WASTE2ROAD

Biofuels from WASTE TO ROAD transport

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Deliverable Report

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Description of the deliverable content and purpose

Deliverable D5.2 is the public report on identified value chains from biogenic residues and waste fractions to biofuels. The purpose of this report is to provide an overview of the identified and potential commercial value chains and covers the alignment of biogenic wastes, identification of the operating, performance and optimization window of the processing steps, and the understanding of the risks involved. It lays the groundwork for further developments in the WASTE2ROAD project on the development, integration and optimization of the overall value chains.

The WASTE2ROAD project goals, together with the specific objectives for the task related to this deliverable (Task 5.2) are provided in the Introduction (Section 1). Background information (Section 2) is provided on the value chain processing steps and process options. An overview is then provided for the different value chain configurations (Section 3), as well as potential locations (Section 4).

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1. Introduction

The aim of the **WASTE2ROAD project** is to valorise low-cost and abundantly available biogenic residues and waste fractions by developing a new generation of cost-effective biofuels. This is done by taking the entire value chain into account, including waste management and pre-treatment, bio-conversion into bio-liquids using fast pyrolysis (FP) and hydrothermal liquefaction (HTL), and converting bio-liquids into biofuels using intermediate and existing refining processes. The final step is to determine the end-use compatibility of the bio-fuels for road transport applications.

This deliverable D5.2 describes the intermediate results of work package 5 (WP5) entitled 'Value chain integration and optimization, life cycle costing, and techno-economic assessment'. The WP5 targeted objectives are to integrate and optimize at least **4 complete value chains** from waste fractions to biofuels at relevant industrial scale. The treatment and processing steps developed in WP2, WP3 and WP4 to produce valuable liquid biofuels from a range of biogenic residues and waste fractions will be integrated into these value chains. The value chains will address the following aspects:

- **Alignment of biogenic wastes** and volumetric production flows of intermediate bio-liquids and products, feedstock and product specifications, routing and logistics. Blending of intermediate biofuels or products from alternative organic waste feedstock will also be considered.
- **Assessment of integration potential** within each value chain and the benefits of centralized versus decentralized production in modular units.
    - Decentralized production units are expected to be attractive for first separation and pre-treatment of organic waste.
    - The logistical aspects like feedstock diversification, transportation scenarios, year-round availability, intermediate storage and stability of organic waste during storage and transport is considered.
- **Identification and understanding of risks** involved in the value chain, in particular technical and economic related, and the roles of stakeholders in the value chain, including those that may need to be involved outside of the consortium.

The feedstocks selected for this project are listed in Table 1. The general distinction between the two liquefaction technologies, is that fast pyrolysis (FP) is more suited for a dry feedstock and hydrothermal liquefaction (HTL) is best suited for a wet feedstock. This being said, it is possible to use the additional heat produced during pyrolysis to further dry the feedstock, although this will result in less sellable energy in the form of steam or electricity. Likewise, the feedstock used for HTL can be further diluted to the required moisture content or viscosity levels if required. It is important that a feedstock is industrially relevant for it to be used in a value chain.

Table 1: Liquefaction technologies and selected feedstocks. FP = Fast Pyrolysis, HTL = Hydrothermal liquefaction

Feedstocks	Location	Primary Conversion
Roadside grass	Netherlands	FP
Food residue pre-treatment reject from bio-reactor	Norway	FP
FFOM: Organic fraction of municipal solid waste	France	FP & HTL
Solid bio-residues from methane reactors - digestate	Norway	FP & HTL
Contaminated wood 1 (B-wood)	Finland	FP – VTT
Contaminated wood 2 (B-wood)	Netherlands	FP – BTG
Black liquor	France	HTL
Food residues from canteens and restaurants	France	HTL
Sunflower husks	Ukraine	FP
<u>Feedstocks to be confirmed:</u>		
Vinasses	France	HTL

2. Background information on value chain processing steps

The value chain includes feedstock collection and sourcing, feedstock pre-treatment, liquefaction, post-treatment or upgrading, and refining or co-refining of bio-oil and bio-crude into useable fuel product(s), shown in Figure 1. Whenever possible, the by-products produced will be sold as co-products. By-products may include char, steam and electricity. For each processing step, a large number of process options exist. Therefore, the total number of potential value chains is also large. After evaluation of the process options a minimum of four (4) attractive value chains will be developed in-depth.

The value chains are developed from the feedstocks obtained for experimental testing. However, feedstocks available in Europe for valorisation are also included and termed the simulated value chains. By including the simulated value chains, it highlights the opportunities for exploitation of waste fractions for biofuel production throughout Europe.

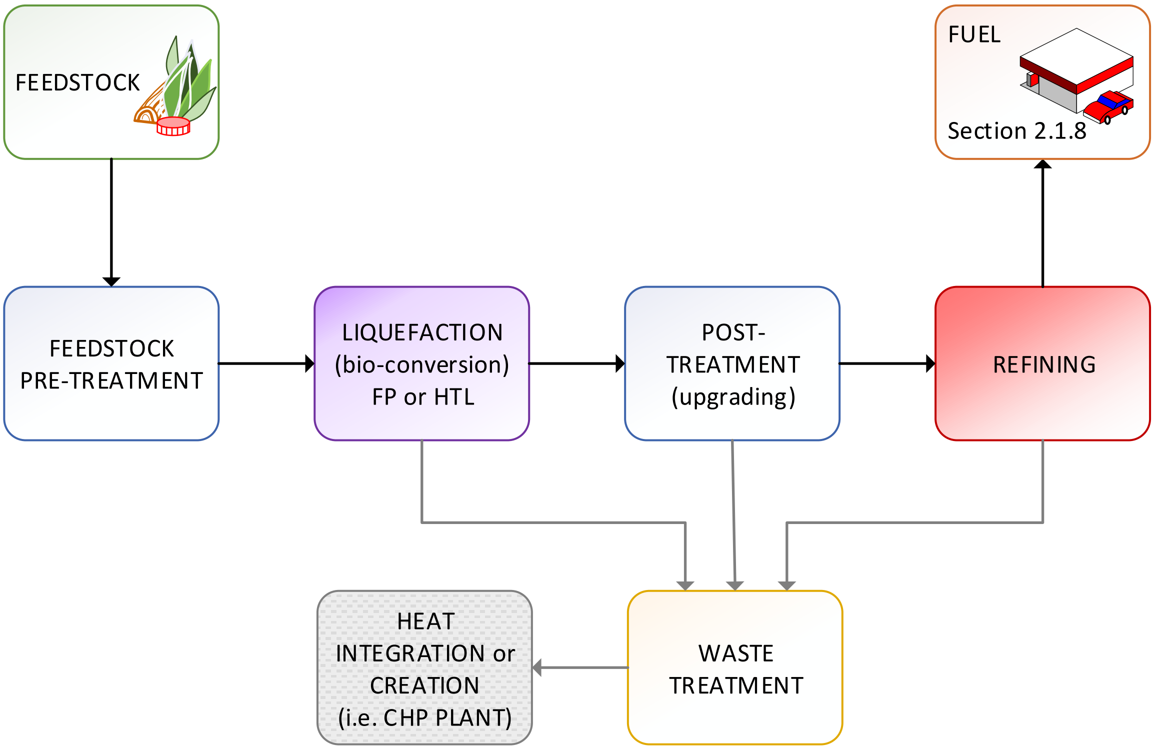

Figure 1: Value chain block flow diagram

2.1 Value chain processing steps

Pre-treatment options include process steps such as viscosity reduction, washing, drying, dilution, sieving, size reduction and metal removal. The pre-treatment required will depend on the type of feedstock and on the liquefaction technology. For example, contaminated wood used for pyrolysis might require a combination of size reduction, sieving, drying, and most likely metal removal. The results from the experimental work will provide clear feedback on which pre-treatment steps will be required. After pre-treatment, the feedstock is sent to **liquefaction** through fast pyrolysis (FP) or hydrothermal liquefaction (HTL). Each value chain will only contain one type of liquefaction technology.

Following the liquefaction step, there are a number of **upgrading or post-pre-treatment steps** available, including ash removal, dewatering, sieving, impurity removal, electrocatalysis, blending, hydrogenation, and solvent addition. Similar to the pre-treatment process, more than one post-treatment step may be required. The number and combination of these steps will depend on the liquefaction product (bio-oil) characteristics and the refining specifications. Therefore, a value chain can include more than one type of post-treatment.

From these post-treatment steps, the subsequent potential **refining steps** are blending, HT (hydrotreating), co-FCC (co-feeding into a fluid catalytic cracking) or co-HT (co-feeding into a hydrocracker). The bio-oil characteristics after post-treatment and the intended end-use of the bio-oil will determine which refining step is the most suitable. Due to the size and cost of the refining step, each value chain will contain only one type of refining technology. Additional refining options for a bio-oil will cause additional value chains to be created. Each downstream processing option becomes a value chain.

Depending on the process, different **waste streams** will be produced, including off-gas (gaseous waste), char and ash (solid waste), and contaminated water (liquid waste). Therefore, different waste management options may be required. Wherever possible, the waste streams will be valorised, such as burning the off-gas and char to produce process heat and electricity. There are two waste management strategies being investigated in WP5, Task 5.3, for treating contaminated water, namely supercritical water gasification (SCWG) and electrocatalysis. During SCWG the organics within the waste water fraction is removed and utilized for hydrogen production. During electrocatalysis, acetic acid is removed while at the same time hydrogen is produced from the organic content, which can be used to simultaneously hydrogenate the bio-oil. To this end, electrocatalysis is more optimally included as a post-treatment method, rather than a dedicated waste management processing step. Therefore, SCWG can be considered for treating contaminated water together with other alternatives such as anaerobic or aerobic digestion.

Additional heat produced, as in the case of pyrolysis, can be used by the waste collection and treatment facility (in-house) or sold as a co-product. Direct heat integration is only feasible if the industrial facilities are co-located. The bio-fuel produced will be validated for its end-use compatibility by characterizing the bio-fuel, together with performing various analyses (WP6). This will contribute towards standardization activities (D6.5), business case development and exploitation strategy (D6.6) leading to the final exploitation plan (D6.6) of WASTE2ROAD.

2.2 Hydrogen use

To reach the GHG (greenhouse gas) emission target, the use of hydrogen produced from fossil-based resources should be avoided as far as possible. The hydrogen (H_2) source options include:

- Buying in 'green-based' H_2 produced commercially (e.g. Total)
- Buying in fossil-based H_2 [1].
- Producing H_2 on site through SCWG (supercritical water gasification) of waste water.
- Producing H_2 on site through electrolysis.
- Producing H_2 on site through steam reforming of the bio-oil [1].
- Producing H_2 on site through steam reforming of natural gas.

In a study done on the economics of biofuels and bioproducts from an integrated pyrolysis biorefinery, it was found that the high capital cost associated with the hydrogen generation (20.96 $MM), and high operating cost for the hydrogen plant catalyst and process water, contributed to low IRR (internal rate of return) values [2]. In this case an IRR of 18.5 % was obtained for a biofuels biorefinery (high biofuels price), compared to an IRR of 42.5 % to 67.9 % obtained for a bioproducts biorefinery (average to high bioproduct price), which did not require hydrogen generation. Similarly, when the economic outcome of a fast pyrolysis plant treating corn stover was investigated, the option where hydrogen was produced off-site and bought in as a consumable rather than produced on-site, resulted in the more economically attractive process option [1]. Therefore, viable hydrogen generation is vital for a favourable economic outcome and the attractiveness of the WASTE2ROAD value chains.

2.3 Bio-oil transportation costs and considerations

Pyrolysis oil can be transported by road, railroad or waterway. Pyrolysis bio-oil is acidic in nature and therefore slightly corrosive, unstable at high temperatures or for long storage periods, non-volatile, and highly polar. It has passed the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) regulation in 2013 [3]. REACH requires companies to identify and manage the risks linked to substances.

Table 2: Pyrolysis bio-oil properties compared to Mineral Oil U.S No. 4 FO (fuel oil) and HFO (heavy fuel oil) [3,4]

Properties	Pyrolysis oil (Forest Biomass)	U.S no. 4 FO	HFO (180 LS)
Water (% wt.)	20 - 30	0.5	-
Solids (% wt.)	< 0.5	0.5	-
Ash (% wt.)	0.01 – 0.2	<= 0.1	-
Nitrogen (% wt.)	< 0.4	-	-
Lower heating value, MJ/kg	15 – 19	-	41.3
Density (kg/dm^3 at 15°C)	1.1 – 1.3	-	0.98
pH	2.5 – 3	-	-
Flash point (ASTM D93)	40 – 110 °C	> 55 °C	80 °C
Pour point (°C)	< -20 °C	> -6 °C	-
Moisture (% wt.)	20 – 30 %	-	0.1 %
Viscosity (cSt at 40 °C)	15 – 35	5.5 – 24	170
Sulphur (% wt.)	< 0.05	varies	0.95

Pyrolysis oil is not classified as a flammable liquid (Class 3) and it is not environmentally hazardous [3]. To this end, it would be classified as UN number 3265, corrosive liquid, acidic, organic and N.O.S, Class 8, package group III and no environmental hazards [3]. The bio-oil properties are compared to the properties of United States no. 4 fuel oil and heavy fuel oil in Table 2.

