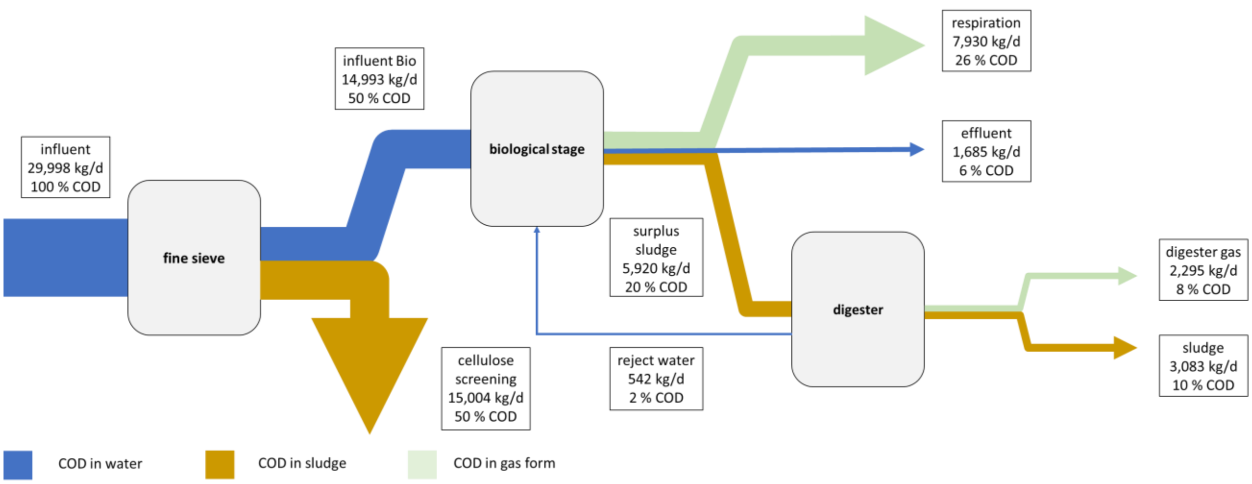

Figure 3-3: Example for a COD flow balancing of a STP with digestion and integration of pyrolysis for 250,000 PE (Abels, 2019)

Figure 3-4 shows the COD balance for the recovery of fats. 9% of the COD at the sewage treatment plant are withdrawn for biodiesel production. The proportion of COD that is respirated is reduced to 30% due to the lower COD concentration in the influent of the biological stage. The other COD percentages are comparable to those of a conventional STP.

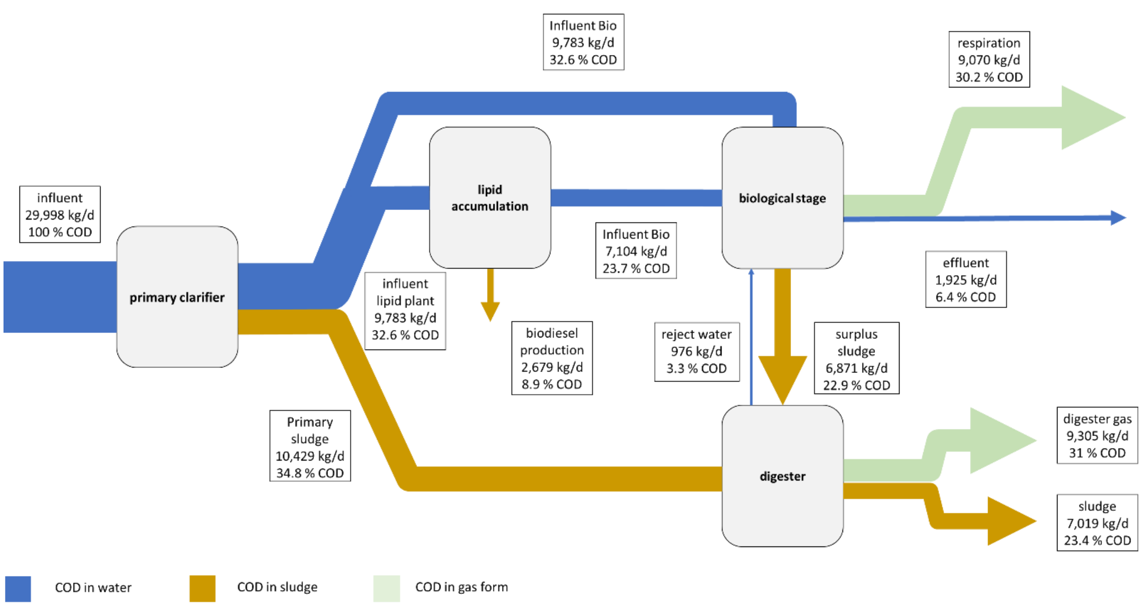

Figure 3-4: Example for a COD flow balancing of a STP with digestion and integration of lipid-production for 250,000 PE (Abels, 2019)

Summarised, the integration of PHA and cellulose production has only a minor influence on the biological stage and the effluent quality. Due to the carbon removal for CBE production in the mechanical stage the energy production at STPs with anaerobic sludge digestion is reduced. This must be taken into account in the economic assessment. Increased carbon removal in the mechanical stage, on the other hand, could also be advantageous in the case of overloaded sewage treatment plants or an expansion of the sewage treatment plant, because the required reactor volume for the biological stage may be reduced.

Lipids removal has only a small influence on energy production at the treatment plant. However, COD removal in the inlet of the biological stage for lipid production leads to a shift in the COD to N ratio. This can results in an increase in the effluent values and must be taken into account when dimensioning a plant for lipid removal.

4 PHA

4.1 Production quantities for bioplastics

According to the association European Bioplastics, which aims to represent the interest of the bioplastic industry, the global plastic production was 335 million tonnes in 2017. The global production capacities of bioplastic are 2.111 million tonnes per year (biodegradable 1.227 million tonnes per year and non-biodegradable 0.884 million tonnes per year) (Figure 4-1) in 2020 (European Bioplastics, 2020). The demand is rising and the market is continuously growing. The PHA production has a share of 1.7% resp. approx. 36,000 tonnes per year (see Figure 4-2). The global bioplastics production capacity is predicted to increase from around 2.111 million tonnes in 2020 to approximately 2.871 million tonnes in 2025 according to the latest market data compiled by European Bioplastics in cooperation with the research nova-Institute (European Bioplastics and nova-Institute, 2020).

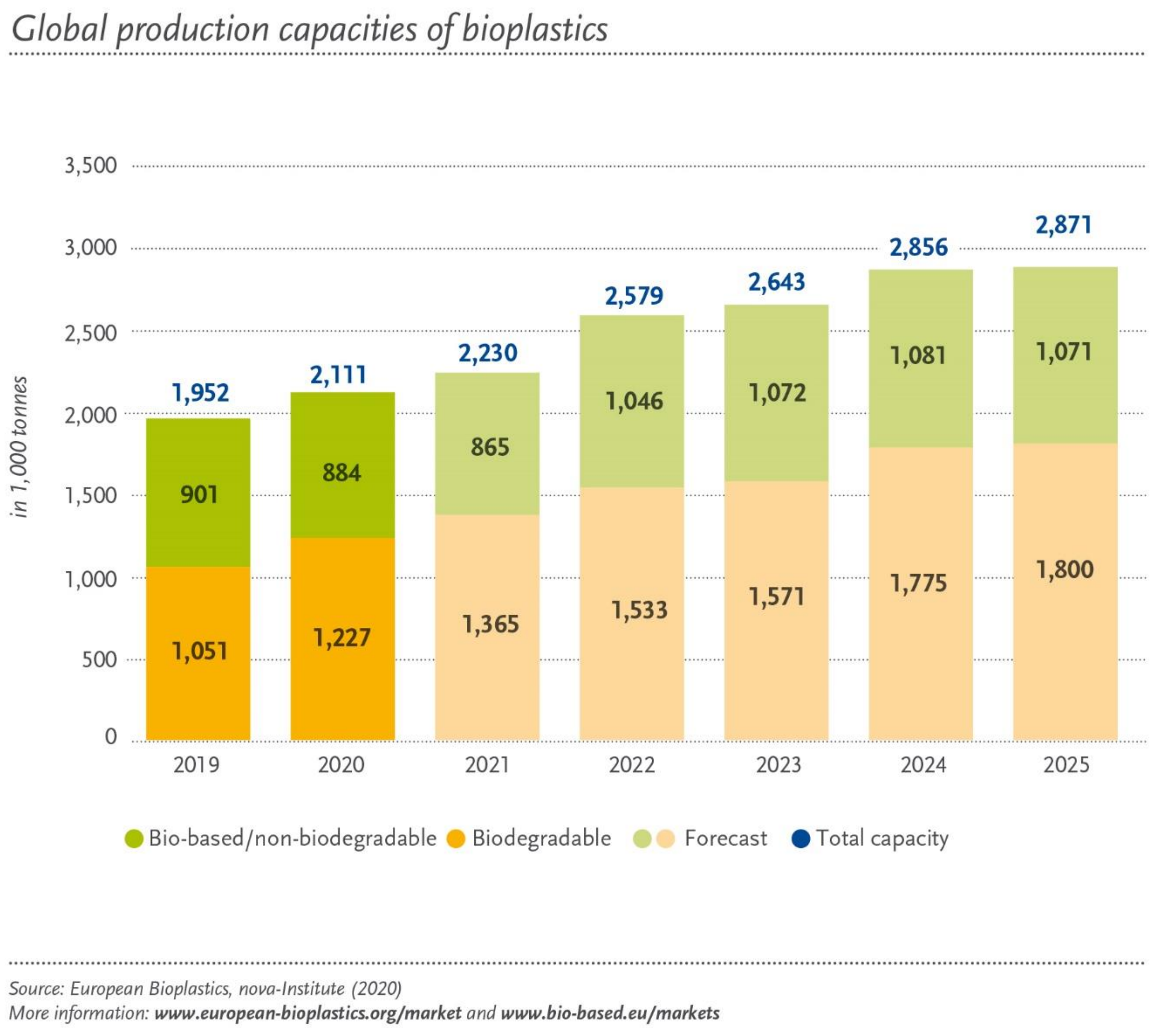

Figure 4-1: Global production capacities of bioplastic (European Bioplastics and nova-Institute, 2020)

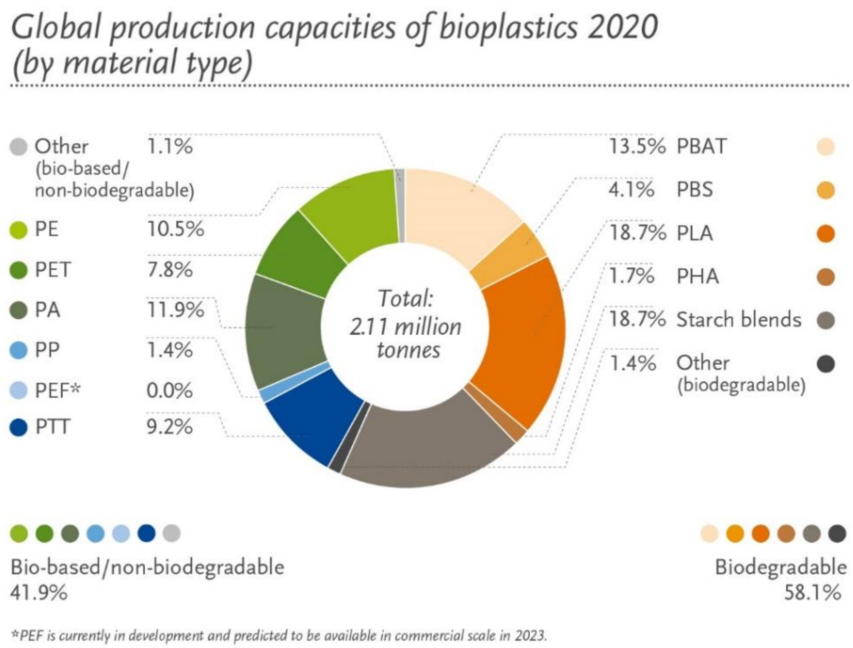

Figure 4-2: Global production capacities of bioplastic 2019 (by material type) (European Bioplastics and nova-Institute, 2020)

A lower global PHA production is estimated by STOWA (2017), who presume a current PHA production of 2,000 – 4,000 tonnes per year, and predict a share of only 15,000 – 25,000 tonnes per year in 2025. In contrary, the IfBB (2019) predicts that total bioplastics production capacity will increase to 2.87 million tonnes in 2025, with PHA as a driver of this growth accounting for 11.5% or 330,000 tonnes per year of this sum (see Figure 4-3).

