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FlexSNG

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1.1	25/02/2022	Final data review	WOOD, CERTH, EIFER, VTT, SF
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Disclaimer

Table of Content

Abbreviations and acronyms

mngt	management
CA$	Canadian dollar
odt	oven-dry tonnes
g	gram
dw	dry weight
d.b.	dry basis
wt%	weight %
m	10^{-3}
k	10^{3}
M	10^{6}
G	10^{9}
T	10^{12}
Wh	Watt hours
RDF	Refused derived fuel
SRF	Solid recovered fuel
SNG	Synthetic Natural Gas

1 Executive summary

This report is part of Task 2.1 of the FlexSNG project, where the specific objective is to identify and assess the availability, quality, and costs of biomass residue and biogenic waste feedstocks in Northern (represented by Sweden and Finland), Central (Germany and France), and Southern Europe (Italy and Greece), and Canada (represented by five target regions); as well as to evaluate the suitability of these feedstocks for the FlexSNG gasification process. The result will be transferred to later project activities and help focus coming work in some suitable feedstocks for more in-depth analyses. The feedstock description is based on open-source data compiled by the project partners as well as experiences from the project group. The analyses based on the feedstock description indicated that the most suitable resources vary between countries. In forest rich countries, such as the Nordics and Canada, the largest share of suitable feedstocks will be origin from the forest sector, however, straw is also available in large quantities in the Nordic countries. The large central European countries (Germany and France) have suitable feedstocks from all the target areas (forest, agricultural and biogenic waste). In Southern Europe, the share of agricultural feedstock streams is more important. Most of the forest feedstocks is suitable for the process, the agricultural residues often come with some challenges and the biogenic waste is the most challenging feedstock, except for wood waste which has many similarities to forest biomasses. The market price is often the other way around. Waste feedstocks can be available to a negative cost, agricultural residues can occasionally be collected for free but most agricultural feedstocks comes with a cost for delivery. The forest feedstocks have in general the highest prices.

2 Introduction

The overall objective of the FlexSNG project is to develop a flexible and cost-effective gasification-based process for the production of pipeline-quality biomethane, high-value biochar, and renewable heat from low-quality biomass residues and biogenic waste feedstocks. The flexibility of the gasification process lies in the ability to switch between two operation modes to produce a mix of end-products (biomethane, biochar and heat) that meets current price signals and market demand. At the same time, cost-effectiveness compared to state-of-the-art biomass-to-SNG technologies is expected by the combining of gasification process development and feedstock supply chain optimisation.

This report is part of Task 2.1 of the FlexSNG project, where the specific objective is to identify and assess the availability, quality, and costs of biomass residue and biogenic waste feedstocks in Northern (represented by Sweden and Finland), Central (Germany and France), and Southern Europe (Italy and Greece), and Canada (represented by five target regions); as well as to evaluate the suitability of these feedstocks for the FlexSNG gasification process. The highest-potential feedstocks will be transferred to Tasks 2.2-2.3 to define or describe tailored strategies for collection or harvesting, pre-treatment, and co-handling operations. The results of the analysis will provide necessary input to both development of feedstock supply chain models in Tasks 2.4-2.5, and the selection of feedstocks for case studies in Work package 8.

Residues and by-products generated within either the forestry or the agricultural sector, and the society through waste of various kinds constitute the three main sources of feedstock presented in this report. These resources are in relative and general terms available at low cost and/or have limited competitive use, aligning with the overall project goal of obtaining significant cost reductions with the FlexSNG concept. Project partners based in the four targeted regions have identified feedstocks and collected data on their quality, regional availability, and market price. While the aim has been to cover most feedstocks that could be relevant to the FlexSNG gasification process, it should be noted that this review is not complete in that sense, nor in the sense of identifying all available volumes of the feedstocks that are covered.

3 General description of identified feedstocks

Feedstocks identified in the forestry and agricultural sectors or in biogenic waste streams are presented in respectively subsections 3.1, 3.2, and 3.3. The aim is to give a general description of the identified feedstocks, addressing in particular the aspects of importance for thermochemical conversion.