By road, the total possible transportation volume cannot be fully utilized since the payload is determined by the maximum possible weight of 60 ton, using acid-proof steel (AISI 316L) or polymers such as PTFE (polytetrafluoroethylene) [3]. By railway, a direct railroad connection would be required between the production plant to the refinery. If this is not possible, tanks could be used for the shorter distances, although this would increase the overall transportation cost. Wagons previously used for acids (sulphuric and/or phosphoric acid) could be used for pyrolysis oils and are 45 m^3 in volume, which is approximately 54 tons of bio-oil per wagon (maximum weight allowed per wagon is 90 ton). A typical Finnish train can pull 2000 tons and has a length of 700 – 800 m [3]. In Finland, pyrolysis oil produced from biomass can be transported in tank containers, only in international waters [3]. Water-based transportation has the largest payload per transport run due to suitable vessel capacity [3].

However, the seasonal changes should be taken into account since inland waterways could be frozen during winter. Furthermore, more strict legislation might prohibit transportation of pyrolysis bio-oil. Lastly, a tank container is considered. These units can be transported by road, railway and seaway transport. The suitable size being 25 m^3 and 25 – 30 ton per payload [3]. The transportation methods are compared in Table 3. Until more information is available, it will be assumed that the same is applicable to the bio-crude produced by HTL.

Table 3: Transportation method comparison for 100,000 tonnes pyrolysis oil per year [4].

Transportation method	Maximum payload per unit, tons	Number of transports runs per year
Road	36 – 42	± 2500
Railway (10 wagons)	540	185
Waterway	3600	28
Tank container	25 - 30	± 3500

3. Value chains

The identified value chains from biogenic waste to biofuel at a relevant industrial scale are described in this section. A high-level overview is provided on the volumetric production flows of intermediate bio-liquids and products from the waste feedstocks, feedstock and product specifications and routing and logistics. The value chains identified at industrial scale are listed below, and cross referenced in Table 4.

- HTL – 1 (MSOW, France)
- FP – 1 (Contaminated wood, Finland)
- FP – 2 (Contaminated wood and roadside grass, Netherlands)
- FP – 3 (Digestate, Norway)
- FP – 4 (MSOW, France)
- FP – 5 (Sewage sludge, Austria)[1]
- FP – 6 (Sunflower husks, Ukraine)

Table 4: Feedstock summary and value chain name

Feedstocks	Supplier	Primary Conversion	Value chain
Roadside grass	Netherlands	FP	FP – 2
Food residue pre-treatment reject from bio-reactor	Norway	FP	n/a
FFOM: Organic fraction of municipal solid waste	France	FP & HTL	HTL – 1 FP – 4
Solid bio-residues from methane reactors - digestate	Norway	FP & HTL	FP – 3
Contaminated wood 1 (B-wood)	Finland	FP – VTT	FP – 1
Contaminated wood 2 (B-wood)	Netherlands	FP - BTG	FP – 2
Black liquor	France	HTL	n/a
Food residues from canteens and restaurants	France	HTL	n/a
Vinasses	France	HTL	n/a
Sewage sludge	Austria	FP	To be confirmed whether it will be included or excluded; FP - 5
Sunflower husks	Ukraine	FP	FP - 6

n/a – not applicable

In the value chain column in Table 4, it is stated that some feedstocks are ‘n/a’ not applicable. For *Food residue pre-treatment reject from bio-reactor* and *Black Liquor* this is due to unfavourable experimental results with FP, respectively HTL. Although food residues from canteens with HTL has promising results (50 % process yield and 75 % energy yield), the feedstock production capacity is not commercially relevant, and the value chain is rather built around the results from the *FFOM: Organic fraction of*

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[1] This feedstock and value chain is optional and is to be confirmed

municipal solid waste (France), HTL - 1 value chain, which is mostly food residues. However, experimental results from this feedstock can also be used to configure value chain HTL – 1. It should be noted that *Roadside grass* is combined with *Contaminated wood 2 (B-wood)* in value chain FP – 2 due to seasonal availability. More information about this is provided in section 3.1.2 Feedstock diversification and availability.

3.1 Assessment of integration potential

The assessment of the integration potential within each value chain and the benefits of centralized versus decentralized production in modular units are discussed in this section. Integration potential refers to the logistical aspects like feedstock diversification, transportation scenarios, and year-round availability.

3.1.1 Centralized versus distributed value chain

Each step in the value chain can be centralized or decentralized. In a centralized chain, different sources are sent to a single node or site, in a 'many-to-one' configuration. In a decentralized chain, there can be linear branches between smaller centralized sites. These concepts are shown in Figure 2. However, when looking at the value chain as a whole, it is better to define it as a **centralized or distributed value chain** (Figure 3). For feedstocks that are easy to transport, the centralized or linear type distributed value chain could be implemented. However, waste feedstocks are usually difficult and problematic to transport, mainly due to factors such as safety (e.g. presence of pathogens), high moisture content, feedstock stability (e.g. degradation or fermentation during transit and storage) or cost. Therefore, the hub-and-spoke distributed value chain is more favourable for waste feedstocks (Figure 3).

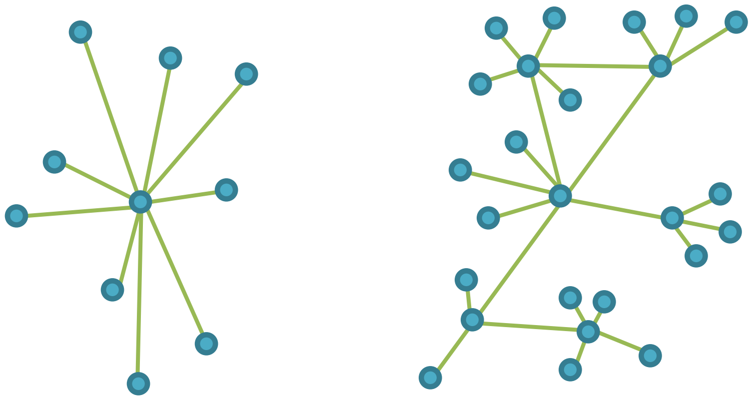

Figure 2: Centralized versus decentralized networks

In the **hub-and-spoke distributed value chain**, the waste collection facility is a centralized site for the biogenic feedstock. The liquefaction FP or HTL plant is co-located at the waste collection facility and the FPBO (fast pyrolysis bio-oil) or bio-crude from HTL is transported to the upgrading facility, which is co-located at the existing refinery for co-refining. The upgrading facility could be annexed to the liquefaction plant if there is sufficient space, but it is more advantageous to place it at the refinery.

Advantages include economies of scale, i.e. a larger upgrading facility since it can be fed by the bio-oil or bio-crude from multiple liquefaction plants, and integration potential. Utilities and auxiliaries such as waste treatment, energy integration and consumption of raw materials and auxiliaries can be more easily integrated with the refinery compared to a stand-alone unit at the waste collection facility. For example, hydrogen required for hydrotreating may be taken from the hydrogen production facility at the refinery site. The transport of the upgraded bio-oil or bio-crude to the refining step is also minimized.

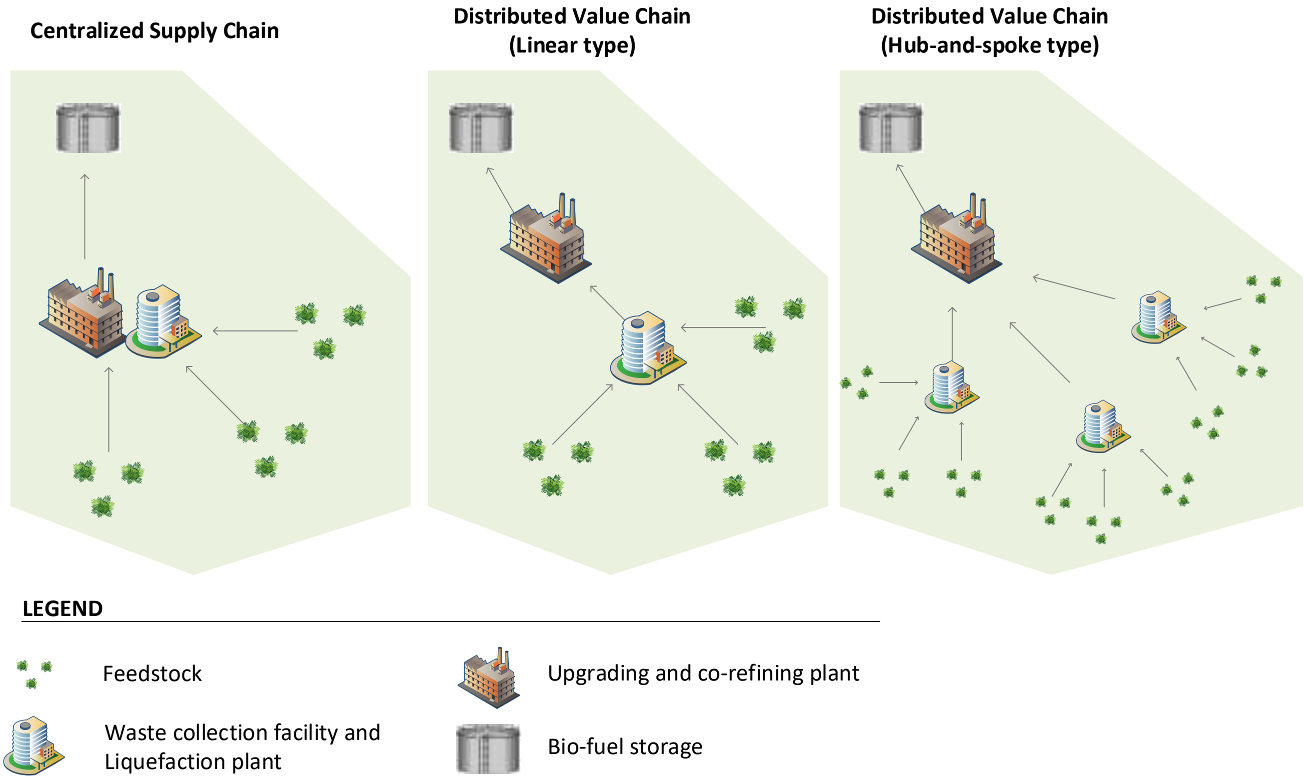

Figure 3: Centralized and distributed (linear and hub-and-spoke type) value chains, redrawn from [5].

3.1.2 Feedstock diversification and availability

Feedstock diversification is addressed by testing a wide range of potential waste feedstocks for FP and HTL. Both of these liquefaction technologies should be able to treat different types of feedstocks in the same unit operations and equipment, as long as the feed conditions are met. Feed conditions include particle size, moisture content, and the absence of certain contaminants that might, for example, damage equipment such as pieces of metal through the high pressure HTL pump, or contaminants that cannot be removed by upgrading steps and will cause severe catalyst deactivation. Feedstock diversification is also an important mitigation step for several risks, discussed in section 3.4.

Feedstock availability could be influenced by seasonal changes. For example, roadside grass grows slower during winter time and it is cut at certain intervals during the year. Since grass cannot be stockpiled or stored (without additional process steps such as drying), a continuous feed stream will not be available. Contaminated wood on the other hand can more easily be stockpiled. Therefore, the seasonal availability of roadside grass can be addressed by feedstock blending or batchwise feeding. For example, for batchwise feeding the pre-treatment setup of a contaminated wood fast pyrolysis plant can be adjusted to treat grass (e.g. no milling is required and the grass may dry faster than wood particles) and then changed over to the available roadside grass as feedstock. The quality of the bio-oil could be affected and therefore the upgrading should also be done, or changed if required, to ensure that the required standards for co-refining are met. Other feedstocks that could be impacted by variable availability and composition is the digester pre-treatment rejects and the secondary sewage sludge. No availability concerns are foreseen for black liquor, food residues or contaminated wood availability.

Feedstock blending might even be advantageous to the conversion process. An example of advantageous feedstock blending is found in the study by Ong *et al.,* (2018), where Kraft black liquor was fed with *Radiate* pine to the HTL process in the ratio of 0.27 : 1 by mass [6]. In this case the sodium rich black liquor acted as a catalyst for the biomass liquefaction.

Table 5: Food residue (from local restaurants) feedstock characteristics

Feedstock description and Structural composition	Unit	FW1 Restaurant H1 CEA	FW2 Restaurant H1 CEA
STRUCTURAL COMPOSITION			
Cellulose/dry basis	wt%	8.6	7.7
Hemicellulose/dry basis	wt%	25.3	12.5
Lignin/dry basis	wt%	1.9	2.8
Sugars/dry basis (by difference)	wt%	27.9	40.1
PROTEINS & LIPIDS			
Proteins		18.2	16.5
Lipids		10	11.5
PROXIMATE ANALYSIS			
Total moisture, as received (before grinding)	wt%	90	82
Analysis moisture, as received (after grinding)	wt%	3.5	6.2
Volatiles, dry basis	wt%	-	-
Ash 550 °C, dry basis	wt%	5.1	4.9
Ash 815 °C, dry basis	wt%	-	-
Fixed carbon	wt%	-	-
ULTIMATE ANALYSIS			
Carbon (C), dry basis	wt%	47.3	43.8
Hydrogen (H), dry basis	wt%	6.3	8.1
Nitrogen (N), dry basis	wt%	3.2	3.2
Sulphur (S), dry basis	wt%	0.1	0.2
Chlorine (Cl), dry basis	wt%	0.7	
Oxygen (O), as received	wt%		
Alkali content	g/L		
HHV, dry basis	MJ/kg	20.3	20.5

3.2 Hydrothermal liquefaction value chain

3.2.1 HTL -1: MSOW food residues

Data from experimental work

The feedstock specifications from the experimental work are provided in Table 5 and the process performance of the feedstocks treated by HTL are provided in Table 6.