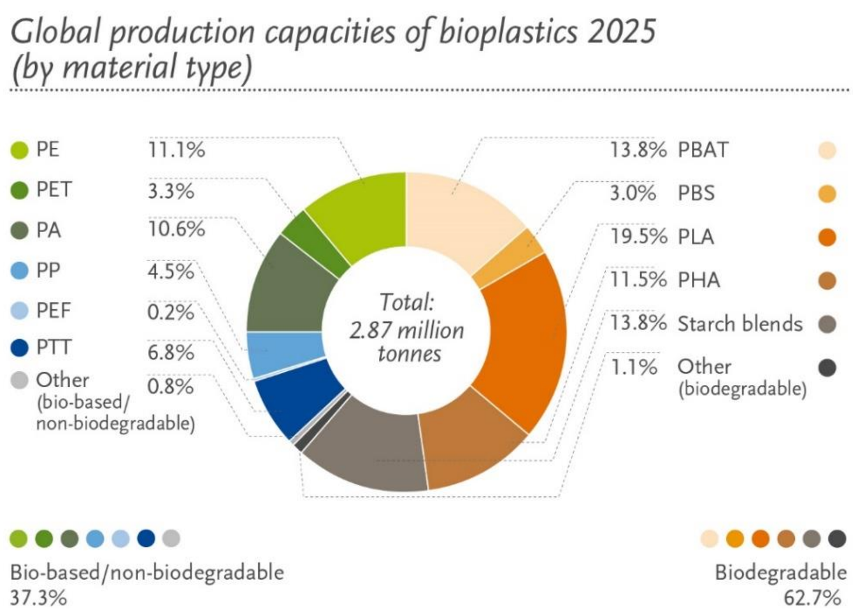

Figure 4-3: Prediction of global production capacities of bioplastic in 2025 (by material type) (European Bioplastics and nova-Institute, 2020)

"Europe is a major hub for the entire bioplastics industry; it ranks highest in the field of research and development and is the industry's largest market worldwide. With a view to the actual production of bioplastics and regional capacity development, Asia is a major production hub. In 2019, over 45 percent of bioplastics were produced in Asia. Around one quarter of the global bioplastics production capacity is located in Europe" (https://www.european-bioplastics.org/market/).

"Innovative biopolymers such as PLA (polylactic acid) and PHAs (polyhydroxyalkanoates) are the main drivers of the growth in the field of bio-based, biodegradable plastics. PHAs are an important polymer family that has been in development for a while and that now finally enters the market at commercial scale, with production capacities set to more than triple in the next five years. These polyesters are 100 percent bio-based, biodegradable, and feature a wide array of physical and mechanical properties depending on their chemical composition" (https://www.european-bioplastics.org/market/).

4.2 Collectable quantity at the sewage treatment plant

With the annual production capacity of 1.4 kg PHA/(PE·a) estimated by Pittmann and Steinmetz (2016), this results in a producible quantity of about 400,000 t PHA/a for NWE (see chapter 5 in the WOW! - State of the art Report, 2019). Considering that not all WWTPs in Europe are equipped with a primary clarifier the PHA production is reduced about 70% to 122,000 t PHA/a

4.3 Market price for conventional products

The market price of PHA is estimated between 3.5 – 4.5 €/kg PHA (STOWA, 2017). NaturePlast (2019) gives prices for PHA, competitors and standard polymers as listed in Table 4-1.

Table 4-1: Price for bio- and conventional plastics (NaturePlast, 2019)

<table>
<tr><th>Material</th><th></th><th>Price [€/kg]</th></tr>
<tr><td>Polyhydroxyalkanoate (PHA)</td><td rowspan="2">based on renewable raw materials, biodegradable</td><td>5 – 7</td></tr>
<tr><td>Polylactic Acid (PLA)</td><td>2 – 3</td></tr>
<tr><td>Polybuthylensuccinat (PBS)</td><td>petroleum-based, biodegradable</td><td>4 – 5</td></tr>
<tr><td>Polythylene (PE)</td><td rowspan="3">conventional polymers (petroleum-based, non-biodegradable)</td><td>1 – 2</td></tr>
<tr><td>Polypropylene (PP)</td><td>1 – 2</td></tr>
<tr><td>Polystyrene (PS)</td><td>1.5 – 2</td></tr>
</table>

4.4 Market potential for bioplastic from sewage

PHA derived from sewage can use the same market as the current PHA on the market. The potential demand for sewage-derived PHA can be estimated from the current world wide PHA production to 36,000 t/a (see chapter 4.1). The potential sewage-derived PHA supply amounts to 122,000 t/a (see chapter 4.2). The presented calculations and results clearly indicate that it would be possible to produce high amounts of PHAs on STPs in NWE.

The quality requirements represent a major challenge for PHA derived from sewage. It must be ensured that the batches produced are of uniform quality (homogeneity of chain length / stable composition of monomers) and quantity. The produced PHA does not necessarily have to be pure, this selectivity would probably be difficult in sewage due to different microorganisms enriching the PHA and varying wastewater composition. A mixture of different PHA species as a natural blend may have good properties. If the PHA is rough, it can be refined with plasticisers (e.g. glycerine). In principle, the use of only a few additives is desirable.

PHA is often used in the food sector, where an authorisation with "food contact" (EU 10/2011) would be required. Customer acceptance is mentioned here as an obstacle to the use of PHA from sewage. Alternatively, it can be used in the agricultural sector, fish keeping and farming sector or in the construction industry.

The main advantage of PHAs materials is their ability to rapidly biodegrade in each end-of-life environment, including water. Additional drivers for this market are the legislation requirements to use more bioplastic and also the shortage of raw materials. On the contrary, the main barriers are the high prices due to small plant sizes and legal issues for the registration of PHA derived from waste water. Some technical properties can also be an obstacle.

Figure 4-4 shows the assessment of end users for the application of PHA from sewage with regard to possible customers and application, competitors, quality requirements, drivers and barriers.

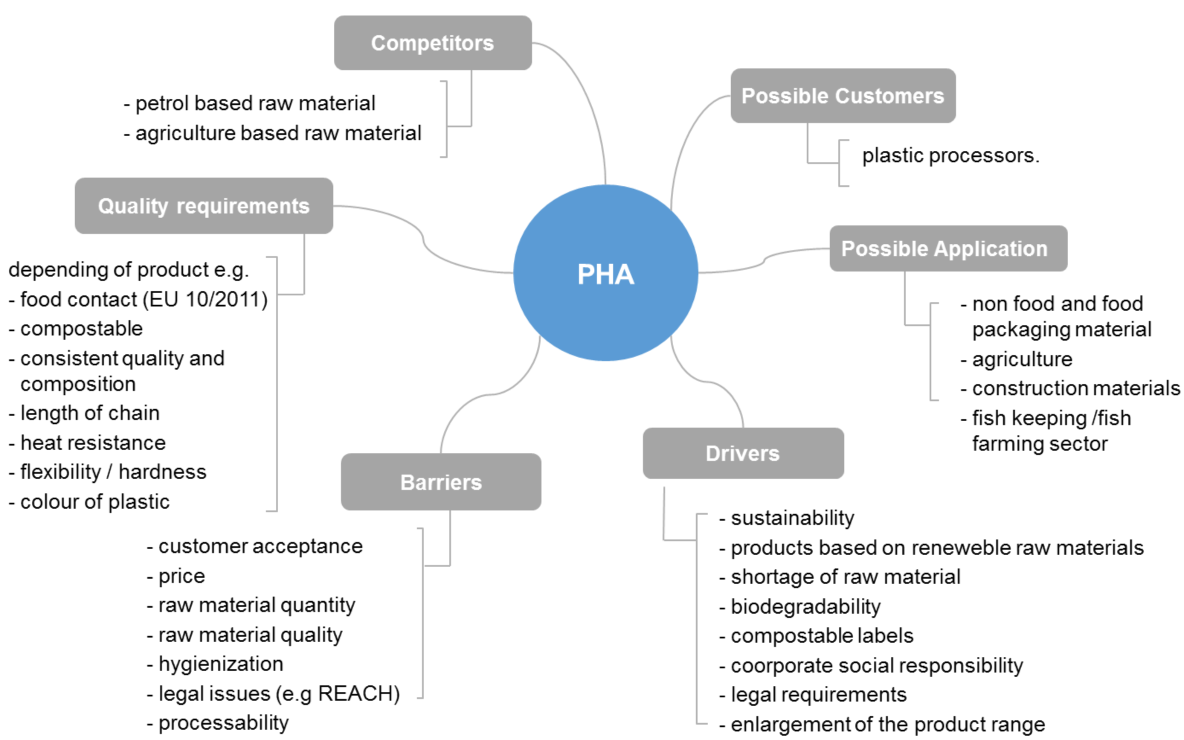

Figure 4-4: Assessment of end users for the application of PHA from sewage

5 Biodiesel

5.1 Production quantities for biodiesel

Since biodiesel is by far the most important biofuel used in the EU and will be produced from sewage sludge within the WOW! project, one main focus of the market potential study is laid on the biodiesel sector. The world wide biodiesel production sums up 41 Mio tonns in 2019 (Eurostat, OECD).

Figure 5-1 shows the timeline of the share of biofuels in the European transport sector. It is obvious that the total share strongly increased between 2006 and 2012. Since 2012 the total share has stagnated at a level of approx. 5%. In 2018, conventional biofuels (e.g. rapeseed biodiesel) shares for about 80% of the total biofuel share. Advanced biofuels, mainly produced from used cooking oil and animal fat, had a strong rise between 2013 and 2015 to a continuing share of around 1% (see Advanced Part B). The contribution of advanced biofuels from biomass fraction of wastes and residues from forestry and forest-based industries (Advanced Part A) is still minor with approx. 0.2%, but has increased relatively a lot since 2013.

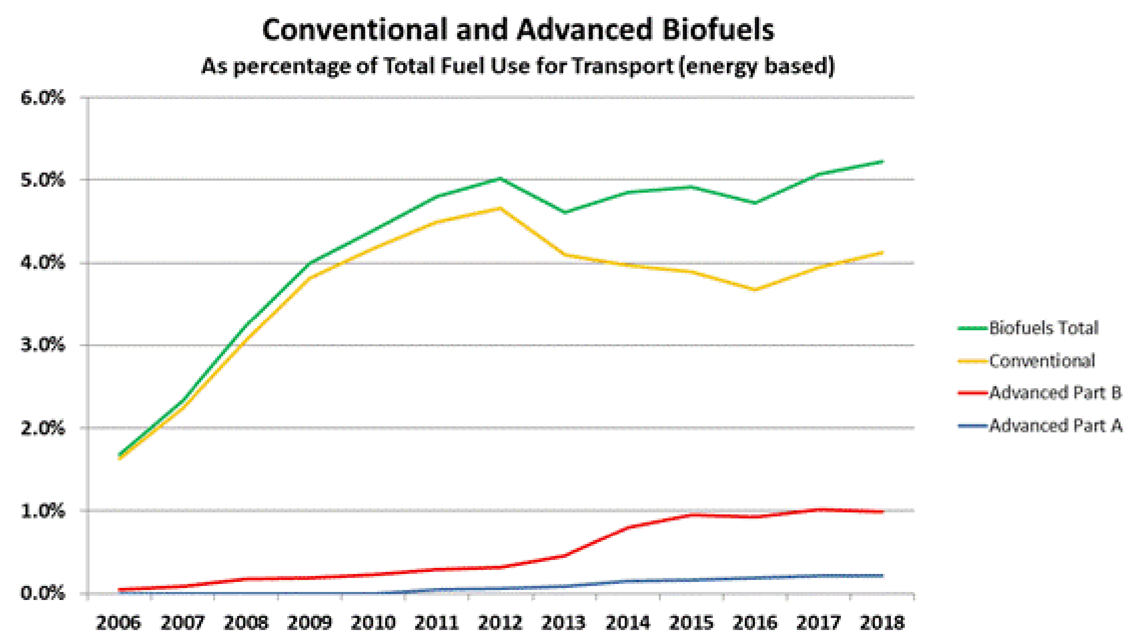

Figure 5-1: Timeline of development of share of biofuels use for transport; (Hague, 2018)

Figure 5-2 visualises the development of the feedstocks, used for biodiesel production, in the EU between 2009 and 2016. The amount processed increased from approx. 10 Mio. litres to approx. 13 Mio. litres during this time. Furthermore, the share of vegetable oils from oilseeds, either imported or produced within the EU, remained stable. The amount of imported palm oil increased sharply as well as the amounts of waste oils, especially since 2011. Advanced biofuels represent until now just a negligible share of the feedstock, used for EU biodiesel production.

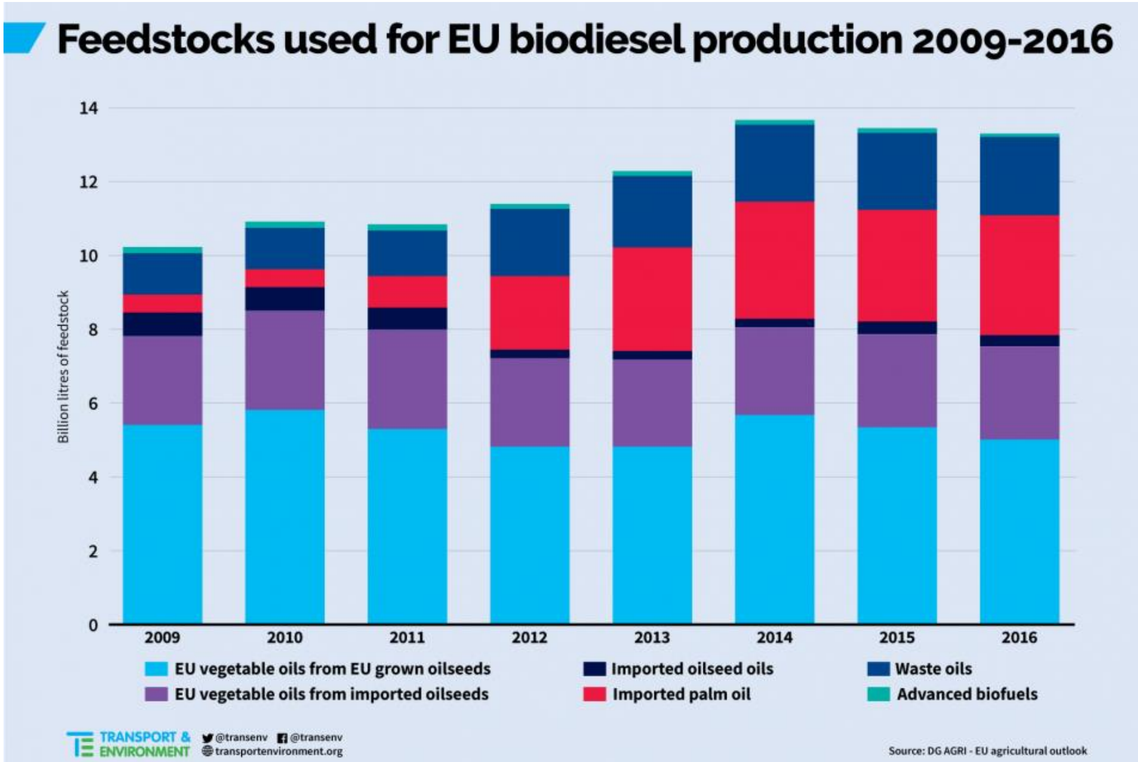

Figure 5-2: Feedstocks used for EU biodiesel production 2009 to 2016; (Transport and Environment, 2018)

The EU is the leading biodiesel producer worldwide. Table 5-1 gives an overview of the most important biodiesel producers in the EU, including the production capacities and the locations of the plants. Neste Oil, with plants in Finland and in the Netherlands, is the biggest single manufacturer comprising more than 35% of the EU production capacity. Further from Table 5-1 it can be concluded that a substantial share of the EU biodiesel production capacity is located within the NWE INTERREG region.

Table 5-1: Production capacity of the main biodiesel producers in 2017; (EUROBSERV'ER, 2018)

Company	Country	Number and location of plants in Europe	Production capacity in 2017 in tonnes
Neste Oil	Finland	Finland, Netherlands	2,600,000
Avril	France	France, Germany, Italy, Austria, Belgium	1,800,000
Infinita	Spain	Spain	900,000
Marseglia Group (Ital Green oil / Ital Bi Oil)	Italy	Italy	560,000
Verbio AG	Germany	Germany	470,000
Eni	Italy	Italy	360,000
Total	France	France	500,000

Today around 50% of the used cooking oil (see Figure 5-3), processed to biodiesel in the EU, is imported from non-European countries. China accounted for around 30% of the 850,000 tonnes, imported in 2018. Thus, already today there is not enough feedstock within the EU to satisfy the European demand for the production of waste-based biodiesel.

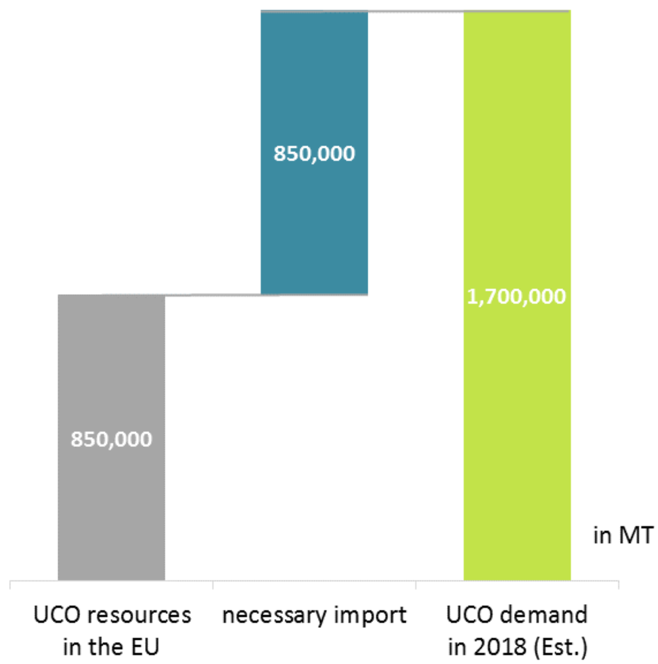

Figure 5-3: Amounts of used cooking oil (UCO) available in the EU compared to the demand of the feedstock for biodiesel production; (Greenea, 2018)

Figure 5-4 shows a projection of the biofuel consumption in the EU into the future (till 2030), assuming that the 14% goal is met and the maximum eligible amount of crop-based biofuel (7%) and waste is used. According to the projection, it becomes apparent that the demand and use of advanced biofuels like e. g. sewage sludge-based biodiesel will increase strongly to meet the renewable energy target of 14% in 2030.

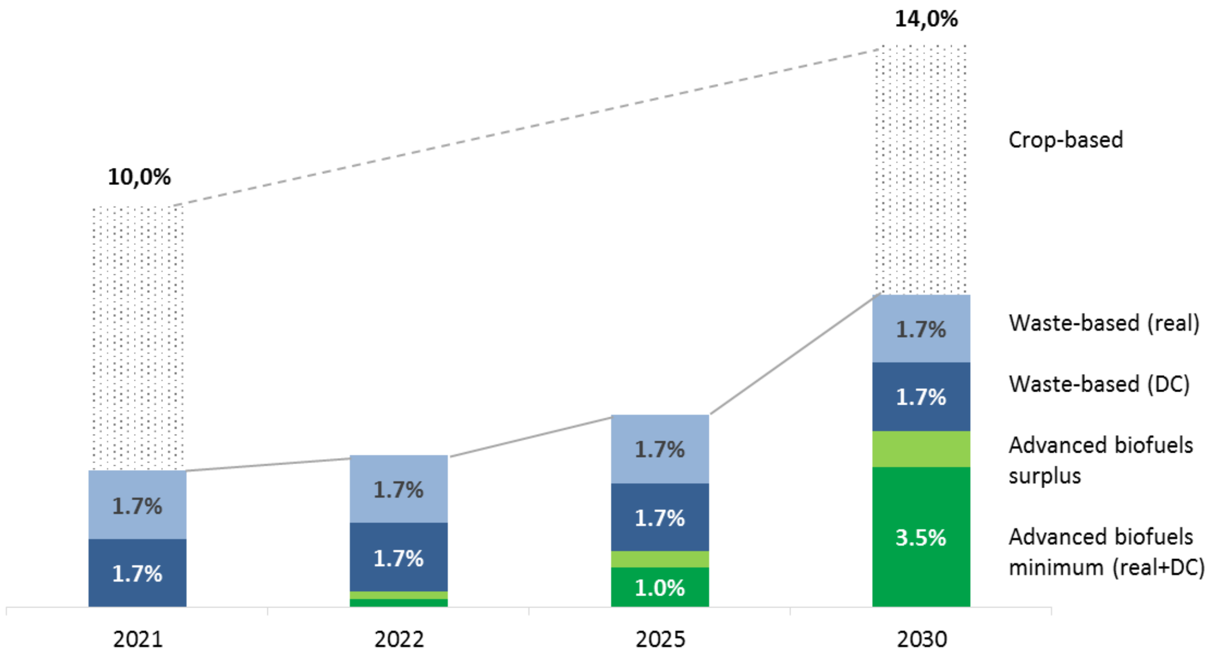

Figure 5-4: Change of split of biofuels (by feedstock) in the EU from 2021 to 2030 according to EU legislation (especially REDII) DC: Double-counting); (Greenea, 2018)

An important trend on the European biofuel market is **H**ydrogenated **V**egetable **O**il-biodiesel HVO. This hydrogenation process was patented and developed by the Finnish oil company, Neste Oil. It is a catalytic reaction similar to the traditional process. However, in the HVO process the applied catalyst is hydrogen rather than methanol, which is used in the production of other types of biodiesel. The advantage of this technology is the avoidance of the co-production of glycerine, which cannot always be used by local outlets. Furthermore, waste oil could be used as a feedstock for the production of HVO. The technique also removes oxygen atoms, resulting in a more stable final product. Lastly, the products of the reaction are essentially alkanes, which obtain higher cetane indexes than their unsaturated counterparts. The final product, which is an HVO synthetic biodiesel, is very similar to the fossil diesel. Its production cost is slightly higher than that of traditional biodiesel, but the product holds a better quality and can be used unblended in a traditional diesel engine.

Today around 18% of the biodiesel used within the EU is HVO-biodiesel. Due to the advantages stated above, it is expected that the production capacity will triple from 2018 to 2025.

5.2 Collectable quantity at the sewage treatment plant

The assessment of potential supply of biodiesel from sewage-derived lipids is based on data regarding population equivalents connected to a sewage treatment in the NWE region (approx. 220 Mio.) The amount of biodiesel that can be produced from lipids from sewage in NWE can be calculated with the inhabitant specific amount of 16 g FOG (Fat/Oil/Grease)/(PE·a). It can be assumed that 65% of the extractable lipids are suitable for biodiesel production (Siddiquee and Rohani, 2011a, 2011b). With a mass conversion coefficient of 0.235 kg biodiesel/(kg saponifiable lipids) (Patiño et al., 2018), the quantity is

251,000 Mg/a. However, not all lipids in the influent of the STP are converted into biomass. Assuming a factor of 10%, the recoverable amount of biodiesel would be 25,100 Mg/a (see chapter 5 in the State of the art Report, 2019). The correctness of this factor will be determined in the further course of the project in the pilot-scale trials.

5.3 Market price for conventional products

The market situation for vegetable oil and biodiesel is critical in the European Union and internationally, because of the constantly growing production of palm oil. Figure 5-5 shows the price intervals between the most important vegetable oils.

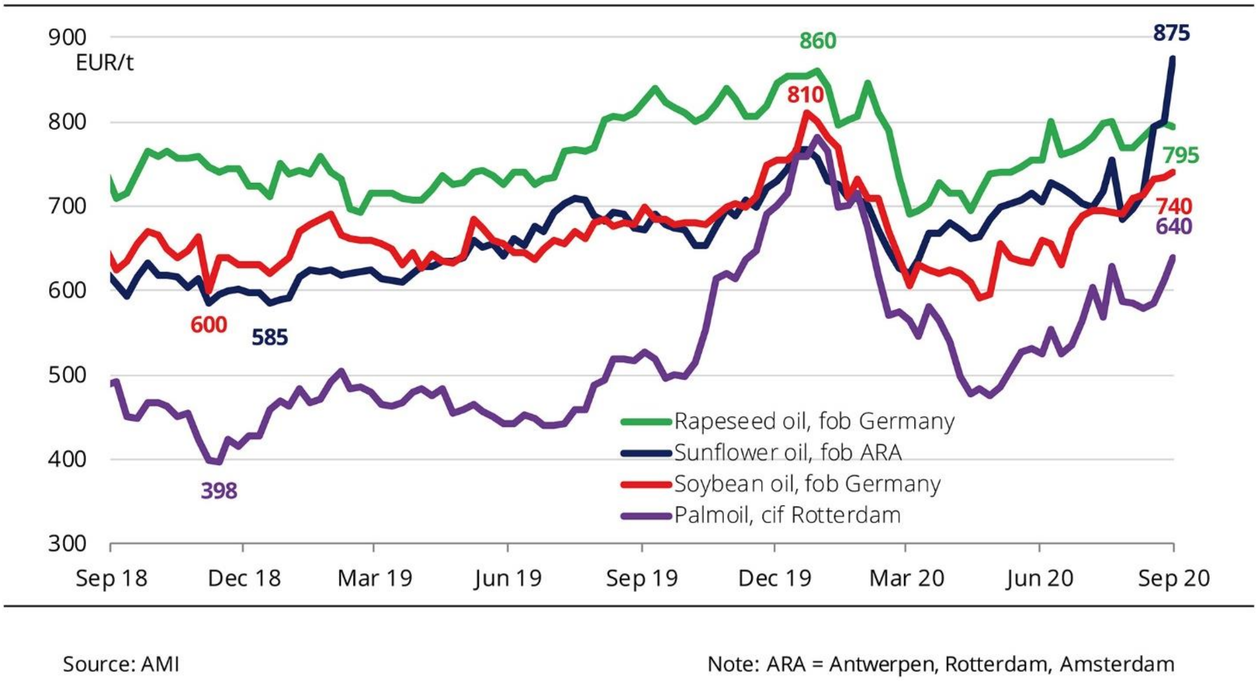

Figure 5-5: Prices of vegetable oils (source AMI); (Ufop, 2020)

Wholesale prices for biodiesel have seen a sharp rise since 2014, from 70.5 euro cents per litre to recently 91.6 euro cents per litre. This indicates an increase of approx. 30%. The price in 2019 exceeds the level a year ago by 27%.

Additionally, higher demand for biodiesel has driven up the wholesale prices for rapeseed oil, which recently exceeded the price of 80.0 euro cents per litre. Only the prices for agricultural diesel have remained at a relatively constant level of around 76 euro cents per litre, since July 2019 (Ufop, 2019).

5.4 Market potential for biodiesel from sewage

The potential demand for sewage-derived biodiesel can be estimated from the current biodiesel production statistics in the NWE-countries (Eurostat, 2019a). Since only parts of Germany and the Netherlands belong to the NWE area and only there statistical data at the country level are available, the actual biodiesel production and demand could be lower than estimated. For the assessment, it is assumed that the sewage-derived biodiesel is of the same quality as the fuel produced from conventional feedstock.