Table 6: Process performance of feedstocks treated by hydrothermal liquefaction (HTL)

Process performance parameters	Black liquor	Digestate	Food residues (canteen)
Process mass yields	20 – 30 %	Dry powder yield of 80 % with high ash content (33 %)	50 % (46 – 52% biocrude yield and 58 - 77 % carbon balance)
Energy yield	30 %	75 %	75 %

The bio-crudes obtained from these feedstocks are to be analysed. Information on the bio-diesel produced from this bio-crude is not available to date. The bio-crude produced from food residues is ready for upgrading and/or co-processing.

Process description

An industrially relevant value chain for HTL is based on food residues. The information from the municipal solid organic waste (MSOW) and the nearby restaurants and canteens are used to build the food residue value chain.

The first value chain configuration, **Option A** (Figure 4), is based on a centralized value chain. It includes pre-treatment, HTL, hydrotreating, CHG (catalytic hydrothermal gasification) and utilities. The pre-treatment include milling for size reduction, pressure increase using a peristaltic pump and preheating of the feedstock slurry before the slurry enters the HTL reactor. After HTL, the product stream is split into three phases: gas, liquid and solid phase. The gas phase contains mainly carbon dioxide, with traces of hydrogen and methane. Therefore, it is sent to the utilities area for co-burning in a furnace. The liquid or aqueous phase is waste water, treated by CHG to produce treated water and fuel gas. The fuel gas is also sent to the utilities area (furnace) and the treated water is returned for re-use, further treatment or disposal depending on the available infrastructure. The bio-crude is sent to hydrotreating, resulting in diesel fuel and heavy oil products. Hydrotreating also produces off-gas and waste water as by-products. The waste water is sent to the CHG area and the off-gas to the utilities area. In the utilities area, there is a NH_3 scrubber (depending if this is present in the off-gas), steam generation area and cooling water plant. For Option A it should be noted that it is assumed that hydrogen is purchased and not produced on site, and no hydrocracking is included.

Option B (Figure 5) is based on a distributed value chain. Both a linear type and a hub & spoke type of distributed configurations (Figure 3) are possible. For Option B, the bio-crude is transported to an existing refinery for co-refining. The bio-crude is co-refined during hydrotreatment and hydrocracking. The by-products produced (off-gas and waste water) are treated in the refinery's utilities area and is outside the battery limits of this value chain. Similarly, the hydrogen supply is from the refinery's supply and the production thereof is outside of the battery limits. The final products for Option B are bio-fuels diesel and gasoline.

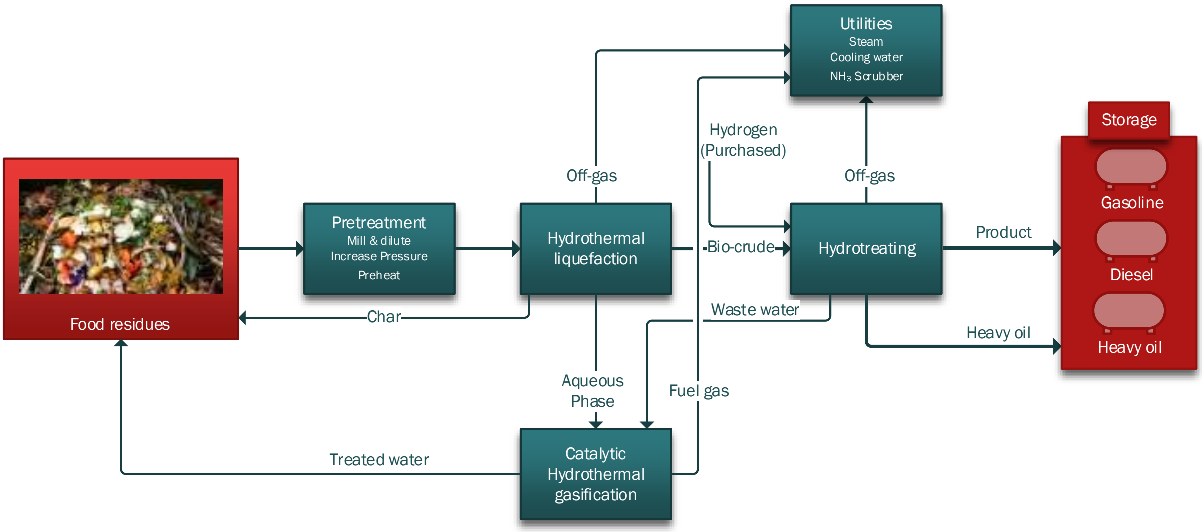

Figure 4: HTL Value chain for food residues Option A (centralized configuration)

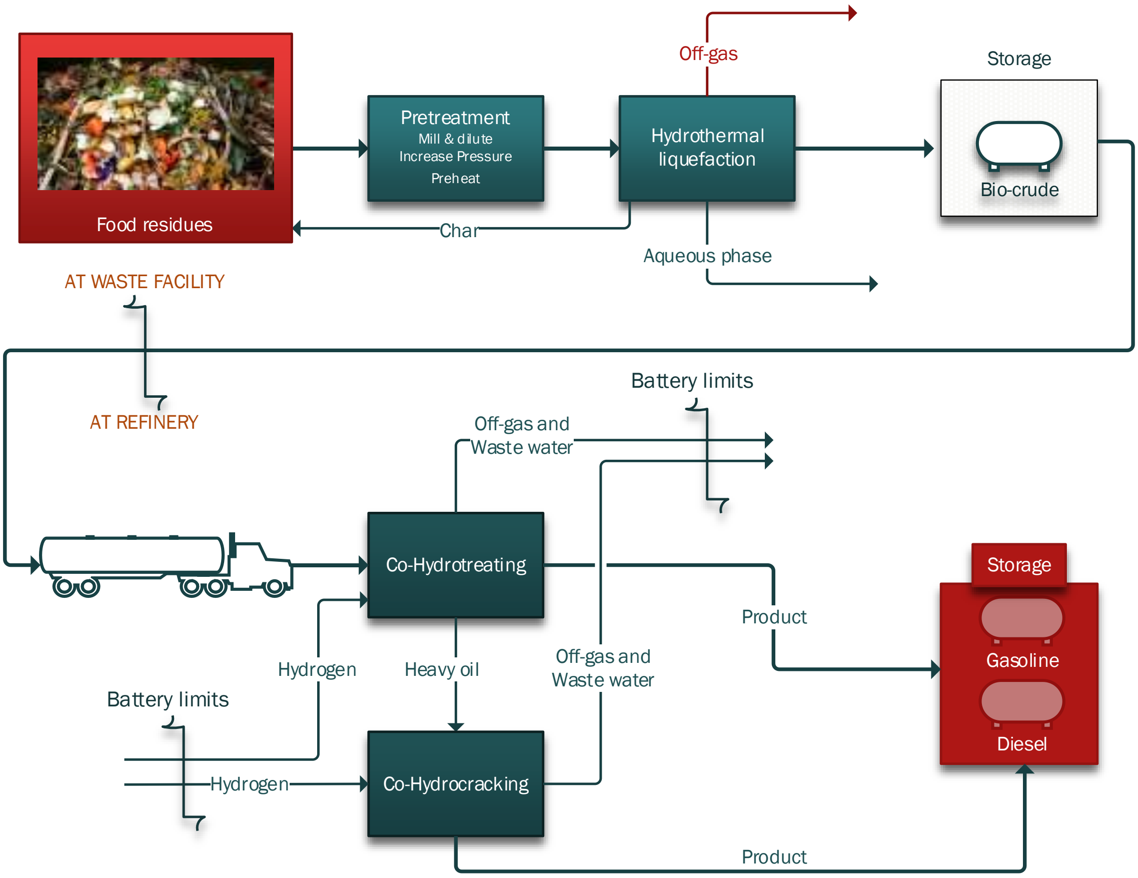

Figure 5: HTL value chain for food residues Option B (distributed configuration)

More concrete, the feedstock site of SUEZ in Montpellier, France, is considered for collection of MSOW (or FFOM). It is assumed that the HTL facility (Option A & B) and the hydrotreating, utilities and CHG (Option A) are annexed next to SUEZ's site. In Option A, the bio-diesel and heavy oil is sold from the liquefaction facility and transport of the intermediate and final product is excluded.

For Option B, the intermediate bio-crude is stored on site (i.e. the liquefaction facility annexed to SUEZ) and then transported, e.g. by truck to the refinery. After co-refining, the biofuels are stored in the refinery's existing storage tanks. For Option B, the refineries listed in Table 7 could be considered for co-refining.

Table 7: Refineries in France

European Countries	Feedstock	Potential refineries for co-FCC
France	Food waste (MSOW)	Total SA, Grandpuits ExxonMobil Refining & Supply Co., Fos sur Mer* ExxonMobil Refining & Supply Co., Port Jerome* Petrolneos Refining Ltd., Lavera* Total SA, Feyzin* Total SA, Gonfreville l'Orcher* Total SA, La Mede* Total SA, Donges*

Based on the available food waste collected on an annual basis by SUEZ in Montpellier and food waste specifications, the potential feedstock supply in tonnes per day is established as well as the resulting production of bio-crude and therefore diesel and gasoline.

3.3 Fast Pyrolysis value chains

The actual value chains for FP are:

- FP – 1 (Contaminated wood, Finland)
- FP – 2 (Contaminated wood and grass, Netherlands)
- FP – 3 (Digestate, Norway)
- FP – 4 (MSOW Food residues, France)
- FP – 5 (Sewage sludge, Austria)[2]
- FP – 6 (Sunflower husks, Ukraine)

The process performance of the feedstocks treated by fast pyrolysis is provided in Table 8. Data for FP – 4 (MSOW), FP – 5 (Sewage sludge) and FP-6 (Sunflower husks) will be supplemented once available.

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[2] This feedstock and value chain is optional and is to be confirmed

Table 8: Process performance of feedstocks treated by fast pyrolysis (FP)

Process performance parameters	Contaminated wood (VTT) (unfiltered)	Contaminated wood (BTG)	Digestate (BTG)	Verge grass (BTG)	Digester pre-treatment rejects (BTG)
Value chain	**FP - 1**	**FP - 2**	**FP - 3**	**FP - 2**	**n/a**
Process yields	55-60 wt% organic yield (oil yield)	60 wt% oil yield	41 wt% oil yield	52 wt% oil yield	38 wt% oil yield
Alkali metals	Total AAEM* content: 0.13 g/kg, from 4.38 g/kg in feedstock. Total metal content: 0.66 g/kg (from 4.38 g/kg in feedstock)	-	-	-	-

*AAEM - Alkali and alkaline earth metallic species

The pyrolysis oil can be **upgraded to SDPO** (stabilized and deoxygenated pyrolysis oil). Results from upgrading bio-oil from *clean* wood are shown in Table 9. These results are used as a starting point for the high-level, overall mass balances.

Table 9: Upgrading (stabilisation and partial deoxygenation) of clean wood, (information obtained from BTG)

Components	wt%	Comments	
Mass yield oil	35.0%	From 1000 kg PO, 350 kg SPBO is obtained	
Yield	42.8%	From 816.3 kg (C, H, O) 349.3 kg (C, H, O) is obtained in the SDPO	
Water removed	99.6%	183.7 kg water is reduced to 0.7 kg water	
Volatiles removed	15.0%	150 kg volatiles are released per 1000 kg PO	
Heating values	Pyrolysis oil	SDPO	Increase
HHV (MJ/kg)	22.7	44.7	Factor 1.97
LHV (MJ/kg)	21.3	51.9	Factor 2.44

Successful **co-refining** experimental runs were performed with SDPO at TUW. The yields (wt%) are shown in Figure 6 for the different product fractions from these runs. The SDPO oil (5 %) co-blended with VGO (vacuum gas oil) resulted in a higher gasoline yield of 41.5 wt% compared to 40.0 wt%. The blended test was run again at a riser temperature of 530 °C which resulted in an even better gasoline yield of 45 wt% compared to 41 wt%. The gas phase included ethylene (2.7 wt%), propylene (12.4 wt%), butenes (7.4 wt%) and 15.4 wt% other gases for the blended feedstock at 530 °C. Experiments of 10 % SDPO co-feeding into the FCC have been performed, showing similar trends as for 5% SDPO.

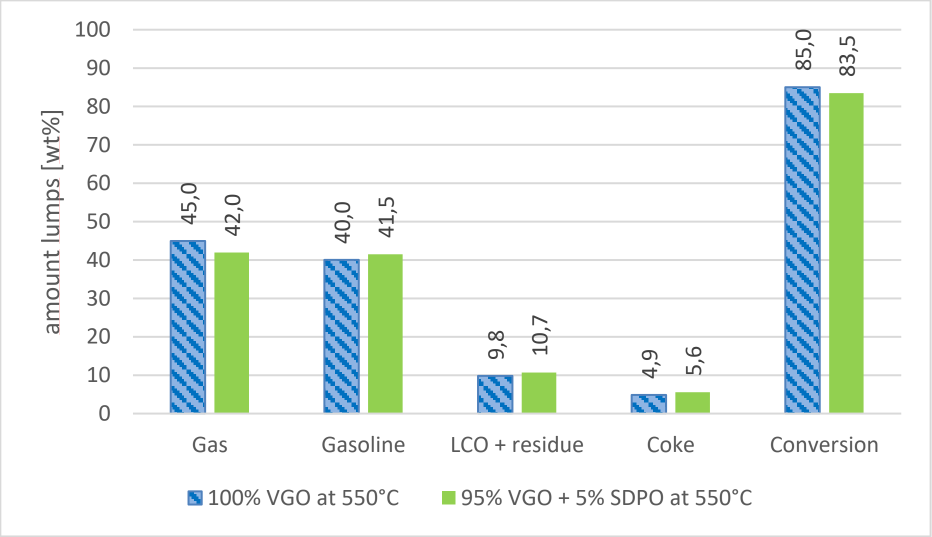


Figure 6: Fluid Catalytic cracking (FCC) results for 100 % VGO and 95 % VGO + 5 % SPDO for gas, gasoline, LCO (light cycle oil) + residue, and coke

3.3.1 FP – 1: Contaminated wood, Finland

This FP value chain treats contaminated wood from the waste collection facility at Lassila and Tikanoja (L&T) in Finland.