Over 60% of the total European biodiesel production is based in the NWE area; today, within the region around two-thirds of the fuel are produced in Germany and France. In 2016, the biodiesel production in the countries (partially) belonging to the NWE area was 7.7 Mio. tonnes. Assuming that the total of the produced fuel was consumed within the region, this number corresponds to the potential demand for sewage-derived biodiesel. Since in Germany diesel fuel is in the centre of current political controversies due to high nitrogen oxides emissions, demand for the fuel might further decrease in the future.

The potential sewage-derived biodiesel supply amounts to 25,100 Mg/a, which is equivalent to 0.31% of the annual biodiesel production in the NWE area. At first glance, this seems rather low. Here it is important to highlight that this was a preliminary calculation considering only the lipid extraction from activated sludge. If (not dissolved) lipid waste from the oil-water separator in the inlet of the sewage treatment plant and primary sewage sludge (which generally has a higher lipid content than activated (secondary) sludge) would have been considered in the assessment, the biodiesel production potential should increase significantly. (Frkova et al., 2020) calculate for the European Union that up to 28% of the European biodiesel market may be covered from sewage-derived lipids, taking activated, blended, primary, scum and EWC sludge into account. This sums up to 2 Mio t/a biodiesel.

According to the EU Renewable Energy Directive II (RED II, 2019), every EU Member state has to reach a share of 14% renewable energy until 2020 in its transport sector. Another directive (Fuel Quality Directive, 2016) challenges the mineral oil industry to reduce the greenhouse gas emissions of the sold fuel mix to a certain extent (currently 4% related to the situation in 2010; from 2020 on the reduction has to be 6% related to the situation in 2010). Both regulations create a market for waste-derived biofuels, since these fuels have an advantageous greenhouse gas balance compared to conventional fossil based fuel.

For fulfilling the RED II-aims for greenhouse gas emissions in the transport sector of 14%, apart from the use of E-mobility and conventional biofuels, the use of a certain amount of advanced biofuels is compulsory for each EU member state. According to RED II, advanced biofuels are defined as fuels that are produced from feedstocks listed in RED II Annex IX A. From 2022 on, the share of advanced biofuels should contribute to at least 0.2%; from 2030 it has to be a minimum share of 3.5%. To encourage the production and use of advanced biofuels they count double in the statistic. Thus, an actual share of 1.75% is enough to fulfil the aim of 3.5%. For fuel produced from material according to RED II Annex IX B (used cooking oil and fat), a share of maximum 3.4% is foreseen. This value is set due to limited availability of the feedstock and to prevent misuses like e.g. deliberately contaminating fresh vegetable oil to turn it into waste.

Fuel from sewage sludge would be an advanced biofuel, as the feedstock sewage sludge is listed on RED II Annex IX A. Therefore, a market demand would be ensured, if a competitive price could be achieved in comparison to other fuels from other feedstocks listed on RED II Annex IX A.

Figure 5-6 shows the assessment of end users for the application of biodiesel from sewage with regard to possible customers and application, competitors, quality requirements, drivers and barriers.

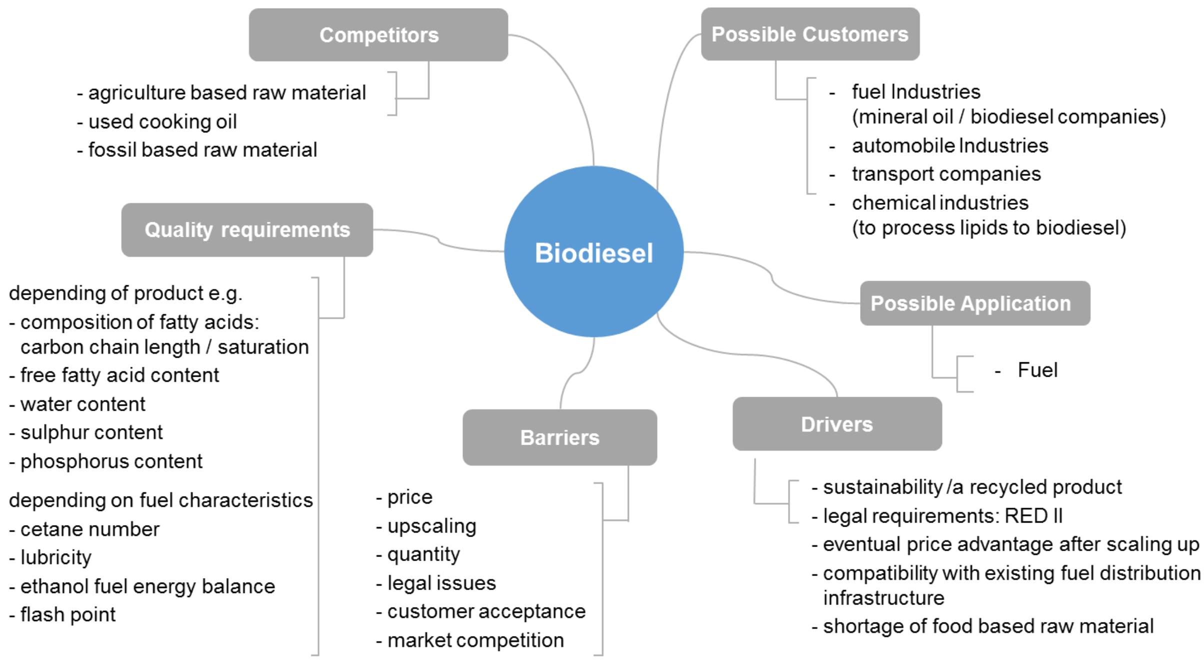

Figure 5-6: Assessment of end users for the application of Biodiesel from sewage

6 Bio-oil

6.1 Production quantities Bio-oil

Pyrolysis oil or bio-oil is a dark brown liquid with a higher energy density than its feedstock, (lignocellulosic) biomass. Currently there are close to 100 fast pyrolysis projects in progress in Europe, and there have been 10 commercial scale plants either build or are under construction.

The commercial biomass fast pyrolysis was first developed in the 1980s in Canada, with the "Waterloo Flash pyrolysis Process" (San Miguel, 2012). Meanwhile the technology has advanced and several players have emerged in Europe with their own technologies for the pyrolysis of lignocellulosic biomass. BTG (Netherlands) and Neste Oil (Finland) use rotating cone reactors, PyTec (Germany) ablative and twin screw reactors, further Fortum (Finland), UPM Biofuels (Finland) and Wellman Process Engineering Ltd. (UK) develop fluidized-bed and circulating fluidized- bed reactors, and Bio Oil Holding NV (Belgium) used twin screw and fluidized bed reactors (Şerbănescu, 2016). In table 6-1 an overview of some operational fast pyrolysis plants in Europe is presented.

Table 6-1: Representative biomass fast pyrolysis commercial operational plants in Europe (Şerbănescu,2016)

Location	Technology provider	Technology	Feedstock	Product
Oldbury (England), 2002	Wellman Process Engineering Ltd.	Circulating fuluidized bed	10 t/h softwood chips	7 t/h bio-oil
Bülkau (Germany), 2006	PYTEC	Ablative rotating disk	6 t/h chipped softwood/straw	3.9 t/h bio-oil
Porvoo (Finland), 2007	Neste Oil	Rotating cone	13 Mt/yr wood res.	5 Mt/yr NExBTL ren. Diesel
Tampere (Finland), 2009	VTT & Fortum	Fluidized bed	10 t/h wood (forest, sawdust)	6.3 t/h bio-oil
Hengelo (Netherlands), 2010	BTG & Empyro	Rotating cone	5 t/h clean wood, org. res. pellet waste	3.2 t/h bio-oil
Jelgava (Latvia), 2013	Fortum	Circulating fuluidized bed	100 000 t/a wood chips	110 GWh(el)/a 213 GWh(th)/a
Laappeenranta (Finland), 2015	UPM Biofuels	Circulating fuluidized bed	0.13 Mt/a wood	100 000 t/a BioVerno Diesel
Joensuu (Finland), 2015	Fortum	Fluidized bed	600 000 m^3/a waste wood	50 000 t/a Fortum Otso® bio-oil

Globally, commercial plants are operating and more are planned to start production within the next two years. Bauer (2017) estimates that the pyrolysis oil production will exceed 500 000 t per year in 2018.

For instance BTG-BTL has announced orders for serval new fast pyrolysis bio-oil plants. In April 2019 an order for a commercial plant in Finland was taken, where 20 Ml/a bio-oil will be produced form sawdust. A further investment of three other plants would be possible (BTG, 2019). In September 2019 BTG announced to be going to construct a fast pyrolysis plant in Sweden. This plant will convert 35 to 40 Mt/a clean waste wood into bio-oil, which will be processed into an advanced bio-fuel by in the oil-refinery in Lysekil (BTG, 2019 II).

6.2 Collectable quantity at the sewage treatment plant

Waste water treatment plants are supplied with daily and stable source of biomass. Necessary are fine screens to harvest the cellulose rich sievings from the sewage and pyrolysis installation. Investments in sieving screens take place, for instance when the STP needs to expand. Screening installations are more common in the Northern part of Europe. In the Netherlands several commercial sized screening installations are already present. The waterboards that responded to our questionnaire, noted that possible future investments in test size and commercial sized installations are on the planning.

In the previously released state of the art report (WIW, 2019), an estimation is made for the production quantity of bio-oil for the North-West European market. The figure is based on a sewage load of 280 M PE. For the calculation of the producible pyrolysis products it was assumed that the following quantities are produced during pyrolysis: 6.2 g/(PE·d) bio-oil, 3.7 g/(PE·d) biochar and 3.7 g/(PE·d) acetic acid (Pulsed-Heat, 2019). This results in 636 592 t/a bio-oil, 376 543 t/a char and 380 671 t/a acetic acid.

The yields and properties of bio-oil are highly variable and depend on process conditions. Some of the initially produced materials were very unstable and corrosive with very high organic oxygen contents. It was difficult to separate the bio-oil from the aqueous phase produced in the process. Development efforts have focused on producing bio-oil with oxygen contents of less than 25 wt% of the oil. This allows easier separation and improves the quality of the oil. (Bauer, 2017)

6.3 Market price for conventional products

Although the bio-oil market has not reached full maturity yet, the produced bio-oil is becoming a commodity product with a clear set of specification. The ASTM (American Society for Testing and Materials) has published a standard specification for bio-oils; D7544-12(20017) that specifies two different bio-oil grades for use in various types of fuel-burning equipment under various climatic and operating conditions. The properties of the two ASTM grades are presented in table 6-2. The EU has also created a standard; EN 16900:2017 that specifies two different fast pyrolysis bio-oils for the use in industrial scale boilers (>1MW(th)).

Table 6-2: Table: bio-oil fuel grades ASTM D7544 (Oasmaa, 2015)

Property	Unit	Grade G	Grade D
Lower heating value	MJ/kg, min	15	15
Water content	wt%, max	30	30
Solids content	wt%, max	2.5	0.25
Kinematic visco at 40 °C	mm^2/s, max	125	125
Density at 20 °C	kg/dm^3	1.1...1.3	1.1...1.3
Sulphur content	wt%, max	0.05	0.05
Ash content	wt%, max	0.25	0.15
pH		report	report
Flash point	°C, min	45	45
Pour point	°C, max	-9	-9

According to Bauer (2017) the price of bio-oil is comparable to that of industrial wood chips on an energy basis per dollar basis. Compared to wood chips bio-oil has a clear advantage in ease of handling and reduced storage cost due to its higher energy density. Further price comparison can be made by Canadian bio-oil delivered to the port of Rotterdam in 2014, the price was comparable to that of heating oil in most markets (~2 $ per gallon, 13.8 $/GJ or 15.3 €/GJ) without environmental credits (see Figure 6-1).

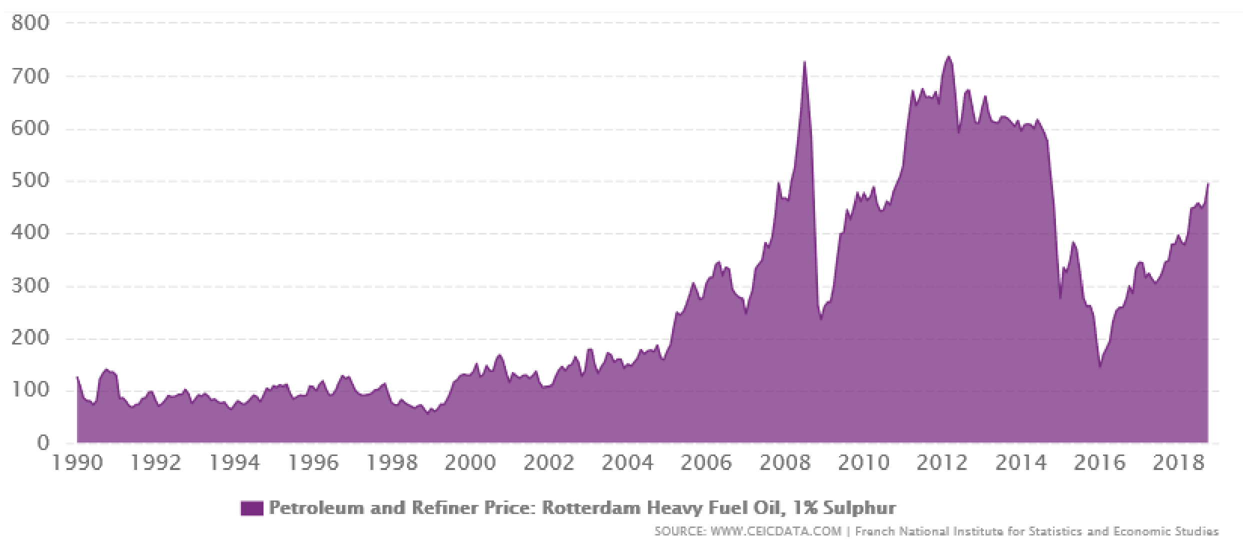

Figure 6-1: Historical price ($/t), Heavy fuel oil, 1%sulpur in the port of Rotterdam (www.CEICDATA.com)

According to Bauer (2017) oil prices would need to rise above 55 $ per barrel for the pyrolysis oil to have a price advantage over fuel oil. Current (2019) oil prices are in the range 50 to 60 $ per barrel. A further estimate for the price of pyrolysis oil (derived from pyrolysis of tires) would be 400 to 600 €/t as it would be compared to the prize of heavy fuel oil (Sousa-Gallagher, 2016).

In figure 6-1 the historical price in $/t for heavy fuel oil (HFO) in the port of Rotterdam is shown. In 2019 the HFO price ranged roughly from 300 to 500 $/t. In Table 6-3 a price comparison on an energy basis for bio-oil is made between three different HFO prices, High (500 $/t), Low (300 $/t) and Average (400 $/t). For the pyrolysis oil a lower heating value (LHV) of 18.0 GJ/t was used (ECN/TNO). For the bio-oil with a LHV of 18.0 GJ/t a competitive price range would be 190…240 €/t.

Table 6-3: Calculate bio-oil price based on HFO on an energy basis

	Heavy fuel oil (HFO)				Bio-oil	
	$/t	€/t	GJ/t	€/GJ	GJ/t	€/t
High	500[1]	556	41.8[2]	13.3	18.0[3]	239
Low	300	333	41.8	8.0	18.0	144
Average	400	444	41.8	10.6	18.0	191

Import cost

The price competitivity of imported pyrolysis oil with fossil fuels for the European market depends on several factors, as was quantified in 2006 by Bradly. The main drivers are the feedstock price and the transportation costs. For a favourable feedstock price, readily available low-cost biomass is necessary. When small tankers are used for the transportation of bio-oil (from Brazil or Canada), the cost of which is estimated at 10.46€/GJ, the biofuels are not competitive with fossil fuels on a price basis. When the imported volume would be sufficient for specialized, low-cost tankers the price would drop to 7.75 €/GJ. At this price the imported biofuels can be competitive with fossil fuels. The 2006 situation is presented in table 6-4.

Table 6-4: Bradly, European Market Study for bio-oil (Pyrolysis Oil) (2006)

Delivered costs:	**€/GJ**	**Prices:**	**€/GJ**
Pyrolysis Oil - small tankers	6.42...10.46	Heavy Fuel Oil	5.53...9.08
Pyrolysis Oil - large tankers	4.82...7.75	Natural gas	6.01...11.50
Char	1.51...2.57	Coal	1.52
Wood pellets Canada	6.5	Pellets	6.8...7.4

[1] 1$=0.9€
[2] https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
[3] ECN/TNO, Phyllis2 database #1174 (23-11-2019), 18 MJ.kg at a moisture fraction of 20 wt%

Production price

The largest contribution to production cost of pyrolysis oil is the price of the biomass used as feedstock. Due to the large feedstock price dependency, regions with an extensive reserve of low-cost biomass can become export centers for pyrolysis oil, such as Canada (sustainable forests), Brazil (bagasse from sugar cane), South Afrika (bagasse from sugar cane), the Baltic Region (forest waste) and Ukraine (energy crops) (Bradley, 2006).

In figure 6-2 BTG-BLT has presented operational costs per gigajoule of pyrolysis oil produced as a function of the cost price of the biomass on a wet basis for 15 and 40 wt% moisture. It is based on conservative values of the other operational costs, including personnel, maintenance and utilities, and a depreciation period of 10 years. The reason for also indicating the influence of the moisture content is that, in case the moisture content of the biomass is lower than 55%, BTG-BTL pyrolysis plants produce excess steam and electricity which can be sold. Steam is valued at 8 [€/GJ] and no green incentives or subsidies are included in this calculation.” (BTG-BTL, 2019)

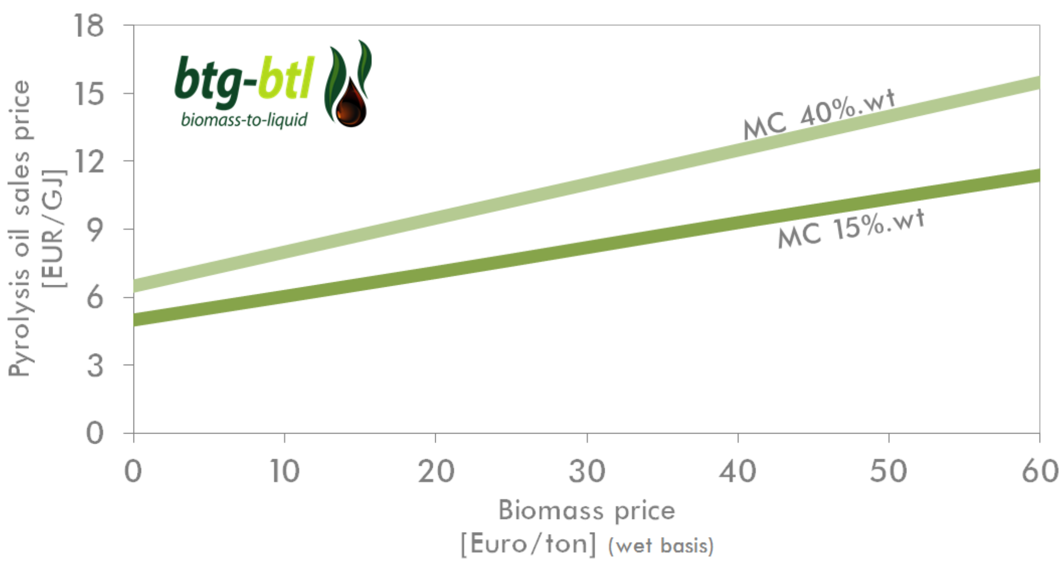

Figure 6-2: Dependence of the sales price of bio-oil on the biomass price (BTG-BTL, 2019)

6.4 Market potential for bio-oil from sewage

The bio-oil derived from sewage (via cellulose screens) can use the same market as the current bio-oil on the market. The bio-oil from sewage differs slightly than that, originating from (waste) wood, since it is based on paper, and thus contains less lignin. Applied CleanTech, who did a demo on the STP of Aarle-Rixtel in the Netherlands reports that pyrolysis oil from cellulose screenings differs from wood derived bio-oil, its smell is not aromatic and it can be diluted in Diesel. (Becker, 2014).

The produced bio-oil has several potential applications.

1) **Process heat and electricity**. The bio-oil will first be used in industrial applications, as a replacement for heavy fuel oil. It requires some modifications to equipment to allow its use in smaller generators and combustion engines. (Bauer, 2017).
2) **Transportation**. The bio-oil obtained from fast pyrolysis can be stabilized and improved through a variety of techniques to produce fuels that are more compatible with current equipment and infrastructure. It can be potentially blended with biodiesels and other fuels" (Bauer, 2017).
3) **Chemicals**. The bio-oil can be used as a source of useful chemicals. The bio-oil contains valuable substituted phenols and aromatics that can potentially be separated and sold at a significant premium over fuel. (Bauer, 2017) Several groups are pursuing this option including Ensyn, UOP, Anellotech and others.

In 2021 the Renewable Energy Directive II (RED II) will take in effect. The RED II proposes a set of policy measures to archive a 27% renewable energy share from energy consumed by the electricity, heating and cooling (EHC) and transportation sectors by 2030 (ICCT, 2017). In the RED II possibilities for applications of pyrolysis bio-oil as a renewable fuel are listed; these would be the heating, electricity and cooling (HEC) or after conversion to an advanced bio-fuel in the transportation sector.

RED II discusses advanced bioenergy, that is produced from lignocellulosic feedstocks, non-food crops, or industrial waste and residue stream and has low CO_2 emission or high green house gas reduction, is compatible with existing infrastructure and reaches zero or has a low indirect land use change (ILUC) impact (fuel versus food debate). The pyrolysis process using one of these feedstocks can produce an intermediate bioenergy carrier.

This intermediate bioenergy carrier (bio-oil) can be either used as a replacement for heavy fuel oil or natural gas in the EHC sector, to reduce green house gas emissions. Further the bio-oil can be converted, for instance by means of co-processing in an (petrochemical) oil-refinery, to an advanced biofuel, that is useable in the transportation sector (see also chapter 5.4). In table 6-5 the size of the different market application is presented in million ton oil equivalent and PJ for the EU in2016.

In several countries there are incentives that can help bio-oils/fuels to bridge the price gap with fossil fuels. For instance the SDE+ subsidy in the Netherlands or the Renewable Heat Incentive in the UK. The RED II and incentives are one of the main drivers for this market.

Table 6-5: Yearly EU energy consumption for industry and transportation in 2016

	Mtoe	PJ
Space and process heat[4]	193.6	8 105
Electricity[4]	73.3	3 068
Cooling[4]	7.2	301
Transportation (oil derived)[5]	389.4	16 300

Process Heat

Pyrolysis Oil is combustible but not flammable, ignites and burns readily when properly atomized, and once ignited burns with a stable, self-sustaining flame (Bridgewater, 2004). From these starting points industrial scale burners have been developed by Dreizler (Germany), Stork Thermeq (the Netherlands) and Oilon (finland). For those developed, the smallest burners are in the range of 1 MW(th) (Letho, 2013). The adaptation needed to use bio-oil in these burners would be that all parts in contact with the bio-oil should be replaced with at least RVS 304, due to the acidic nature of the fuel. The suitability of gaskets and instruments also needs to be checked (Letho, 2013).

On several locations in Europe, commercially produced bio-oil is being combusted in burners to replace fossil fuels. For instance Fortrum Power & Heat (Finland) who produces pyrolysis oil in its Valmet plant, and partially sell the oil to external customers and also uses the bio-oil in its own plants to replace heavy fuel oil (Oasmaa, 2015). The Empyoro plant in the Netherlands is supplying the dairy production plant of Royal Friesland Campina with bio-oil. The bio-oil is being used in a boiler to replace natural gas. The plant's direct carbon emissions have dropped by 15%, and an amount of 10 million m^3 of natural gas are saved every year (btg-btl). In table 6-6 other industrial sized bio-oil burners with their thermal capacities are presented.

Table 6-6: Locations industrial sized bio-oil burners with their thermal capacities (Sikanen, 2016)

Location	Capacity MW(th)
Fortum, Joensuu, Finland	10
Savon Voima, Iisalmi, Finland	10
Fortum, Vermo, Finland	50
E.ON, Karlshamn, Sweden	174

The emissions from the combustion of bio-oil are very dependent on the original levels of solids, water, sulfur and nitrogen in the fuel. Typical the emissions are between those of light fuels and the lightest heavy fuel oil. There are practically no SO_2 emissions from bio-oil generated in the combustion. The NO_x emission from bio-oil combustion mainly originates from fuel-bound nitrogen (Letho, 2013).

[4] Mappingand Analysis of the Current and Future (2020-2030) heating/cooling fuel deployment (fossils/renewables), Fraunhofer and Alia, 2016

[5] TERM1, Final energy consumption in Europe by mode of transport, (03-12-2019)

For the bio-oil from cellulose screenings, it is important that the bio-oil would receive product status. Otherwise its combustion would be considered the incineration of a waste product, and more stringent emission regulation would apply in the environmental permit. This would lead to a more expensive flue gas emission treatment installation.

Solids content in the fuel will add to additional dust. According to Letho, (2013) the majority of the particles are typical incombustible material. The boiler or furnace used must be able to handle the dust load, that is an order of magnitude larger than heavy fuels. Therefore it is also recommended to reduce the solid particle content in bio-oil to <0.1%.

Current burner designs are quite sensitive to the changes in the quality of bio-oil. This may cause problems, in ignition, flame detection and flame stabilization. To create more reliable bio-oil combustion systems, that can operate at high efficiency, bio-oil grades should be standardised for combustion applications (Oasmaa, 2015).

Electricity

Generation of electricity from bio-oil can be done using gas turbines or diesel engines. Due to polar components present in the bio-oil, it does not mix readily with hydrocarbons, like biodiesel.

Diesel engines are widely used in power production, either as a medium speed engine (350-900 rpm, with a power output of 1…15 MW) or slow speed (90-150 rpm 10…50 MW) (Solantausta, 1994). The medium- and slow-speed diesel engines are known to be able to operate on quite low grade fuel oils. Pyrolysis oil with its high water and oxygen content, make it difficult to ignite. The viscosity of the bio-oil is higher than that of diesel, and its acidity could affect materials and maintenance intervals (Solantausta, 1994).

Wongkhorsub (2013) performed test using pyrolysis oil from plastic and tires in a multi-purpose agricultural direct injection diesel engine (Kubota ET-70). They found that pyrolysis oils were both technically and economically able to replace the diesel oil. Further the engine could be modified to follow ther combustion condition of the plastic oil.

BTG experimented with an one-cylinder, 20 kW(el) diesel engine that was adapted for pyrolysis oil. A stainless steel fuel injection system and different measures to overcome the difficult and slow ignition behavior of the pyrolysis oil were used (v.d. Beld, 2013).