Data from experimental work

The feedstock analyses from the experimental work are shown in Table 10.

Table 10: Contaminated wood feedstock analysis for VTT samples

Origin	Unit	VTT, Finland 1	VTT, Finland 2
Moisture	wt%	8.0	28.2
Volatiles	wt%	84.7	75.4
Ash 550 °C	wt%	0.8	7.0
Carbon	wt%	50.4	48.4
Hydrogen	wt%	6.0	5.6
Nitrogen	wt%	0.4	1.3
Oxygen[1]	wt%		
HHV	MJ/kg	20.2	20.7
LHV	MJ/kg	18.9	19.4
Cl	wt%	0.02	0.065
S	wt%	0.017	0.085
Total		65.64	90.65

[1] by difference

Without hot filtration, applied to remove ash, the pyrolysis of contaminated wood from Finland by VTT resulted in 54.73 wt% bio-oil, 14.82 wt% char, 12.85 wt% gas, and 10.75 wt% reaction water yield. The bio-oil has a lower heating value (LHV) of 21.2 – 21.4 MJ/kg and a higher heating value (HHV) of 22.6 – 22.8 MJ/kg, summarized in Table 11.

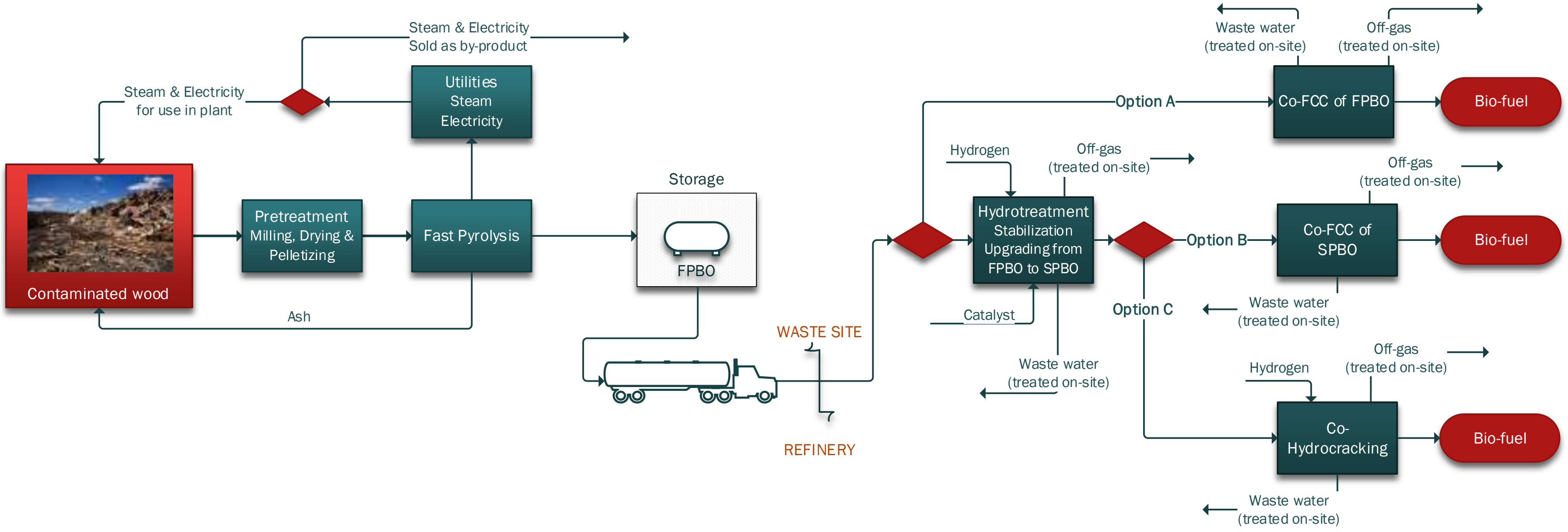
Table 11: Fast pyrolysis results of contaminated wood, on an ash free basis

Component	wt%
Bio-oil	54.73
Char	14.82
Gas	12.85
Water	10.75
Total	93.15
Heating values	MJ/kg
LHV	21.3
HHV	22.7

Process description

The contaminated wood is milled to a particle size of 3 mm, dried to 5 wt% moisture content and sent underneath a belt magnet. If any screws or metal particles are present, they will be removed by the magnet. It will still be confirmed whether additional pre-treatment steps are required to treat the contaminants present in the contaminated wood. After pre-treatment the feedstock enters the FP reactor. A gas phase and solid phase is formed. The char solid phase is removed with the sand in a cyclone, and the gas phase passes through a condenser. The condensable gases are separated from the non-condensable gases. The condensable gases are liquefied and form the organic liquid product stream, or FPBO (fast pyrolysis bio-oil). The non-condensable gases are sent to a furnace, where they are burned for steam and electricity generation using a boiler and turbine in the utilities area. Steam and electricity can be used on-site or sold to neighbour companies. Any ash present after the char has been burned from the sand is returned to the waste collection facility for disposal. The FPBO is stored on site and then transported to an existing refinery for upgrading and co-refining.

There are three options for upgrading and co-refining. It has already been proven at pilot and commercial scale that crude FPBO can be co-fed with VGO into an FCC. However, in this project we prefer to investigate option B in more detail. Ideally, the FPBO could be co-fed with VGO (vacuum gas oil) in an FCC (fluid catalytic cracker) to produce bio-fuel as shown in Option A, Figure 7. In Option B, the FPBO is upgraded through stabilization and partial deoxygenation, resulting in stabilized deoxygenated pyrolysis oil (SDPO). The SDPO is then co-fed into an FCC and good experimental results have been obtained (Figure 6). There is also the option of co-feeding the FPBO directly into a hydrocracker instead of an FCC to produce bio-fuel. This is Option C, but has not been tested yet. To this end, the FP Value Chains 2, 3 & 4 will be described for Option B. For Options A, B and C, it is assumed that the hydrogen is obtained from the refinery and the by-products produced (off-gas and waste water) are also treated by existing infrastructure at the refinery. It is therefore outside of the battery limits of this value chain.



FP Contaminated wood Value Chain 1-A/B/C

Figure 7: FP - 1: Contaminated wood (distributed) value chain configuration

3.3.2 FP – 2: Contaminated wood and roadside grass, Netherlands

This FP value chain treats contaminated wood and roadside grass obtained from the waste collection facility at Twence in Hengelo, The Netherlands. Since roadside grass is seasonal, the main feedstock is contaminated wood. When available, the roadside grass will be fed to the FP plant.

Data from experimental work

The feedstock analysis from the experimental work are shown in Table 12 for contaminated wood and roadside grass. Roadside grass or verge grass from a local greenery and wood waste disposal company was washed, dried and grinded before fast pyrolysis.

Table 12: Contaminated wood and Roadside grass feedstock analysis for the BTG sample

Origin	Unit	Contaminated wood BTG, Netherlands	Roadside grass, BTG, Netherlands
Moisture	wt%	8.5	5
Volatiles	wt%	78.4	-
Ash 550 °C	wt%	1.9	11.7
Carbon	wt%	48.8	40.9
Hydrogen	wt%	5.9	4.8
Nitrogen	wt%	2.6	2.1
Oxygen[1]	wt%		
Cl	wt%	0.08	-
S	wt%	0.055	-
Total		67.7	64.5
Heating values		MJ/kg	
HHV	MJ/kg	19.8	-
LHV	MJ/kg	18.5	13.1

[1] by difference

Fast pyrolysis results (ash free basis) of contaminated wood and roadside grass analysed by BTG is shown in Table 13. FP of contaminated wood resulted in 60 wt% bio-oil, 20 wt% char, 19 wt% gas, and 1.5 wt% ash yield, or 45 wt% organic liquid, 20 wt% gas, 8 wt% water and 21 wt% char on an ash free basis. Pyrolysis of the verge grass resulted in 52 wt% bio-oil, 17 wt% char, 18 wt% gas, and 10 wt% ash yield, or 44 wt% organic liquid, 8 wt% water, 20 wt% gas and 20 wt% char on an ash-free basis.

Table 13: Fast Pyrolysis results for contaminated wood and roadside grass, respectively, (dry, ash free basis)

Feedstock Components	Contaminated wood wt. %	Roadside grass wt. %
Bio-oil	45	44
Char	21	20
Gas	20	20
Water	8	8
Total	94	92
Heating values (calculated), MJ/kg		
HHV	16.87	16.02
LHV	17.3	16.3

The results from upgrading (stabilization and partial deoxygenation) and co-feeding with VGO in an FCC unit using clean wood pyrolysis oil (Table 9) is used in the overall mass balances for contaminated wood and roadside grass, respectively.

Process description

The process description is largely analogous to the description provided for FP-1, contaminated wood. The main difference is that FP-2 also includes roadside grass as a feedstock. The value chain configuration is shown in Figure 8.

1.1.1 FP – 3: Digestate

Digestate is a slurry and a by-product from anaerobic digestion. During anaerobic digestion, organic waste is converted into biogas, a gas mixture containing mostly methane and carbon dioxide. The digestate is the slurry by-product and can have a moisture content as high as 98 wt% However, for the overall mass balance, a feed moisture content of 90 % was assumed. As a result, a feedstock rate of 49.7 t/h is required to obtain a dry feed rate of 5 t/h.

Data from experimental work

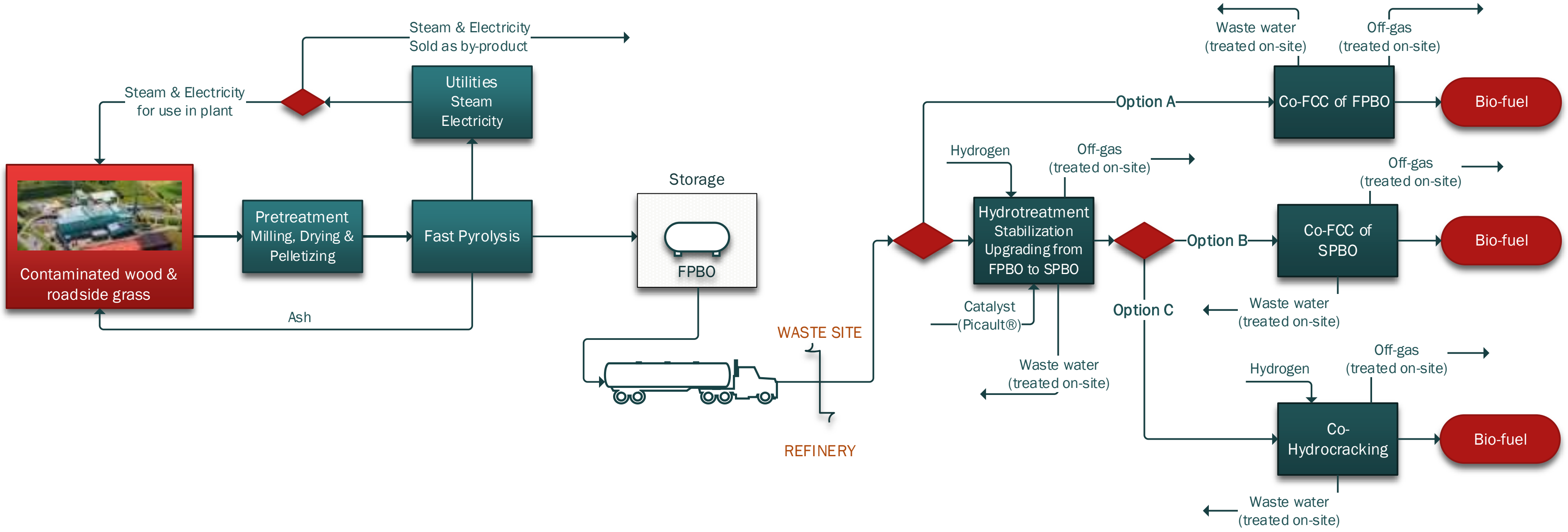
The digestate characterization as performed by BTG is shown in Table 14. The experimental yields of digestate fast pyrolysis are summarized in Table 15.

Table 14: Digestate feed characterization after drying as measured, and before drying (90 wt% moisture) as calculated

Components	% wt.	Before drying
Moisture	5.0*	**90 %** (assumed value)
Volatiles	-	-
Ash 550 °C	27.24	2.7 %
Carbon	40.503	7.3 %
Hydrogen	5.27	
Nitrogen	4.862	
Oxygen	22.12**	
HHV		-
LHV MJ/kg	15.05	-
Cl	n.a.	-
S	n.a.	-
Total	105	100 %

Table 15: Fast pyrolysis of digestate - experimental results

Feedstock Components	Digestate wt. %
Bio-oil	32
Char	14
Gas	16
Water	27
Total	89
Heating values (calculated), MJ/kg	
HHV	12.5 (calculated)
LHV	24.3 (calculated)



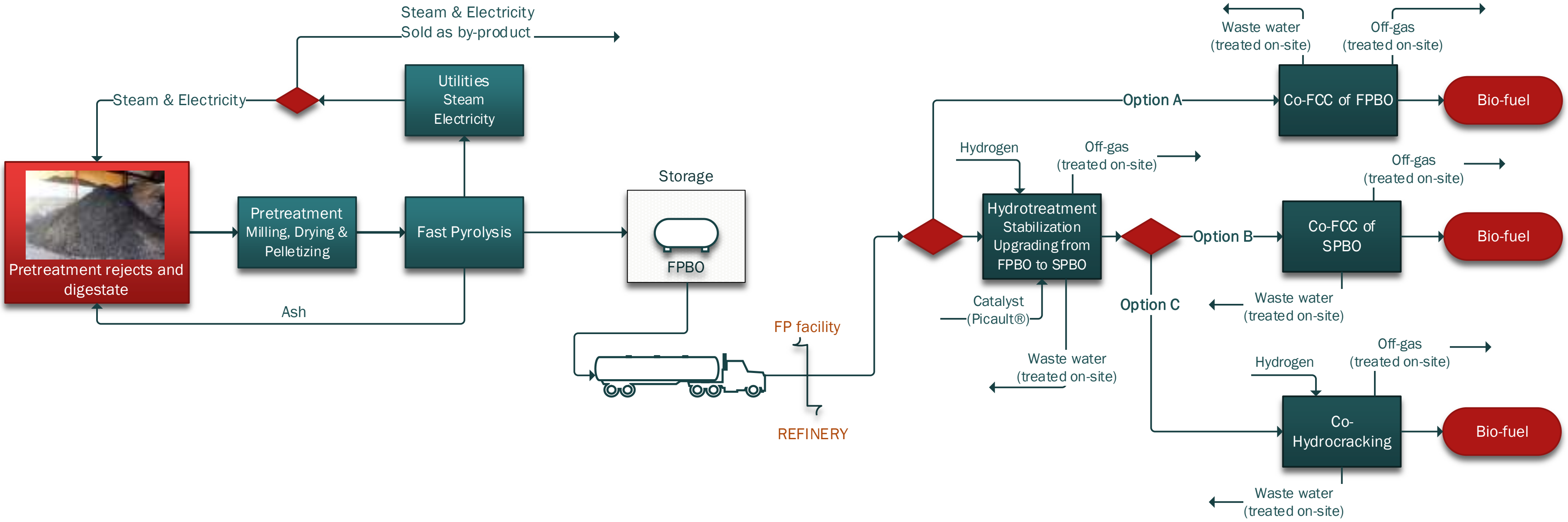
FP Contaminated wood and Roadside (verge) grass Value Chain 2-A/B/C

Figure 8: FP - 2: Contaminated wood and roadside grass (distributed) value chain configuration

Process description

Due to the high moisture content of the digestate, the moisture content is first reduced with a screw press. The digestate is dried further to 5 %.wt moisture using steam from the utilities area. If the dried digestate is too fine, resulting in flow problems, it can be pelletized first. After FP, the gas and solid products are separated in a cyclone. The solid char fraction is removed with the sand (heat transfer agent) and the gas stream is sent through a condenser, where the condensable and non-condensable gases are separated. The condensable gases are liquefied and form the organic liquid product stream, or FPBO (fast pyrolysis bio-oil). The non-condensable gases are sent to a furnace, where they are burned for steam and electricity generation using a boiler and turbine in the utilities area. Steam and electricity can be used on-site or sold to neighbour companies. Any ash present after the char has been burned from the sand is returned to the waste collection facility for disposal. The FPBO is stored on site and then transported to an existing refinery for upgrading and co-refining. This value chain is shown in Figure 9.

Another feedstock stream from the anaerobic digestor, is the pre-treatment rejects. Anything that cannot be fed to the anaerobic digestor (plastics, bones etc.) can be milled (3 mm) and fed to the pyrolysis plant. It should be noted that this may impact the FPBO quality and therefore downstream processing. However, the pre-treatment rejects can be stored and fed to the FP plant in batches, between the digestate feed. Digestate can also be stored for a while without degradation of the feedstock.



FP pretreatment rejects & digestate Value Chain 3-A/B/C

Figure 9: FP - 3: Digestate value chain configuration. This plant can also treat the pre-treatment rejects.

1.1.2 FP – 4: Municipal solid organic waste (MSOW) Food residues

The food residues collected in France, more specifically by SUEZ in Montpellier, will also be used by the FP technology to produce FPBO.

Data from experimental work

The feedstock and product specifications from the experimental work are being determined. From literature, food waste has 36.9 %(w/v) cellulose, 26.6 %(w/v) hemicellulose, 12.6 %(w/v) lignin and the balance 23.9 %(w/v) water soluble compounds [7]. From the proximate and ultimate analysis, food waste has 73.4 % volatile matter, 21.1 % fixed carbon, 5.5 % ash, C (46.1 %), H (5.7 %), O (40.79%), N (1.74 %) and S (0.17 %) with a gross dry calorific value of 15.7 MJ/kg [7,8]. This results – from theoretical calculations - in pyrolysis products, at 500 °C, of 7.4 wt%, 32.3 wt%, and 60.3 wt% gas, char and liquid yields, respectively. The calculated heat of combustion of biogas, biochar and bio-oil are 15.7, 24.8 and 11.2 MJ/kg, respectively.

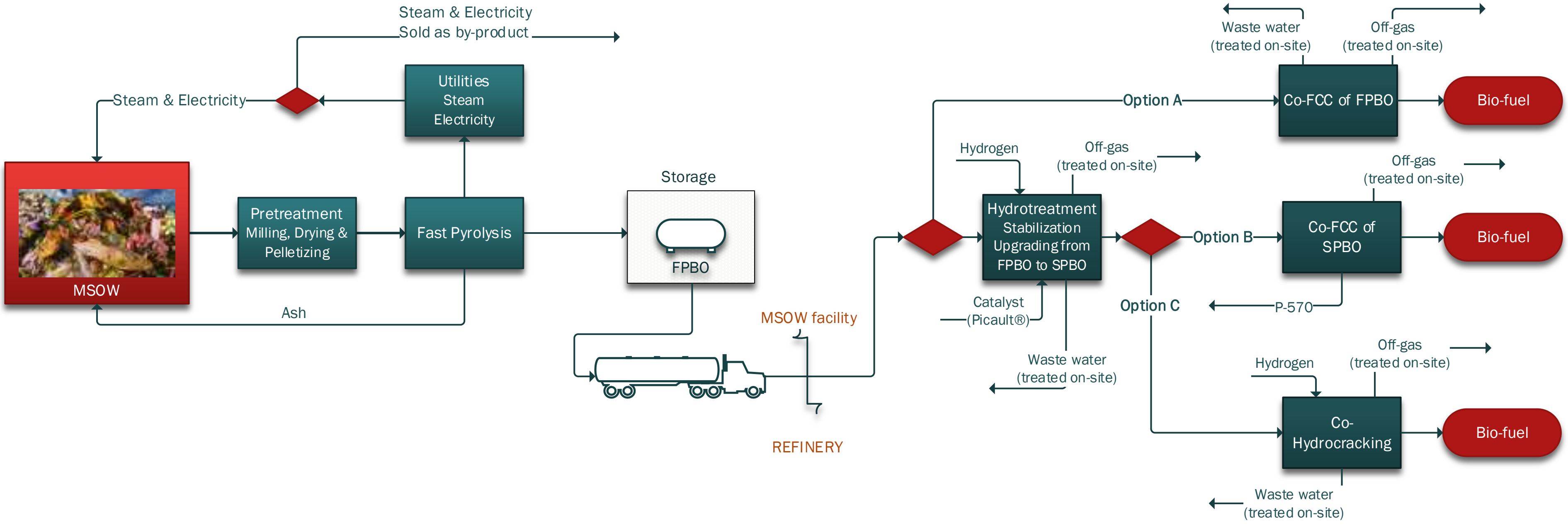
Process description

For this value chain, the moisture content of the food residue will be reduced to 3-5 wt% using the steam produced in the utilities area. Pre-treatment will also include size reduction to 3 mm particles if required, since it depends on the status of the feedstock. For example, food residue such as banana peels, vegetable cuttings and bread will require size reduction. The pre-treated food residues are then fed to the FP reactor.

After FP, the gas and solid products are separated in a cyclone. The solid char fraction is removed with the sand (heat transfer agent) and the gas stream is sent through a condenser, where the condensable and non-condensable gases are separated. The condensable gases are liquefied and form the organic liquid product stream, or FPBO (fast pyrolysis bio-oil). The non-condensable gases are sent to a furnace, where they are burned for steam and electricity generation using a boiler and turbine in the utilities area. Steam and electricity can be used on-site or sold to neighbour companies. Any ash present after the char has been burned from the sand is returned to the waste collection facility for disposal. The FPBO is stored on site and then transported to an existing refinery for upgrading and co-refining. This value chain is shown in Figure 10.

In Option B, the FPBO is stabilized through hydrotreating. The SPO is then further upgraded by deoxygenation, resulting in SDPO. The SDPO is then co-fed into an FCC. It is assumed that the hydrogen is obtained from the refinery and the by-products produced (off-gas and waste water) are also treated by existing infrastructure at the refinery. It is therefore outside of the battery limits of this value chain.

Once experimental results become available the mass balance can be established and determined how much FPBO, SDPO and gasoline can be produced as well as the gasoline biogenic content.



FP Municipal organic solid waste Value Chain 4-A/B/C

Figure 10: FP - 4: MSOW value chain configuration

1.1.3 FP – 5: Sewage sludge

Sewage sludge is a product of aerobic digestion of waste water. The usage of sewage sludge as fertilizer is a controversial topic and the use thereof has been banned (i.e. in the Netherlands and Flanders) or restricted in several countries (i.e. in Denmark, Germany and Sweden). This being said, sewage sludge removed from all pathogens is Class A sewage sludge, and there are no restrictions for selling and distribution. In Class B sewage sludge, the pathogens are reduced, but still present, and can be used as fertilizer on agricultural or non-agricultural land subject to any restrictions that might apply. It will be determined if Class A or B sewage sludge will be tested in this project.

Data from experimental work

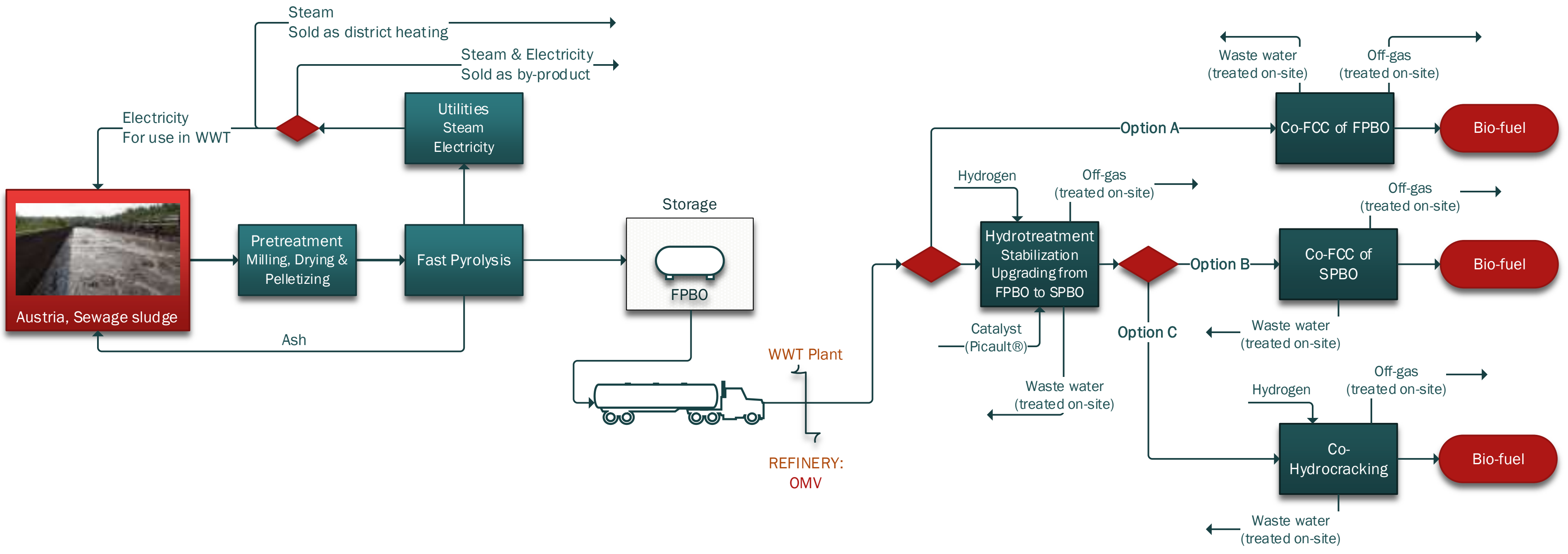
The feedstock and product specifications from the experimental work are not available to date, since it still needs to confirmed whether sewage sludge will be included as a feedstock.