BTG-BTL expects that the market introduction of diesel engines that can operate on pyrolysis oil in the coming years. This would open a large market for the sale of pyrolysis oil as these engines can be used for both heat and power applications on ships (BTG).

Transportation

Fast pyrolysis came to the attention of the biofuel community because it produces high yields of liquid bio-oil. The goal of the development effort is to use this hydrocarbon rich bio-oil to produce a fuel that could replace crude oil as starting material for transportation use (Bauer, 2017). For using the bio-oil in the transportation sector to replace diesel, it needs upgrading to an advanced bio-fuel. The pyrolysis could be viewed as a pre-treatment step to create an effective energy carrier for a second generation fuel.

The bio-oil produced from fast pyrolysis can be stabilized and upgraded by a variety of techniques including separation, derivatization, hydroprocessing, and other techniques to fuels more compatible with current equipment and infrastructure. The U.S. government's NREL lab estimates the minimum selling price per gallon of a drop-in fuel made from current fast pyrolysis oil is about $2.53 per gallon (0,74 €/l). (Bauer, 2017)

Upgrading bio-oil to fuel is currently being done on a commercial scale by co-processing it in an existing refinery. Since 2015 UPM Biofuels is operating a commercial scale Biorefinery in Lappeenranta (Finland), producing 120 M liters per year of renewable diesel from forestry residues pyrolysis oil (UPM). Further BTG-BTL is building a commercial scale 40 000 t/a wood waste pyrolysis plant in Sweden, that will be operational in 2021. The produced bio-oil will be transported to a refinery in Lysekill, for upgrading to fuel to supply 15 000 family cars on a yearly basis.

Chemicals

Bio-oil can also be used as a source of useful chemicals. The bio-oil contains valuable substituted phenols and aromatics that can potentially be separated and sold at a significant premium over fuel. There are several groups pursuing this option include Ensyn, UOP, Anellotech, and others (Bauer, 2017).

When the price of oil rises to over $60 per barrel, advanced pyrolysis technologies may make more economic sense and may be more widely adopted. Cost reduction and higher carbon yields are the main targets of continued research efforts. However, these are coming at the price of increased complexity that may make operation difficult. Development for improved methods for upgrading the pyrolysis products to chemicals may also help pyrolysis process economics; however, it will be difficult to justify these costs for smaller plants. (Bauer, 2017)

Pyrolysis oil from sewage

For pyrolysis oil from sewage the most obvious application would be co-combustion to replace fossil fuels on an external location to generate process heat. According to Becker (2014), the pyrolysis oil from sewage (cellulose screenings) is mixable with diesel, making its application in diesel engines easier. Sufficient scale and constant availability is needed to supply industrial burners. Waste water treatment plants could, due to its continuous influent of biomass offer a stable feedstock supply. Potential customers for this application would be industrial companies with sustainable ambitions who currently rely on fossil fuel for their process heat.

The EU has published the EN 16900 norm for bio-oil from fast pyrolysis, defining grades for the combustion in industrial burners. Bio-oil with a consistent quality, with a low fraction of water, a low solid content and a reduced acidity would be favorable.

A compatible price for the bio-oil would be needed, in comparison to heavy fuel oil. Otherwise environmental credits could give the bio-fuel an edge. Legislation in the form of the RED II could also be a driver for the application of bio-oil.

A potential barrier is the declaration of a product status for sewage bio-oil. Without the product status the bio-oil be categorized as waste, instead of biomass, since it originates from a lignocellulosic source. Otherwise the transportation movement, and the receiving company would be needing a permit to handle waste. Further the emission limits for the flue gas imposed in the environmental permit would be more stringent for waste incineration than biomass combustion. This could also endanger a possible governmental subsidy for the use of a green fuel to compensate the higher bio-oil price.

The need for burner modifications, and the higher dust load from the combustion of bio-oil compared to HFO, which needs to be removed from the boiler could also be a potential barrier.

The main drivers for this market is the sustainability. Figure 7-1 shows the assessment of end users for the application of bio-oil from sewage with regard to possible customers and application, competitors, quality requirements, drivers and barriers.

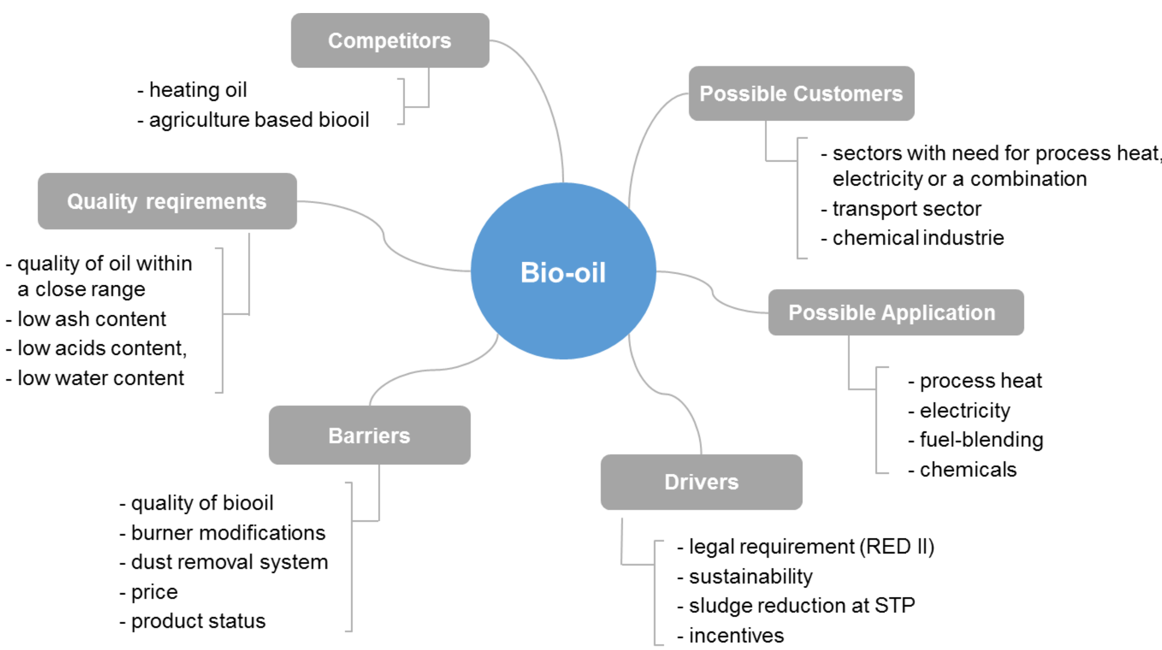

Figure 6-3: Assessment of end users for the application of bio-oil from sewage

7 Activated biochar

7.1 Production quantities

First of all a distinction has to be made between biochar and activated biochar. These are two different products with two different markets. Biochar is used in agriculture to improve soil quality. Activated biochar or activated carbon is widely used to remove dissolved- and particle impurities.

The global production size of biochar was 280,000 t/a in 2015; the market is predicted to grow to over 800,000 t/a in 2025 (Bauer, 2017). The demand for activated biochar was estimated at 395,300 t/a in 2018 (Market Research Report, 2019). The global activated carbon consumption has kept growing to approximating 1.437 million tonnes in 2014. The world's demand for activated carbon is expected to hit 1.733 million tonnes in 2017 (China Activated Carbon Industry Report, 2015). A quarter of the activated carbon produced and sold worldwide is used in water and sewage treatment facilities (Elemente, 2016).

7.2 Collectable quantity at the sewage treatment plant

In chapter 6.1 and in the previously released state of the art report (WIW, 2019) an estimation is made for producible pyrolysis products for the North-West European market. Besides bio-oil and acetic acid there is a collectable amount of 376,543 t/a bio char. With further processing activated bio char can be produced. The activated carbon produced will be a powdered activated carbon (PAC). The amount of activated carbon is about 50-60% of the amount of biochar for sewage sludge (Hagemann et al. 2019), which results in 188,000 to 226,000 t/a activated biochar. This is a considerable amount looking at the demands for activated carbon.

One of the most obvious applications is the use for removal of pharmaceuticals and other organic micropollutants from sewage. Applying the activated carbon in the treatment process itself would simplify complying with quality requirements and regulations. The amount of activated carbon to be produced from sievings (1.8 to 2.2 g/PE/d) is slightly less than the amount needed for removal of micropollutants (20 g PAC/m^3 and 0.15 m^3/PE/d which is 3 g/PE/a).

7.3 Market price for conventional products

The costs for fossil based activated carbon are between 1.5 and 2.0 €/kg (Baumgarten et al., 2015), (China Activated carbon industry report, 2015), (Pyreg, 2019). When agriculture based carbon is used as raw material the prises rises due to the higher cost of raw materials. Current costs for PAC incl. transport but excl. VAT for the Netherlands and Germany are 2 €/kg, respectively € 1.5 €/kg.

7.4 Market potential for (activated) biochar from sewage

Biochar is used in agriculture to improve soil quality. Soil water retention properties, saturated hydraulic conductivity and nutrients availability increase with the application of biochar. Biochar application reduced CO_2 respiration, nitrous oxide and methane production, and decreased dissipation rate of herbicide in the soil (Pramod et al., 2010). Biochar can also be applied in the production of polymers and building materials. Although biochar has a large existing market, for the market potential we will focus on activated biochar.

Activated biochar has a range of sectors where it is used in different ways. It is widely used in sewage treatment plants and potable water purification facilities where it is used to remove dissolved- and particle impurities. It is used in manufacturing and greenhouse industries to remove toxic gases, odours and dust particles. It is applied to use in the automotive industry, food and beverage processing and pharmaceutical industries. It can even be bought by consumers for personal consumption where it claims to have health benefits. Of course these markets have high quality requirements for the activated carbon.

On the basis of product type, the activated carbon market is categorized into powdered activated carbon (PAC) and granular activated carbon (GAC). PAC is the most common used due to its high adsorption capacity. In 2018, PAC accounted for more than 60% by volume of total product manufactured in the world. Rising demand and stringent environmental regulations are drivers for the application of activated carbon. GAC is generally manufactured from carbon rich organic raw materials, such as coal and coconut shell charcoal. GAC have regenerating properties that make it very popular. However, the iodine number (I.e. the activity) of regenerated activated carbon reduces after regeneration. GAC is often used in air treatment, especially in mercury and chlorine removal process and municipal water treatment plants. (source: https://www.grandviewresearch.com/industry-analysis/activated-carbon-market)

Water treatment technology is gaining prominence all over the world. Companies are trying to adopt environment friendly and efficient water disposal techniques, which has increased demand for activated carbon over the past few years. In year 2018, consumption of the product in water treatment application has reached more than 40% of the total volume manufactured in the world. (source: https://www.grandviewresearch.com/industry-analysis/activated-carbon-market)

In food and beverage sector, activated carbon is consumed in processes such as removal of contaminants or impurities such as colour and odour from sweeteners, food liquids, syrups, beverages, glycerin, and amino and organic acids. Growing demand for processed foods and beverages is a major factor expected to drive the market in near future. The demand for activated carbon in pharmaceutical and medical was about 0.1 Million tonnes in 2018. The product is used for purification of raw material compounds, kidney machines, nursing supplies, and respirators. Increasing population and health concerns are expected a rising demand. (source: https://www.grandviewresearch.com/industry-analysis/activated-carbon-market)

Barriers for the application of activated biochar are legal requirements. The manufacturer of activated carbon has to register his product under the REACH Regulation and join the responsible REACH consortium, if the amount of activated carbon exceed one tonne per year (Hagemann et al. 2019). The quality of the activated carbon depends on the feedstock. Activated carbon based on woody residues has a similar good elimination performance with regard to DOC and micropollutants as reference carbon, as well as a similar specific surface.

The degree of activation is decisive. Activated carbon based on sewage sludge shows a lower performance, higher dosages are required. Organic pollutants are practically completely destroyed during the production/reactivation of activated carbon. However, minerals and metals are enriched. Further studies are required to determine whether these will be washed out again later (Hagemann et al. 2019).

First results on the elimination performance of activated carbon based on biochar from sieving shows that 65% of the bio char can be activated. The activated biochar has a mineral fraction of 6.9 wt%. The adsorption capacity is lower in comparison to a reference PAC which is used at a STP of the Waterschap Vallei en Veluve. The adsorption capacity of activated carbon based on biochar from sieving depends on the chemicals, e.g. diclofenac: 23%, bezotrazole: 95%, cabazepine: 50% (WSVV, 2020).

The main drivers for this market is the sustainability. The production of activated carbon is often e.g in emerging markets not a clean business. It also has to be transported over long distances and is often based on fossil raw materials. The DWA working group KA-8.6 "Use of activated carbon in sewage treatment plants" (DWA, 2016) calculated a CO_2 footprint of 11 to 18 tonnes of CO_2 equivalents per ton of activated carbon based on lignite or hard coal or of 5 to 7 tonnes of CO_2 equivalents per ton of activated carbon for coconut shell activated carbon.

A further advantage is the direct use at the STP for removal of organic micropollutants. In this case regulations and requirements will be more easily met, especially when the activation of the biochar can take place on the premises of the STP. Probably an End of waste (EOW) status and a Reach declaration are not needed.

Figure 7-1 shows the assessment of end users for the application of biochar from sewage with regard to possible customers and application, competitors, quality requirements, drivers and barriers.