Process description

For this value chain, the moisture content of the sewage sludge will be reduced to 3-5 wt% using the steam produced in the utilities area. If the dried sewage sludge forms a cake, this will be broken into smaller pieces using size reduction equipment. If the dried sewage sludge forms a powder, palletization might be required to prevent flow and dust problems. The pre-treated sewage sludge is then sent to the FP reactor. After FP, the gas and solid products are separated in a cyclone. The solid char fraction is removed with the sand (heat transfer agent) and the gas stream is sent through a condenser, where the condensable and non-condensable gases are separated. The condensable gases are liquefied and form the organic liquid product stream, or FPBO (fast pyrolysis bio-oil). The non-condensable gases are sent to a furnace, where they are burned for steam and electricity generation using a boiler and turbine in the utilities area. Steam and electricity can be used on-site or sold to neighbour companies. Any ash present after the char has been burned from the sand is returned to the waste collection facility for disposal. The FPBO is stored on site and then transported to an existing refinery for upgrading and co-refining. This value chain is shown in Figure 11.

In Option B, the FPBO is stabilized through hydrotreating. The SPO is then further upgraded by deoxygenation, resulting in SDPO. The SDPO is then co-fed into an FCC. It is assumed that the hydrogen is obtained from the refinery and the by-products produced (off-gas and waste water) are also treated by existing infrastructure at the refinery. It is therefore outside of the battery limits of this value chain.

Once experimental results become available the mass balance can be established and determined how much and in which quality FPBO, SDPO and gasoline can be produced from a typical waste water site producing sewage sludge.



FP Sewage sludge (Austria) Value Chain 5-A/B/C* optional

Figure 11: FP - 5: Sewage sludge

1.1.4 FP – 6: Sunflower husks

Sunflower husks are the shells of sunflower fruits after taking the seeds out and is a by-product of the sunflower seeds processing industry. The utilization rate is relatively low as sunflower husk is generally thrown away or burnt. Sunflower husk is considered ideal feedstock for fast pyrolysis as its main ingredient is cellulose, which gives it a high caloric value, and has a low moisture content. An interesting location for sourcing of sunflower husk is Ukraine. Sunflower is a strategically important oilseed crop in Ukraine, who holds first place in terms of world sunflower seed production covering about 25% of the world market.

Data from experimental work

First experiments on fast pyrolysis of sunflower husk are being conducted. However, data could not be included in this document.

Process description

Based on the results of the experiments the process concept can be developed for this value chain. Given the characteristics of sunflower husk it may be required to include a pelletizing step to improve transport and processing properties. On the other hand, a drying step can possibly be omitted.

1.2 Fuel specifications

The fuel specifications are reported elsewhere (Deliverable D6.1). These include the properties of fast pyrolysis bio-oils (FPBO) with their respective test methods, and of HTL bio-crude obtained from various lignocelluloses and micro-algae with a comparison to diesel and biodiesel. The selected reference norm for defining the specifications of diesel fuel produced is CEN/TS 15940:2012 “Automotive fuels - Paraffinic diesel fuel from synthesis or hydro-treatment - Requirements and test methods”. The norm defines the quality specification for diesel fuel produced from synthesis gas (from natural gas, coal or biomass) or of hydrotreated vegetable or animal oils. In the case of gasoline there is not a specific norm for synthetic fuels so the general EN 228:2012 “Automotive fuels - Unleaded petrol - Requirements and test methods” norm for fossil gasoline was adopted for defining the specification. Besides this, unleaded petrol may contain up to 10 % (V/V) of ethanol complying with the norm EN 15376. Because the high oxygen content of the ethanol molecule and its tendency to oxidize into acetic acid may cause compatibility issues, the norm defines two "grades" providing a separate statement for unleaded petrol with a maximum oxygen content of 2.7 and 3.7 % (m/m). The parameters that will be tested under fuel performance for gasoline and diesel are listed in Table 16 and Table 17.

Table 16: Automotive fuels – Gasoline – Requirements and test methods.

Property	Method	Unit	EN 228 Limits
Visual Analysis – Colour	-	-	-
Existent gum content	EN ISO 6246	mg/100 ml	< 5
Oxidation stability	EN ISO 7536	Min	>360
Sulphur content	EN ISO 13032	mg/kg	≤10.0
Benzene content	EN 238	% (V/V)	<1.00
Aromatics hydrocarbon content	-	% (V/V)	<35

Olefins hydrocarbon content		-	% (V/V)	<18
Oxygenates total content		EN 13132	% (m/m)	<2.7
Oxygenate	Methanol		% (V/V)	<3.0
	Ethanol		% (V/V)	<5.0
MTBE		EN 1601	% (V/V)	-
ETBE		EN 1601	% (V/V)	-
Density at 15°C		EN ISO 3675	kg/m^3	720.0÷775.0
Vapour pressure (VP)	Class A	EN 13016-1	hPa	450÷600
	Class C1		hPa	500÷800
	Class D		hPa	600÷900
Distillation	% evaporated at 70°C (Class A)	EN ISO 3405	% (V/V)	20.0 ÷ 48.0
	% evaporated at 70°C (Class C1 - D)		% (V/V)	22.0 ÷ 50.0
	% evaporated at 100°C (Class A - C1 - D)		% (V/V)	46.0 ÷ 71.0
	% evaporated at 150°C (Class A - C1 - D)		% (V/V)	> 75.0
	Final Boiling point – FBP		°C	<210
	Distillation residue		% (V/V)	<2
Vapour Lock (Class C1)			-	< 1050
Lead content		EN 237	mg/l	< 5
RON		EN ISO 5164	-	> 95
MON		EN ISO 5163	-	> 85

Table 17: Automotive fuels – Diesel – Requirements and test methods.

Property		Method	Unit	EN 590 limits
Visual Analysis – Colour		-	-	-
Flash point		EN ISO 2719	°C	> 55.0
Water content		EN ISO 12937	mg/kg	≤ 200
sulphur content		EN ISO 13032	mg/kg	≤ 10.0
Total contamination		EN 12662	mg/kg	≤ 24
Oxidation stability		EN 15751	H	≥ 20
Density at 15°C		EN ISO 3675	kg/m^3	820.0 ÷ 845.0
Lubricity (HFRR)		ISO 12156-1	µm	≤ 460
Viscosity a 40°C		ASTM D7042 ASTM D445	cSt	2.000 ÷ 4.500
Cetane number		EN ISO 5165	-	≥ 51
Cetane index		EN ISO 4264	-	≥ 46.0
Cloud point		EN 23015	°C	**
Pour point		ISO 3016	°C	**
C.F.P.P.		EN 116	°C	**(*)
Distillation	% evaporated at 180°C (arctic)	EN ISO 3405	% (V/V)	≤ 10
	% evaporated at 250°C		% (V/V)	< 65
	% evaporated at 340°C (arctic)		% (V/V)	≥ 95
	% evaporated at 350°C		% (V/V)	≥ 85
	95% (V/V)		°C	≤ 360

Biodiesel content	EN 14078	% (V/V)	≤ 7.0
Aluminium	ASTM D7111	mg/kg	n.a.
Barium			n.a.
Calcium			n.a.
Chromium			n.a.
Copper			n.a.
Iron			n.a.
Magnesium			n.a.
Manganese			n.a.
Molybdenum			n.a.
Sodium			n.a.
Nickel			n.a.
Lead			n.a.
Silicon			n.a.
Titanium			n.a.
Vanadium			n.a.
Zinc			n.a.
Potassium			n.a.
Silver			n.a.

1.3 Identification and understanding of risks

This section includes the risks involved in the value chain and the roles of stakeholders in the value chain, including those that may been to be involved outside of the consortium. The most important stakeholders in the value chain that are outside of the consortium is the waste collection sites or companies such as pulp mills, waste water treatment sites, municipal organic waste collectors, municipalities (roadside grass) and contaminated wood collectors. Other stakeholders are the existing refineries with FCCs.

The risks have been reported in D5.7 and D8.3. The risks related to the value chain, and not the life cycle costing, are:

- Poor technical performance, resulting in a non-feasible value chain. This can be mitigated by extensive experimental work of different feedstocks (FP and HTL testing), bio-oil workup in refinery processes, and biofuel testing.
- Incomplete value chain (e.g. no or uncertain technical solution or solution cannot be developed within the project, resulting in a non-feasible value chain). This is mitigated by the large number of potential value chains.
- Logistics are underestimated, resulting in overestimation of the economic and sustainability benefits. This is mitigated by clearly stated assumptions for the logistics so that it is easy to see if the assumptions are realistic and accurate.
- Feedstock availability, e.g. other applications or technologies can create higher added-value competition for a feedstock, and as a result we cannot exploit the value chain on the locked feedstock. Alternatively, the feedstock price may increase, also resulting in a lost business case. Both these risks can be mitigated by feedstock diversification.
- The categorization of waste may change, so that a feedstock is no longer considered a waste. This might result in a lost business case, but can be mitigated by feedstock diversification.

2. Potential locations of the value chains

The value chains are based on the feedstocks and the waste collection facilities used for experimental work in the project. The feedstocks from other locations in Europe that can be utilized are termed the **simulated value chains** as these will be based on the models developed in WP3 and WP4 for these feedstocks. For the simulated value chains, the important assumption is made that the feedstock composition does not differ significantly from one site to another.

For example, if it is assumed that the composition of black liquor does not vary significantly between paper mills, then the liquefaction models based on black liquor from one region or mill can be used to simulate the HTL of black liquor obtained from a different region or mill. Consequently, the assumption that a type of feedstock is not bound to a specific region or facility enables the use of the models developed for the liquefaction of each feedstock, respectively, to be used in the simulated value chain development for industrial applications. Therefore, a value chain could be placed in an area where it makes most economic, social and environmental sense when the feedstock availability, volume, transport, facility locations and final refining and end-use are taken into account.

The primary objective is to develop attractive value chains that can be applied in as many countries and locations as possible. However, the feedstock cost, availability and transport considerations may be country specific. Not only is the number of potential value chains large, the physical placement of the liquefaction and upgrading facilities within a specific area or in whole Europe is large. To illustrate the extent to which the value chain can be optimized, an overview of the study done by Zhang & Wright (2014) for a fast pyrolysis and biorefinery system for the Minnesota state in America is given as an example [9]. The authors used a mixed-integer nonlinear programming (MINLP) model for the product selection and supply chain optimization. The MINLP model had 14 802 single equations, 41 337 variables and could take up to 30h to run. They considered forest residue (raw and roadside chipped biomass) as the selected feedstock and seven plant capacities ranging from 100 – 8000 t/day. The MINLP model was developed to determine the product distribution, optimal capacities, and locations of the fast pyrolysis and biorefinery facilities in Minnesota by maximizing the annual profit. As a result, 6 FP facilities and one biorefinery facility could be built for maximum profit, using raw biomass from 42 counties and roadside chipped biomass from 35 counties, shown in Figure 12.

However, considering that the WASTE2ROAD project includes more than one type of feedstock, liquefaction technology and country, a similar approach is expected unfeasible within the available time frame and resources. Instead, the initial approach was to find a suitable value chain per country. This was done by considering the feedstock. An overview of European countries of interest for black liquor, contaminated wood, MSOW (food residues and sewage sludge) and digestate are provided.

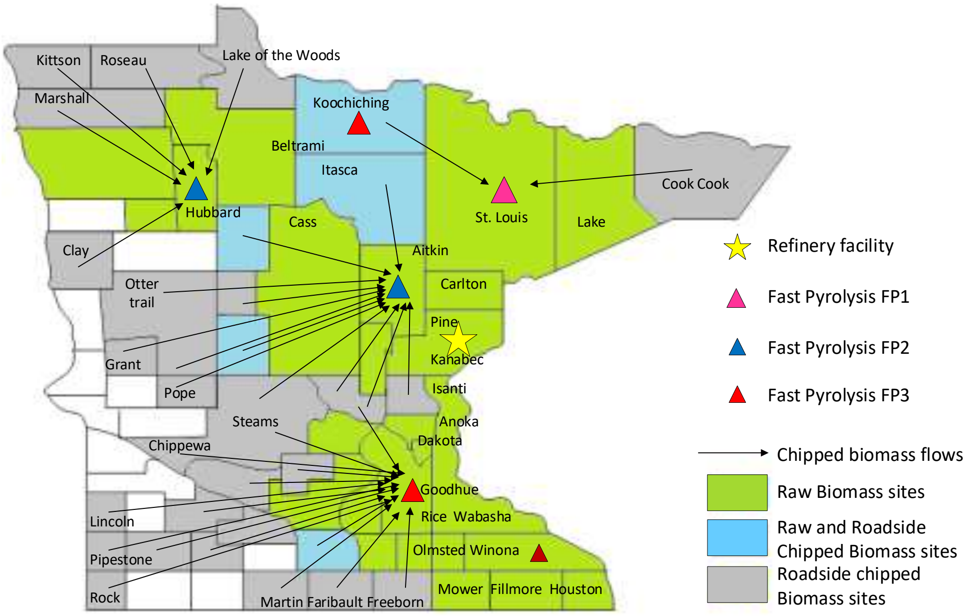


Figure 12: Optimal fast pyrolysis and refinery locations for a biomass distribution network in Minnesota (redrawn from Zhang & Wright, 2014, [9]*)*

2.1 Location options for Black Liquor

A pulp mill using the Kraft chemical pulping process produces 1.7 – 1.8 dry tonnes of black liquor (BL) per tonne of pulp, which can be used as potential energy source in the region of 250 – 500 MW per mill [10]. BL is usually treated to recover the sodium and sulphur components and burned for energy. Therefore, the BL used in the WASTE2ROAD value chain could be priced at the cost required to replace the sodium and sulphur components ‘lost’ to the liquefaction waste fraction. Although modern kraft pulp mills have a surplus of energy [10], the BL removed from the process may result in an energy deficit if the pulping mill is integrated with a paper mill, which can be made up by combusting bio-crude in the recovery boiler.

Market pulp is supplied by a few large mills in Finland, Sweden, Portugal, Spain, Austria, Germany and Poland [11]. However, Finland and Sweden have by far the largest pulp production per year, with 11.6 and 12.1 million tonnes, respectively, shown in Figure 13 [11]. As a result, BL is the key source of energy from biomass for Sweden and Finland [10]. The first countries of focus will be for **Finland and Sweden** due to their massive pulping production and close association with project partner VTT and BTG-BTL.

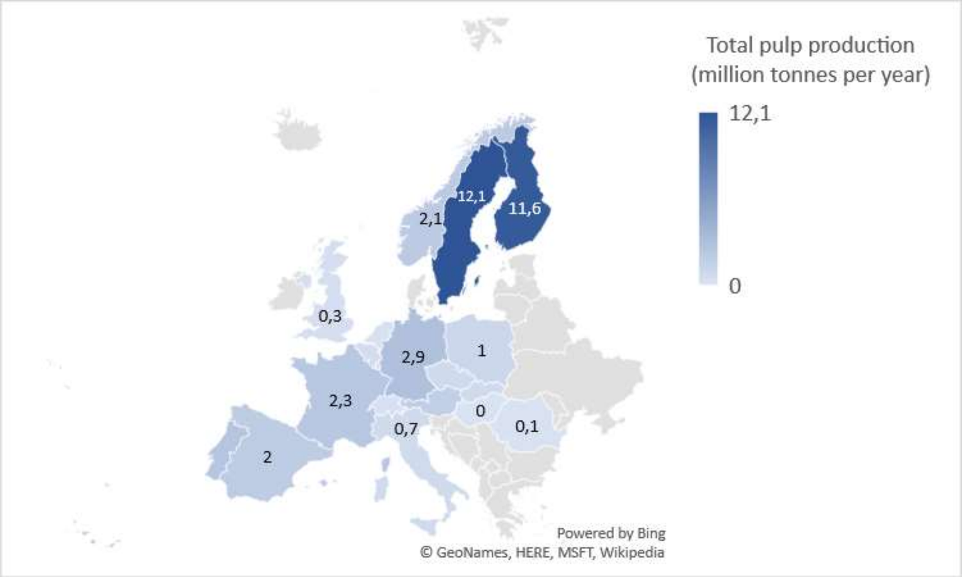


Figure 13: Total pulp production (million tonnes per year) per country [11]

In a modern pulp mill, the BL leaving the digestor (where the wood pulping takes place) is concentrated from 15 – 17 % solids to 70 – 80 % dry solids [10]. However, depending on the liquefaction feed requirements it could be that the high solid concentration is not required, which will result in an energy saving for the pulp mill. The typical elemental analysis and heating value of BL is provided in Table 18. Although the BL is rich in lignin, which has a high heating value, its inorganic content is high (+- 45 %), resulting in a relatively low heating value for BL [10].

In summary:

- 1.7 – 1.8 dry tonnes of black liquor (BL) is produced per tonne of pulp treated
- BL is priced at the cost required to replace the sodium and sulphur components 'lost' to the liquefaction waste fraction

Table 18: Elemental analysis and combustible characteristics

Component	Typical elemental analysis [10]
C	35.7
H	3.7
S	4.4
O	35.8
Na	19
K	1.1
Cl	0.3
N	<0.1
Total (%)	100
Combustible Characteristics	
BL, Dry solids	80 % Mass [10]
HHV	14.5 MJ/kg, DS
NHV	12.29 MJ/kg, DS

2.2 Location options for Contaminated wood and roadside grass

Contaminated wood can be classified as type A, B or C. Wood type A is chemically untreated, type B is chemically treated but not hazardous (incl. paint and glue), and type C is chemically treated and hazardous (incl. halogenated organic compounds or heavy metals used for wood preservation). The contaminated wood considered for this value chain is type B wood. The UK, Netherlands and Norway are the main exporters of non-hazardous (class or type B) and Sweden, Germany and Belgium are the main importers thereof [12].

As a first approach, **the Netherlands, Germany, the UK and Belgium** are of interest for this value chain. The annual market volume of type B wood in the Netherlands was 705 kt in 2004, of which 50 kt was used nationally and 655 kt was exported, mainly to Germany for utility use [13]. The transboundary shipments of Class B wood in North-western Europe in kilo tonne for 2016 is shown in Figure 14. The increasing use of contaminated wood for bioenergy production in the Netherlands has led to an increase in contaminated wood import (144 kt), accompanied by a reduction in the export of wood to Belgium. Likewise, it is expected that the UK will also reduce its wood exports due to the use of wood for bioenergy production. This might necessitate that the Netherlands and Germany will have to source type B wood from elsewhere in the future to sustain the demand for bioenergy use [12], or decrease the export of contaminated wood.

The price of contaminated wood is based on the delivery price of wood at the required board or energy company, and therefore includes the transport price [13]. The 2007 price for B-quality wood payable by energy companies in Germany was 7 – 15 €/ton air dry wood, compared to 20 – 30 €/ton air dry wood which was payable by the board industry in Belgium and Northwest Germany for A and B quality wood [13], shown in Table 19. The cost of disposal of type B and C wood has also been reported as 5 – 30 euros in 2008, presumably per air-dry ton [12]. This is similar to the prices quoted for 2014 at 17 €/ton minimum up to 40 – 50 €/ton on average. If the contaminated wood needs to be transported elsewhere, it will cost 40 €/ton to transport mixed waste in Germany [12].

Table 19: Cost of contaminated wood [12,13]

Class B wood	2007 [13]	2014 [12]
Low end Class B wood	7 - 15	17
High end Class B wood	20 - 30	40 - 50
Transportation of mixed waste	-	52 €/ton in Germany

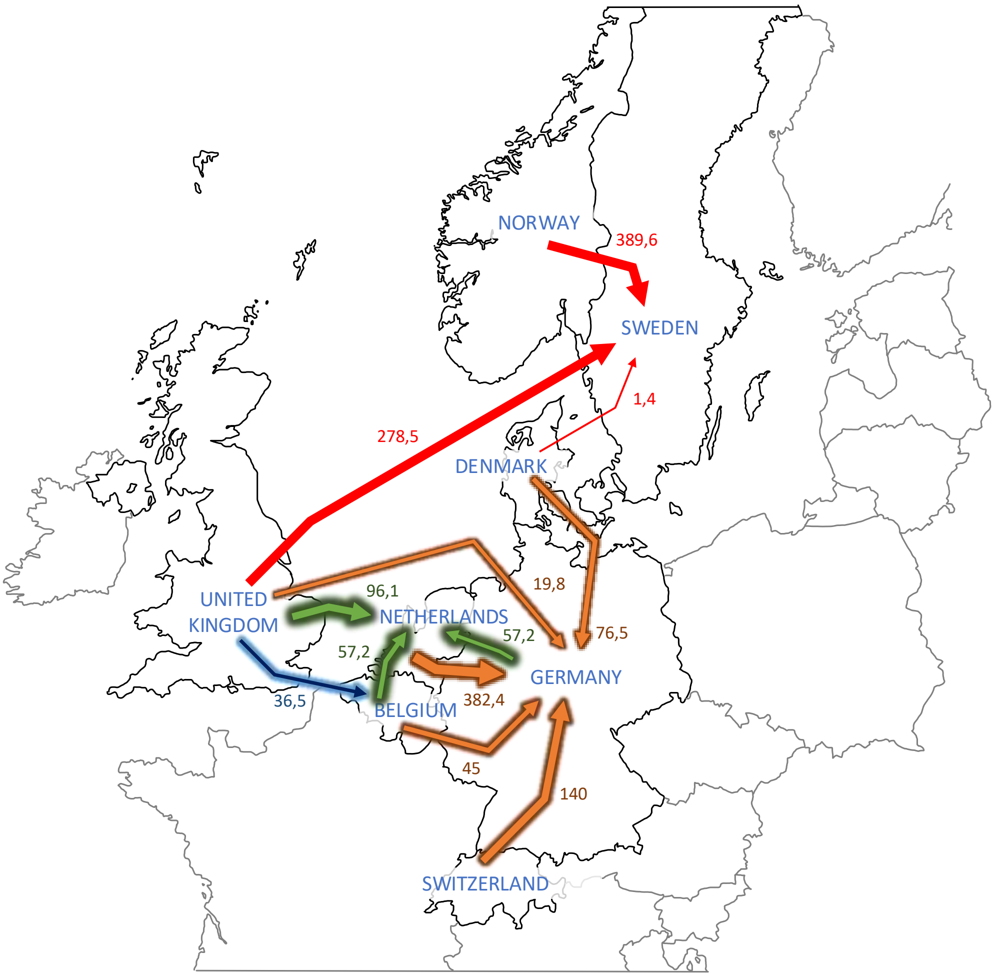


Figure 14: Transboundary shipments of Class B wood in North-western Europe in kilo tonne (2016) [redrawn from [12]*]*

Roadside grass or road verge clippings is a Low Input High Diversity (LIHD) biomass, since it is collected from land which is not designated for agricultural use and has no deliberate fertilizer addition [14]. It is also a lignocellulosic biomass, similar to wood, and since its regulations for use and transport is known, it will be considered for this value chain configuration in the Netherlands, where approximately 1 million tonnes of roadside grass is available annually [15]. The cost of processing the roadside grass varies from a few euros for the local processing of grass, to 10 – 20 €/ton (2014) for professional composting of the grass [15].

The use of roadside grass has also been investigated for the UK, in Lincolnshire specifically where there are 8750 km of high-way bounded by verge grass, for the use of biogas production through anaerobic digestion [14,16]. In Belgium, roadside grass is cut only two times per year, and it is not allowed to mow roadside grass before the 15th of June or leave the grass lying for more than 10 days [17]. Leaving the grass lying after mowing for several days decreases the moisture content from the initial 70 %, to about 50 % [18], but wilting may also decreases the biogas energy production potential due to respiration [14]. The total estimated verge grass available in Flanders is estimated at 72 kt dry material per year [17].

However, roadside grass is not listed in Germany's approved list of 'clean biomass' for energy production, due to the contamination thereof caused by the road traffic [15]. Therefore, no value chain containing roadside grass will be developed for Germany. Germany's roadside grass is currently treated via composting [15]. Therefore, the countries of interested for this value chain are Belgium and the Netherlands.

In summary:

- The annual market volume of type B wood in the Netherlands was 705 kt in 2004, of which
- 655 kt was exported, mainly to Germany for utility use
- Approximately 1 million tonnes of roadside grass are available annually in the Netherlands
- Cost of class B wood varies from 7 – 50 €/ton (DM)
- Transport of mixed waste is 52 €/ton in Germany

2.3 Location options for MSOW – Food residues

For the Municipal Solid Organic Waste (MSOW) food residues, food residue pre-treatment reject, sewage sludge and roadside grass has been identified. For this value chain, the focus is on the food residue resource. To identify the countries of interest for this feedstock, the annual food wastage per country was considered [19], in combination with the municipal waste treatment strategy of each country [20]. For countries with high percentages landfill and low waste-to-energy treatment reported, it could be stated that a need exists to utilize the MSOW generated in these countries to prevent it from being landfilled. The combination of these two datasets are shown in Figure 15.

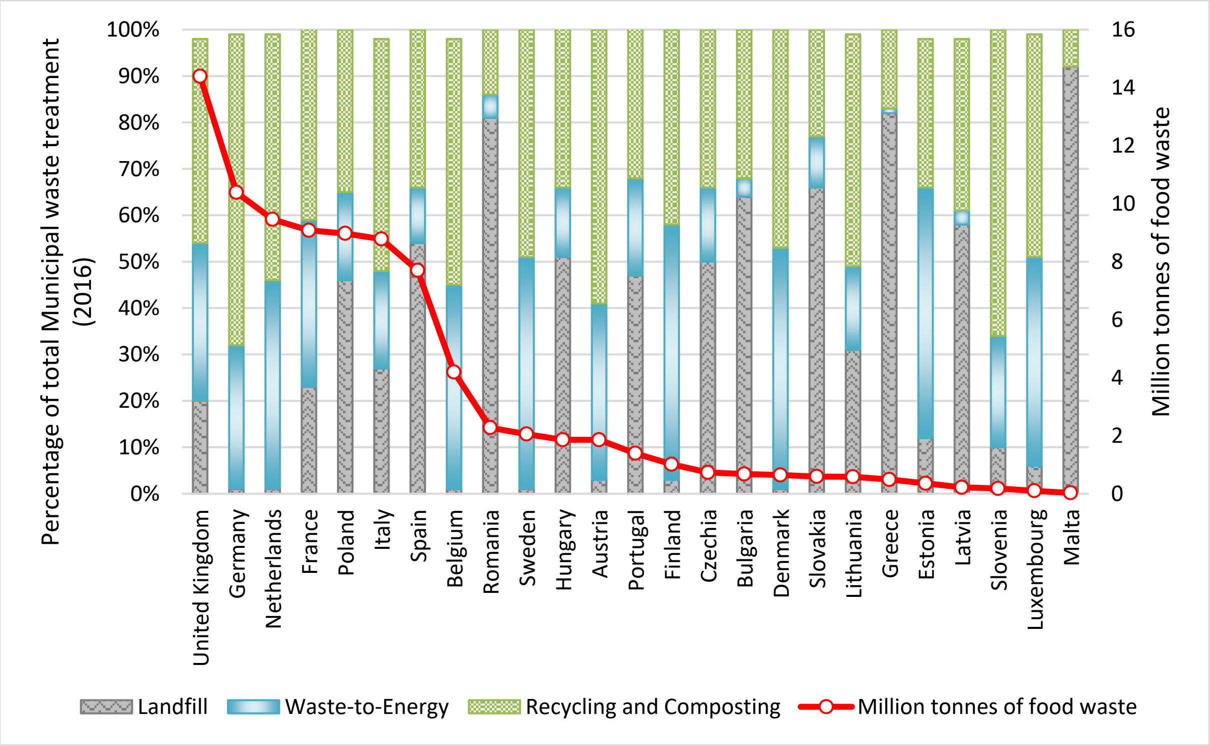


Figure 15: Annual food waste (red line) and municipal waste treatment strategy for landfill, waste-to-energy and recycling and composting [19,20].