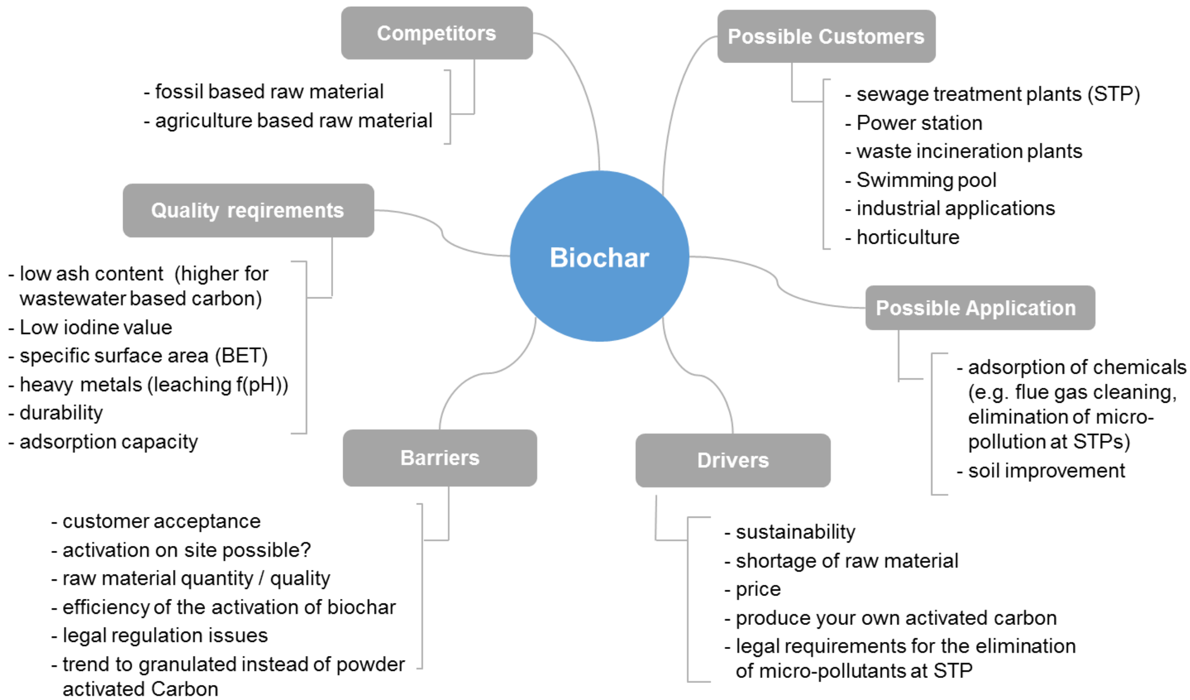

Figure 7-1: Assessment of end users for the application of biochar from sewage

8 Acetic Acid

8.1 Production quantities

Acetic acid is an important industrial chemical for the production of polymers such as polyvinyl acetate or cellulose acetate. At STPs it is used as external carbon source to improve biological P-elimination, denitrification, PHA production, co-substrate digester. Global demand in 2014 was around ten million tonnes per year (Röper, 2020). Acetic acid for industrial purposes is usually obtained by the carbonylation of methanol or by the oxidation of acetaldehyde.

Bio-acetic acid (wood vinegar) can by produced by slow pyrolysis. The properties of pyrolysis products are highly dependent on the feedstocks (e.g. wood) and process conditions. Wood vinegar is an aqueous fraction containing organic acids but also small quantities of e.g. bio-oil and tar. Wood vinegar is produced and commercially used in China, Indonesia, Malaysia, Brazil, and Chile. (Bauer, 2017). The wood vinegar market, in terms of value, is projected to reach around USD 6 Million by 2024, at a Compound annual growth rate of 7.6% from 2016 to 2024 (Market research outlet., 2017). The European market is small (estimated around 1 to 1.5 M$ per year).

8.2 Collectable quantity at the sewage treatment plant

In chapter 6.1 and in the previously released state of the art report (WOW! - State of the art Report, 2019) an estimation is made for producible pyrolysis products for the North-West European market. Besides bio-oil and bio char there is a collectable amount of 380,671 Mg/a aqueous fraction containing organic acids (7% solution).

8.3 Market price for conventional products

The market price of acetic acid is estimated to 500 €/t acetic acid (based on 100% acetic acid). Higher prizes can be achieved for wood vinegar (see Table 8-1). The current wholesale price of wood vinegar on the Asian market is about $4 per gallon respective 900 €/t (Bauer, 2017). The extent to which comparable prices can be achieved for acetic acid derived from waste water depends on product quality. No experience is available so far.

At STPs besides acetic acid different external carbon sources can be used. In Table 8-2 are prices for different external carbon sources listed. The produced acetic acid derived from waste water has high water content of 93%. This has to be taken into account when comparing prices.

Table 8-1: Price for conventional acetic acid and wood vinegar, wood vinegar (internal survey WiW mbH, 2020)

Material		Price [€/t]
acetic acid (based on 100%)	based on fossil raw materials	500
wood vinegar	based on renewable raw materials	900

Table 8-2: Price for different carbon source for STP (internal survey WiW mbH, 2020)

Material	CSB-concentration [mg/l]	Price [€/t CSB]
methanol	1,500,000	200
glycerin	950,000	250
Brentaplus (mixture of alcohols, saccharides, proteins)	1,000,000	400

8.4 Market potential for acetic acid from sewage

There are the following market potential for the use of acetic acid from sewage:

- sewage treatment plants as carbon source
- agriculture as pesticide (wood vinegar)
- production of hydrogen / hydrocabons (C_xH_y) (research)

Acetic acid can improve the denitrification and biological P-Elimination at STPs. The addition to the digester increases the gas production. For PHA production in the first process step also acetic acid can be used. The application will be tested in the WOW! Project. The use of the aqueous fraction with acetic acid directly at the sewage treatment plant is the most appropriate solution.

Wood vinegar has been used in Asia for several decades as an agricultural chemical. There are numerous reports that it improves plant growth and is a "natural" method for insect control. It is of interest to organic farmers. In Europe, the commercialization of biological control agents including wood vinegar is practically impossible for small to medium enterprises (SME), if the registration procedure, developed for the registration of synthetic chemicals, cannot be modified (Tiilikkala, 2010). The quality requirements represent a major challenge for the use of acetic acid derived from sewage. The aqueous fraction includes beside organic acid phenolic compounds, ester, acetals, ketones, formic acid, and many others. These minor components in the wood vinegar may be critical to many of the applications of the material. They also can present problems because of their potential toxicity" (Bauer, 2017). It is therefore more difficult to use in this area.

The main drivers for this market is the sustainability and the direct use at the STP. Figure 4-4 shows the assessment of end users for the application of acetic acid from sewage with regard to possible customers and application, competitors, quality requirements, drivers and barriers.

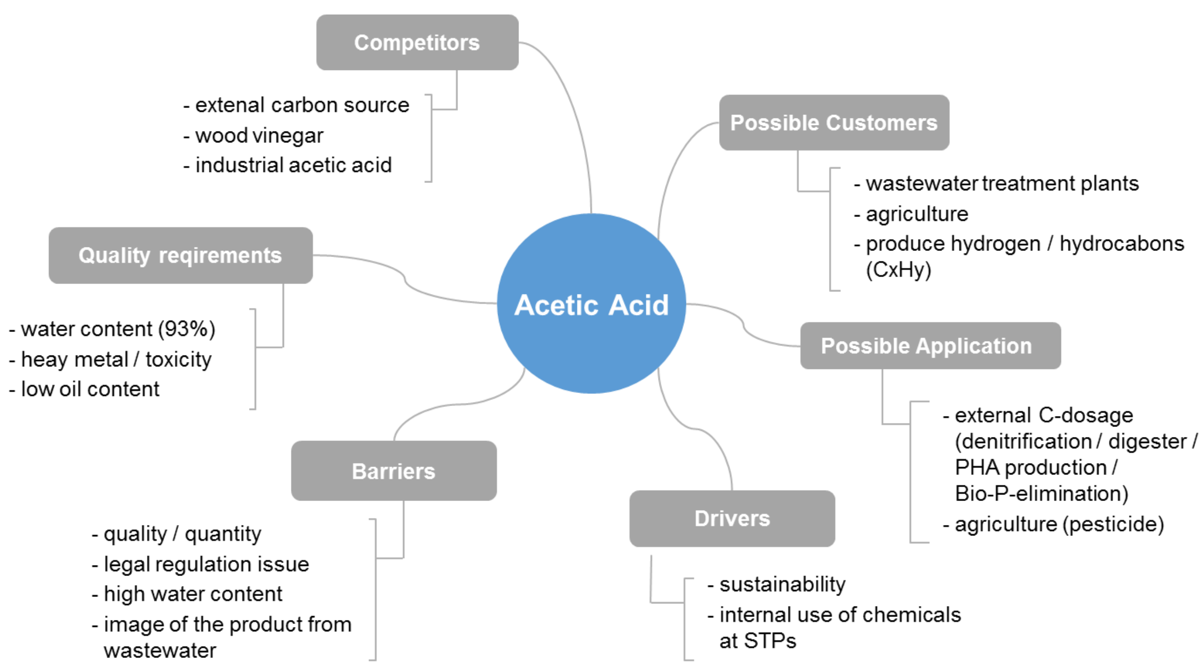

Figure 8-1: Assessment of end users for the application of acetic acid from sewage

9 Conclusions

This study addresses challenges and possibilities for transition in the urban water cycle, where CBEs are recovered from sewage and used as a raw material for new products or as alternative to fossil sources based products. Sewage has a high potential as a possible feedstock because of its disposal necessity, low cost as raw material and expected constant availability. The recovery of the five CBEs has only a minor influence on the effluent concentration of the sewage treatment plants. But with the integration of CBE recovery the COD-balance of the STP is changed. Carbon which is converted into biogas or respired is then converted in carbon based products with a higher value in comparison to digester gas.

Until today, supply of the considered five CBEs from sewage has not been realised in industrial scale and consequently, a market uptake of those materials does not occur yet. However, it is possible to estimate from results of laboratory and pilot plant operation how much of each product could be produced at NWE's sewage treatment plants in the future (see Figure 8-1). Basically, the five CBEs are won from different shares of the COD, but especially the PHA-plant and the pyrolysis use a similar input source. So the total production potential for all products cannot just be added. Furthermore, Figure 8-1 shows the possible share of the five CBEs produced at NWE's STP's at the worldwide market. The share varies between 0.27% for acetic acid and 339% for PHA (see also Table 12-1). The market research shows that especially PHA and activated biochar can make a contribution to the worldwide market. The market price for comparable conventional products based on both fossil raw materials and renewable raw materials was determined and gives an estimation of the sales revenue of sewage based products.

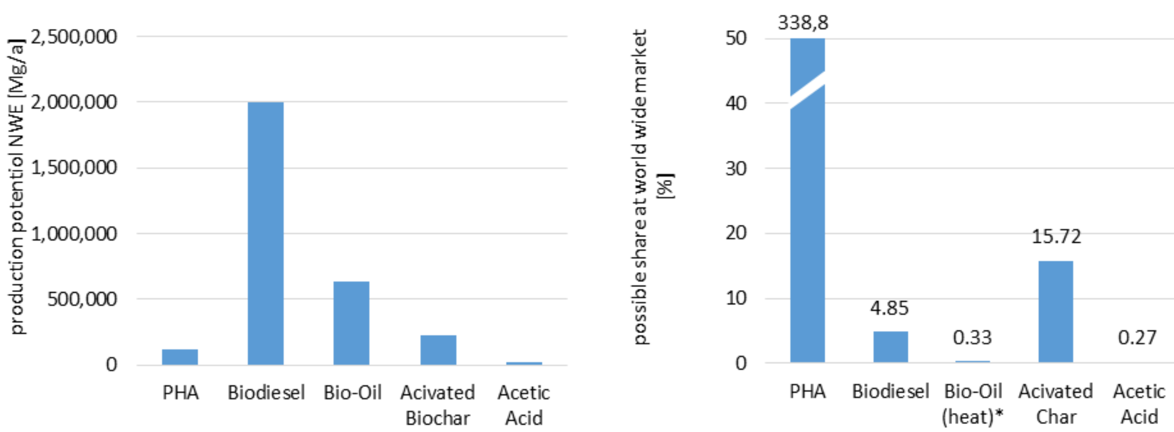

Figure 9-1: Extrapolation of product quantities in NWE for the five CBEs derived from waste water (WOW-state of the art report, 2019) and the share of the world wide production (consumption in Europe)*

One of the biggest challenges is to ensure the required quality standards of the products derived from sewage, as the production conditions vary due to the fluctuating sewage composition as well as the size of the STP. Within the WOW! project, experiences at the pilot plants will be gathered with regard to the achievable product qualities. For the PHA, questions regarding the colour and homogeneity of the product have to be clarified.

For the production of biodiesel, the composition of fatty acid and the chain length is decisive. Bio-oil is directly available as a fuel, and modifications at the burner may be necessary. For activated biochar, it should be checked whether a similar adsorption capacity can be achieved compared to conventional coal. The leaching rate of heavy metals has to be determined. Acetic acid is available as an aqueous solution. A direct application on the sewage treatment plant is target-oriented here. Another option might be the use as substrate for PHA production.

In the discussion with end users the drivers and barriers for the five CBEs were identified. The main barriers are their high prices due to small plant sizes, quality requirements and legal issues for the registration of products derived from sewage. Drivers are the legislation requirements to use more bio-based products, shortage of raw materials and also sustainability. CBEs from sewage can replace a significant amount of fossil carbon. Furthermore, the demand for biobased products continues to rise.