When the data is filtered to remove countries with less than 10 % landfill, and sorted according to food waste, then the UK (14.4 million tonnes), France (9.1 million tonnes), Poland (9.0 million tonnes), Italy (8.8 million tonnes), and Spain (7.7 million tonnes) as the major food wasting countries identified [19], shown in Figure 16.

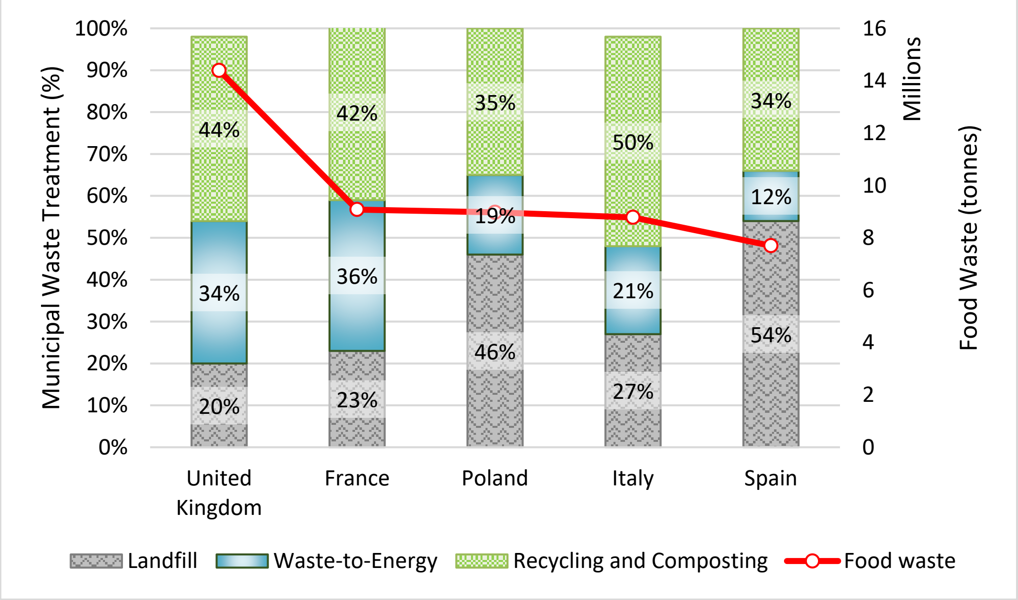


Figure 16: Municipal solid waste and food waste per year shown for the UK, France, Poland, Italy, Spain and Belgium [19,20].

On 3 February 2016, France passed legislation aimed at reducing food waste which placed them at the forefront of the international fight against food waste [21]. This progressive law mandates that supermarkets are not allowed to dispose of edible food and should recycle inedible food. Edible food should be donated to food banks and charities. As a result, France is ranked number one on food sustainability, with Italy placed at number 6 of 25 countries investigated [21]. Therefore, **France** was selected as the main country of interested for this value chain, since the producers of inedible food waste may actively be pursuing viable disposal routes. Alternatively, Italy, Poland, Spain and/or the UK could also be selected as potential countries for this value chain, since they have a high level of food waste and landfill with low waste-to-energy initiatives compared to the waste-to-energy initiatives of other EU countries such as the Netherlands (53 %) and Germany (67 %). Other countries of interest for this value chain are **Italy, Poland, and Spain**. The UK is selected for the contaminated wood and roadside grass feedstock.

2.4 Location options for MSOW – Sewage sludge

Sewage sludge is a product of aerobic digestion of waste water. The usage of sewage sludge as fertilizer is a controversial topic and the use thereof has been banned (i.e. in the Netherlands and Flanders) or restricted (i.e. in Denmark, Germany and Sweden) in several countries. This being said, sewage sludge that has been stabilized to eliminate all pathogens is Class A sewage sludge, which can be used as fertilizer in residential gardens and easily handled (i.e. with no restrictions) for selling and distribution. In Class B sewage sludge, the pathogens are reduced, but still present, and can be used as fertilizer on agricultural or non-agricultural land subject to any restrictions that might apply. The sewage sludge that is not used as fertilizer, is then either incinerated or landfilled. The data on Sewage Sludge production and disposal from Eurostat (updated 19-11-2018) is summarized in Figure 17 [22].

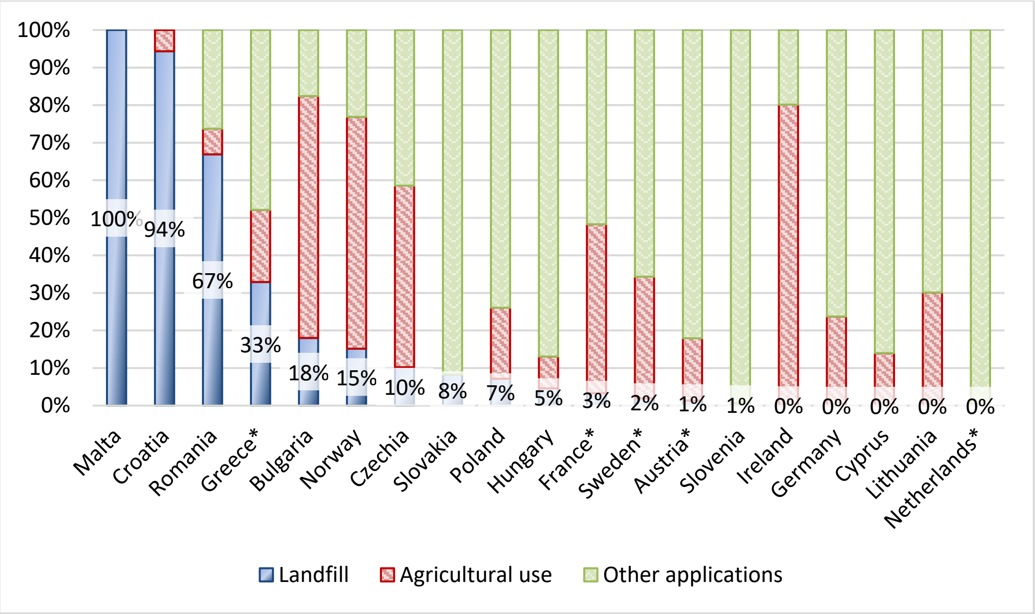


Figure 17: Sewage sludge landfilled, applied for agricultural use and other applications, as a percentage of the total sewage sludge disposal for 2015; Countries marked with an asterisk represent 2014 statistics (redrawn from [22]*)*

There are a number of countries that do not landfill their sewage sludge such as the Netherlands and Germany. When the countries with more than 10 thousand tonnes sewage sludge landfilled per annum are combined with the disposal method, Romania, Poland, Greece, France, Norway, Czechia and Croatia are potential countries for this value chain configuration, shown in Figure 18.

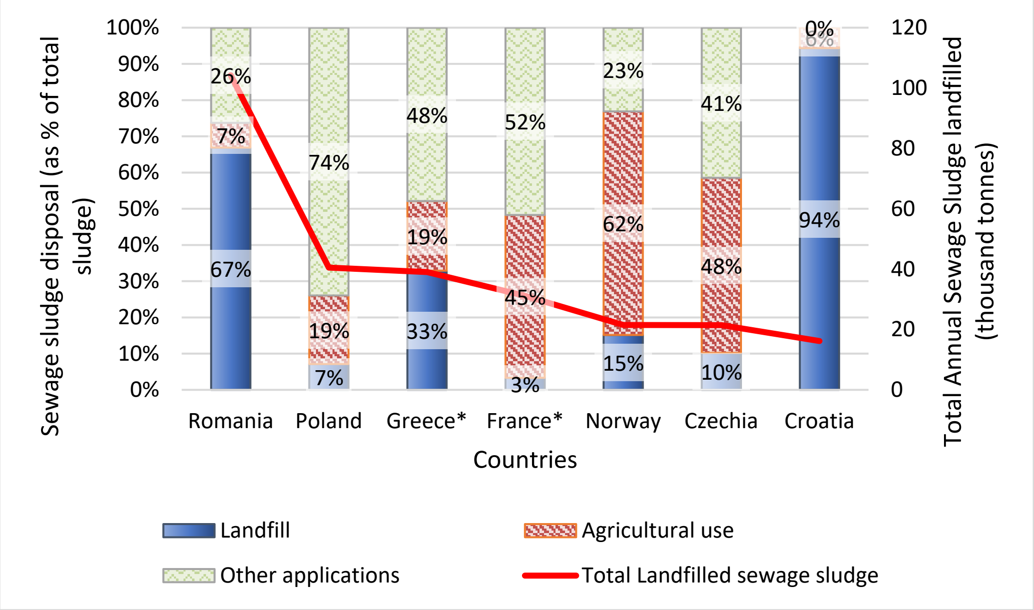


Figure 18: Total annual Sewage sludge landfilled (red line) with the sewage sludge disposal method as a percentage of the total sewage sludge disposal for 2015; Countries marked with an asterisk represent 2014 statistics (redrawn from [22]*)*

2.5 Location options for Digestate

Digestate is the solid fraction left from anaerobic digestion of organic material. Since there are no nitrogen, phosphorous or potassium present in the biogas (mainly CO_2, CH_4 and trace elements of SO_2), all of these elements will remain in the digestate. Therefore, 90 – 95 % of the material fed to the digestor will end up in the digestate.[3] Germany has the most developed biogas infrastructure with 62 % of the European biogas plants (i.e. approximately 8000 plants), followed by Italy with 9.5 %, UK (approximately 5.2 % [23]), Switzerland with 4.3 % and France with 4.2 % of the total biogas plants in 2013 [24]. The digestor feedstocks in Germany include agricultural feedstock (energy crops) sewage, and substrates such as industrial food and beverage biowaste.

2.6 Value Chain locations summary

As a general overview, the countries considered with their associated feedstock(s) are summarized in Table 7. At this point in time, no value chain configuration has been included for the countries shaded in grey, However, Finland and the Netherlands are also included. As a first estimate, there is one value chain per country, marked with a ‘P’ in Table 20, resulting in 17 potential value chains identified. Additional information, such as the feedstock volumes, distances between liquefactions facilities and the refinery process, and country specific policies and legislation can be used to further narrow down the list of potential value chains.

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[3] http://www.biogas-info.co.uk/about/digestate/ (Accessed 17/03/2020)

Table 20: Value chain configurations per country of interest for HTL (hydrothermal liquefaction) and FP (Fast Pyrolysis) per feedstock source.

European Countries	Black liquor	Contaminated Wood & Roadside Grass	MSOW – food waste	MSOW - Sewage Sludge	Digestate
Austria	**P**				
Belgium		**P**			
Bulgaria					
Croatia				**P**	
Cyprus					
Czechia				**P**	
Denmark					
Estonia					
Finland	**P**				
France	P		**P**	P	P
Germany	P	P			**P**
Greece				**P**	
Hungary					
Ireland					
Italy			**P**		P
Latvia					
Lithuania					
Luxembourg					
Malta					
Netherlands		**P**			
Poland	P		**P**	P	
Portugal	**P**				
Romania				**P**	
Slovakia					
Slovenia					
Spain	P		**P**		
Sweden	**P**	P			
United Kingdom	**P**	P			
Norway		P		P	

3. Conclusion

This deliverable report describes the identified value chains from biogenic residues and waste fractions to biofuels. The value chains have been characterised on feedstock availability and composition, routing, logistics, and processing steps, and the identification of potential locations and risks.

Based on experimental results initial mass balances were established for the pre-treatment of the specific biogenic residues or waste fractions, conversion through fast pyrolysis or hydrothermal liquefaction to intermediate bio-oils, and upgrading and co-refining of the bio-oils to bio-fuels. For the assessment of integration potential, the concept of centralized versus decentralized plants have been investigated as well as feedstock diversification, transport considerations, year-round availability of feedstocks, intermediate storage, and the stability of the organic waste during storage and transport.

Although the value chains are based on the location of the feedstock providers and the respective feedstocks tested in the experimental work, a second approach of the simulated value chains is also followed. This approach takes a wider view on the European context and on how the WASTE2ROAD technology developed in this project can be applied to waste feedstocks available throughout Europe, thereby highlighting future exploitation opportunities.

The identified value chains are therefore:

1. HTL Value Chain 1: Food residues
2. FP Value Chain 1: Contaminated wood
3. FP Value Chain 2: Contaminated wood and roadside grass
4. FP Value Chain 3: Digestate
5. FP Value Chain 4: Municipal solid organic waste
6. FP Value Chain 5: Sewage sludge
7. FP Value Chain 6: Sunflower husks

These value chains will be further developed and evaluated by life cycle costing and impact assessment. The outcome will be applied for WASTE2ROAD exploitation through the development of business cases.

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