10 Literature

Abels, Jan (2019): Kosten-Nutzen-Bewertung der Gewinnung kohlenstoffbasierter Rohstoffe aus kommunalem Abwasser Masterarbeit, RWTH Aachen.

Bauer (2017): Biomass Pyrolysis Comes of Age, biofuelsdigest.com

Ahmed, A.S., Bahreini, G., Ho, D., Sridhar, G., Gupta, M., Wessels, C., Marcelis, P., Elbeshbishy, E., Rosso, D., Santoro, D., Nakhla, G. (2019): Fate of cellulose in primary and secondary treatment at municipal water resource recovery facilities. Water Environment Federation, DOI: 10.1002/wer.1145

Bauer, L. *(*2017): Biomass pyrolysis comes of age. https://www.biofuelsdigest.com/bdigest/2017/06/08/biomass-pyrolysis-comes-of-age/ Last access on 23.08.2019

Baumgarten, S., di Pofi, M., Lehky, M., Lehmann, C. (2015): PAC-MBR technology for the removal of micro pollutants from municipal wastewater. 11. Aachener Tagung Wassertechnologie, 27. – 28.10.2015 in Aachen, Germany

N. Becker (2014): Installation of SRS (Sewage Recycle System at Aarle-Rixtel WWTP)

B. van de Beld, E. Holle, J. Florijn (2013): The use of pyrolysis oil and pyrolysis oil derived fuels in diesel enginesfor CHP applications, Applied Energy

Bradley (2006): European Market Study for Bio-oil, December 2006

BTG (2019): Mega-order uit Finland voor Twentse energie-innovatie, presrelease (www.btg-btl.com, 02-04-2019)

BTG (2019 II): Zweedse auto's rijden op hout dankzij pyrolyse olie, presrelease (www.btg-btl.com, 16-09-2019)

BTG-BTL (2019): https://www.btg-btl.com

A.V. Bridgewater, S. Czernick (2004): Overview of Applications of Biomass Fast Pyrolysis Oil

H. Chum, A. de Rezede Pinho (2015): Co-processing raw bio-oil and gasoil in an FCC unit (Brazil Bilateral: Petrobras-NREL)

China Activated Carbon Industry Report (2015): https://www.reportbuyer.com/product/694453/china-activated-carbon-industry-report-2014-2017.html (last access 27.08.2019)

DWA (2016): Aktivkohleeinsatz auf kommunalen Kläranlagen zur Spurenstoffentfernung – Arbeitsbericht der DWA-Arbeitsgruppe KA-8.6 «Aktivkohleeinsatz auf Kläranlagen». Korrespondenz Abwasser, Abfall 63: 1062–1067

DWA-Arbeitsgruppe KEK-1.2 (2014): Abwasser und Klärschlamm in Deutschland – statistische Betrachtungen. Arbeitsbericht der DWA Arbeitsgruppe KEK-1.2 Statistik, Nachdruck aus der Zeitschrift Korrespondenz Abwasser, Abfall – 2014 (61) Nr. 12, 2015 (62) Nr. 1

ECN/TNO (2019): Phyllis2 database #1174 (23-11-2019)

Elemente (2016): Customer magazine of the Donau Chemie Group, 2/2016 online: https://www.donau-chemie-group.com/Downloads/DCG_Elemente_2_2016.aspx (last access 18.09.2019)

European Bioplastics (2019): Bioplastic market data, online https://www.european-bioplastics.org/market/ (retrieved 21.02.2019)

European Bioplastics and nova-Institute (2018): Global production capacities of bioplastic 2018 (by market segment) online https://www.european-bioplastics.org/market/ (retrieved 1.03.2019)

R. Escrivani Guedesa, L.S. Aderval, A. Rodrigues Torres (2018): Operating parameters for bio-oil production in biomass pyrolysis: A review, Journal of Analytical and applied Pyrolysis

Eurostat, (2019). Energy Balances - Early Estimates URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_balances_-_early_estimates (accessed 30.11.2020).

Full Quality Directive (2016): Directive 2009/30/EC, 2016

Frkova, Zuzana, Vendittia, Silvia, Herr, Patrick, Hansen, Joachim: Assessment of the production of biodiesel from urban wastewater-derived lipids. Resources, Conservation and Recycling, Volume 162, November 2020, 105044.

Greenea. (2018). Waste based feedstock and biodiesel market in the EU: how new regualtions may influence the market. http://www.greenea.com/wp-content/uploads/2018/04/Greenea-Platts-Geneva-2018.pdf

Hagemann, N., Bucheli, T. D., Schmidt, H.-P., Kägi, R., Böhler, M., McArdell, C. S. (2019) Aktivkohle – made in Switzerland. Abwasser & ARA, Nr. 1/2019, pp. 32 – 38

Hague, T. (2018). EU Biofuels Annual 2018.

ICCT (2017): The European commission's renewable energy proposal for 2030 (2017)

IfBB (2018): Biopolymers, facts and statistics 2018. Production capacities, processing routes, feedstock, land and water use. Hochschule Hannover, University of applied sciences and arts, Fakultät II Maschienenbau und Bioverfahrenstechnik

J. Lehto, A. Oasmaa, Y. Solantausta (2013): Fuel oil quality and combustion of fast pyrolysis bio-oils (VTT TECHNOLOGY 87)

Market Research Report (2019): Biochar Market Size, Share & Trends Analysis Report By Technology (Gasification, Pyrolysis), By Application (Agriculture (Farming, Livestock)), By Region, And Segment Forecasts, 2019 – 2025. Report ID: 978-1-68038-681-3

Market research Report (2017): Wood Vinegar Market (By Manufacturing Process, By Application, By Geography) Global Scenario, Market Size, Outlook, Trend and Forecast, 2015 – 2024. https://www.marketresearchoutlet.com/report/wood-vinegar-market

Natureplast (2019): personal communication

Naumann, K., Oehmichen, K., Remmele, E., Thuneke, K., Schröder, J., Zeymer, M., Zech, K., Müller-Langer, F. (2016): Monitoring Biokraftstoffsektor. 3. Überarbeitete und erweiterte Auflage. Leipzig: DBFZ (DBFZ-Report Nr. 11). ISBN 978-3-946629-04-7.

A. Oasmaa, B. vd Beld, P. Saari, D.C. Elliott, Y. Solantausta (2015): Norms Standards, and Legislation for fast pyrolysis Bio-oils from Lingocellulosic Biomass, Energy&Fuels

Patiño, Y., Mantecón, L.G., Polo, S., Faba, L., Díaz, E., Ordóñez, S. (2018): Effect of sludge features and extraction-esterification technology on the synthesis of biodiesel from secondary sewage treatment sludges. Bioresour. Technol. 247, 209–216. https://doi.org/10.1016/j.biortech.2017.09.058

Pittmann, T., Steinmetz, H. (2016): Potential for polyhydroxyalkanoate production on German or European municipal waste water treatment plants. Bioresource technology 214, S. 9–15. DOI: 10.1016/j.biortech.2016.04.074

PulsedHeat (2019): personal message from PulsedHeat BV. The quantities are based on a mass balance derived from a pyrolysis experiment. Not published.

Pyreg (2019): https://www.pyreg.de/ (last access on 16.09.2019)

RED II (2019): EU Renewable Energy Directive II , 2019

Röper, M. (2020): Die Geschichte der Essigsäureproduktion auf chemanager-online.com. (last access on 30.10.2020)

G. San Miguel, J. Makibar, A.R. Fernandez-Akarregi (2012): New advances in the fast pyrolysis of biomass. Journal of bioased Materials and Bioenergy

C. Şerbănescu, A Oprescu (2016): A short Comparative review of commercial technologies for lignocellulosic biomass pyrolysis in Europe(JoERaP, vol13,issue 4)

Siddiquee, M. N., Rohani, S. (2011a): Experimental analysis of lipid extraction and biodiesel production from wastewater sludge. Fuel Processing Technology. https://doi.org/10.1016/j.fuproc.2011.07.018

Siddiquee, M. N., Rohani, S. (2011b): Lipid extraction and biodiesel production from municipal sewage sludges: A review. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2010.11.029

L. Sikanen (2016): Natural Resources Institute Finland (Luke) 28-okt-2016

Sousa-Gallagher, M (2016): Technological and economical feasibility of a 40,000 t/y tyre pyrolysis plant: results of a H2020 SME Phase 1 study, ETRA conference 18th March 2016

STOWA (2017): PHARIO. Stepping stone to a sustainable value chain for PHA bioplastic using municipal activated sludge. Amersfoort-Niederlande (15). Online https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202017/STOWA%202017-15.pdf (retrieved 18.02.2019)

Transport and Environment (2018). Transport and Environment. https://www.transportenvironment.org/publications/reality-check-10-things-you-didn%E2%80%99t-know-about-eu-biofuels-policy (last access 2019)

Tiilikkala, K., Fagernäs, L., Tiilikkala, J. (2010): History and Use of Wood Pyrolysis Liquids as Biocide and Plant Protection Product. The Open Agriculture Journal, 2010, 4, 111-118

UFOP (2020): Vegetable oil prices under pressure due to Corona. Chart of the week. https://www.ufop.de/english/news/chart-week/archive-chart-week/chart-week-2020/ last access on 01.12.2020

UFOP (2019): Biodieselpreise steigen sprunghaft. Chart of the week https://www.ufop.de/biodiesel-und-co/biodiesel/grafik-der-woche/archiv-grafiken-der-woche/grafik-der-woche-2019/

UPM biofuels: UPM Biofuels - commercial plant in Lappeenranta, Finland (Biofuel Fact sheet)

WSVV (2020): Internal study from the waterschap Vallei en Veluve

11 Abbreviations

ASTM	American society for testing and material
CBE	Carbon based elements
COD	Chemical oxygen demand
EHC	Electricity, heating and cooling
el	Electrical
EOW	End of waste
FOG	Fat, oil and grease
GAC	Granulated activated carbon
HFO	Heavy oil fuel
LHV	Low heating value
NWE	North West Europe
PAC	Powdered activated carbon
PBS	Polybuthylensuccinat
PE	Population equivalent
PE	Polythylene
PHA	Polyhydroxyalkanoate
PHBV	Polyhydroxy-butyrate-co-valerate
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
RED	Renewable Energy Directive
STP	Sewage treatment plant
th	Thermal
WP	Work package

12 Appendix

12.1 Survey by questionnaire: Template

Questionnaire: Market potential of wastewater- based resources

Interreg Project: WOW!
Wider business Opportunities for raw materials from Wastewater

Dear respondent,

As part of the WOW research project funded by the EU, we are working on the recovery of recyclable materials from wastewater. Further information can be found at: http://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/

The purpose of this questionnaire is to get a better insight into the market potential of materials recovered from wastewater.

Thank you for your input.

1. General information

Company	Name		
	Postcode, City		
	Country		
Contact person	Name		
	Telephone		
	E-Mail		
What does your company do? (in relation to the question)			

2. Resource - Please tick the box for the end product for which you want to answer the questions.

	Polyhydroxyalkanoate (PHA)	☐	Bioplastic in general	☐
	Biodiesel	☐	Other	
	Cellulose	☐		
Pyrolysis products	Bio-Oil	☐		
	Activated Carbon	☐		
	Acetic acid	☐		

Raw material commonly used today		
Price for raw material		€/kg

3. Market potential

Production capacity	at your enterprise		t/a
	general, e.g. global, EU (please specify)		t/a
Production volume	at your enterprise		t/a
	general, e.g. global, EU (please specify)		t/a
Market demand	e.g. global, EU, national (please specify)		t/a
Expected annual growth rate (CAGR) or trend			
Current market prices			€/kg

4. Market potential for materials from wastewater

Quality requirements		
Minimum and maximum delivery quantity		
Possible applications		
Possible customers		
Drivers (e.g. legal requirements, shortage of raw material etc.)		
Barriers / main challenges of the application (e.g. customer acceptance, legal issues, price etc.)?		
Competitors	Main competitors	
	Competitive products	

5. Comments

12.2 End user meeting: Template for report

WOW! Product	
Company	
Address	
Homepage	
Contact Person	
Participants meeting	
Date	
Summary meeting	
Production capacity/volume/ market demand	
Quality requirements	
Delivery quantity	
Possible application	
Possible customers	
Price	
Drivers	
Barriers	
Competitors	
Comments	

12.3 Summery market potential

Table 12-1: Extrapolation of product quantities in NWE for the five CBEs derived from waste water (WOW-state of the art report, 2019) and the share of the world wide production

	consumption worldwide Mg/y	production WWTP NWE Mg/y	portion %
acetic acid	10,000,000	26,647	0.27%
activated char	1,437,000	225,926	15.72%
bio diesel (all streams)	41,200,000	2,000,000	4.85%
bio diesel (only conected PE)	41,200,000	25,100	0.06%
bio oill [1)]	194,000,000	636,592	0.33%
PHA	35,887	121,594	338.8%

[1)] production only European Community: fossil fuel consumption use for process und space heating

13 Contribution to this report

NL: Regional Water Authority Vallei en Veluwe, WSVV

DE: Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH, WiW

DE: University of Kaiserlautern, TUK

LU: University of Luxembourg, UL

FR: Natureplast, NTP

DE: REMONDIS Aqua Industry

NL: Pulsed Heat BV, PH

NL: CirTec B.V.