3.1 Residues from the forestry sector

Identified feedstocks from the forestry sector include primary residues generated at the time of harvest, and industry by-products generated during processing at industries. An overview of feedstock categories is given in Figure 1.

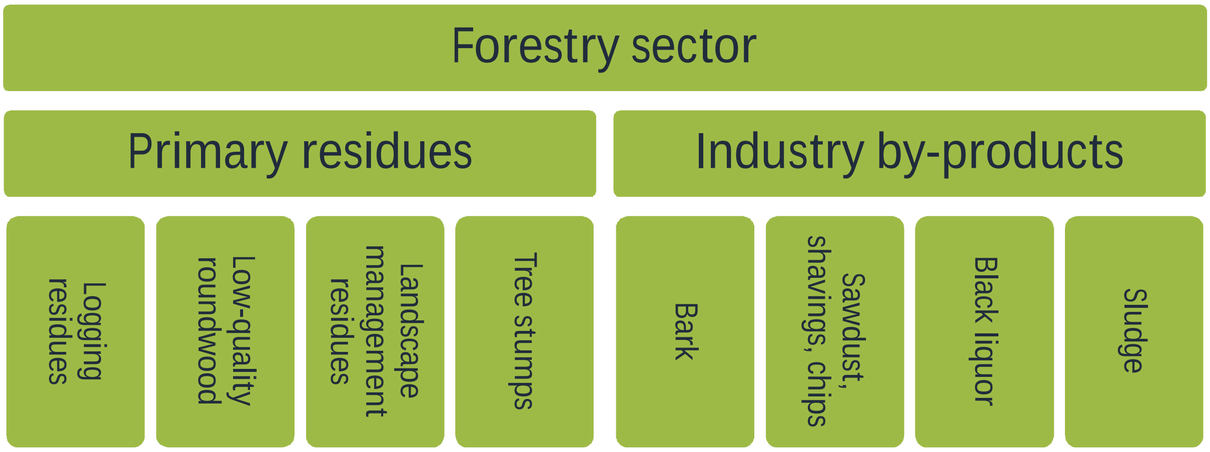


Figure 1. Categories of identified feedstocks within the forestry sector.

Figure 4 shows the ranges of moisture and ash content, heating value (LHV), and density, and averages of elemental and ash compositions of the identified feedstocks. In general, forestry residues and forest industry by-products are similar in their composition. Woody biomass consists of water, cellulose, hemicellulose, lignin, extractives, and ash elements derived from minerals within the wood or from contamination by soil. The moisture contents are to a large extent dependent on storage methods and conditions. Variations in ash content and composition are, in addition to natural variation within and between species, due to for example different soil types and different levels of contamination by sand and gravel.

Sawdust, shavings, and chips are by-products from various wood-working operations at sawmills and consist of pure wood without contaminants. The moisture content is predictable with good accuracy: dry and moister by-products are generated from the processing of respectively dried and fresh wood. The ash content is low in general. Pre-processing can be applied to improve thermochemical or other properties; for example, sawdust can be pelletized to facilitate handling (Strömberg and Herstad, 2012).

Bark is the by-product from debarking at sawmills and pulp and paper mills. Bark has slightly higher ash content compared to pure wood, mostly due to the contact with soil during handling and therefore a higher risk of contamination. But pure bark also contains more ash compared to pure stem wood. The ash composition varies widely, differing in some elements by more than 100 percent between samples. In combustion applications, there is a risk of high-temperature corrosion. The heating value differs between tree species and bark fractions. The moisture content is in general high. The particle sizes and shapes are irregular, thus a frequent need for pre-processing in order to meet feeding system and other combustion requirements (Strömberg and Herstad, 2012).

Black liquor is the by-product from the digesting of pulpwood into pulp at pulp and paper mills and consists of lignin, hemicellulose, and chemicals such as sodium hydroxide and sodium sulfide. The moisture content is initially high but is reduced prior to combustion in a conventional recovery boiler. The heating value is low due to high moisture and ash content.

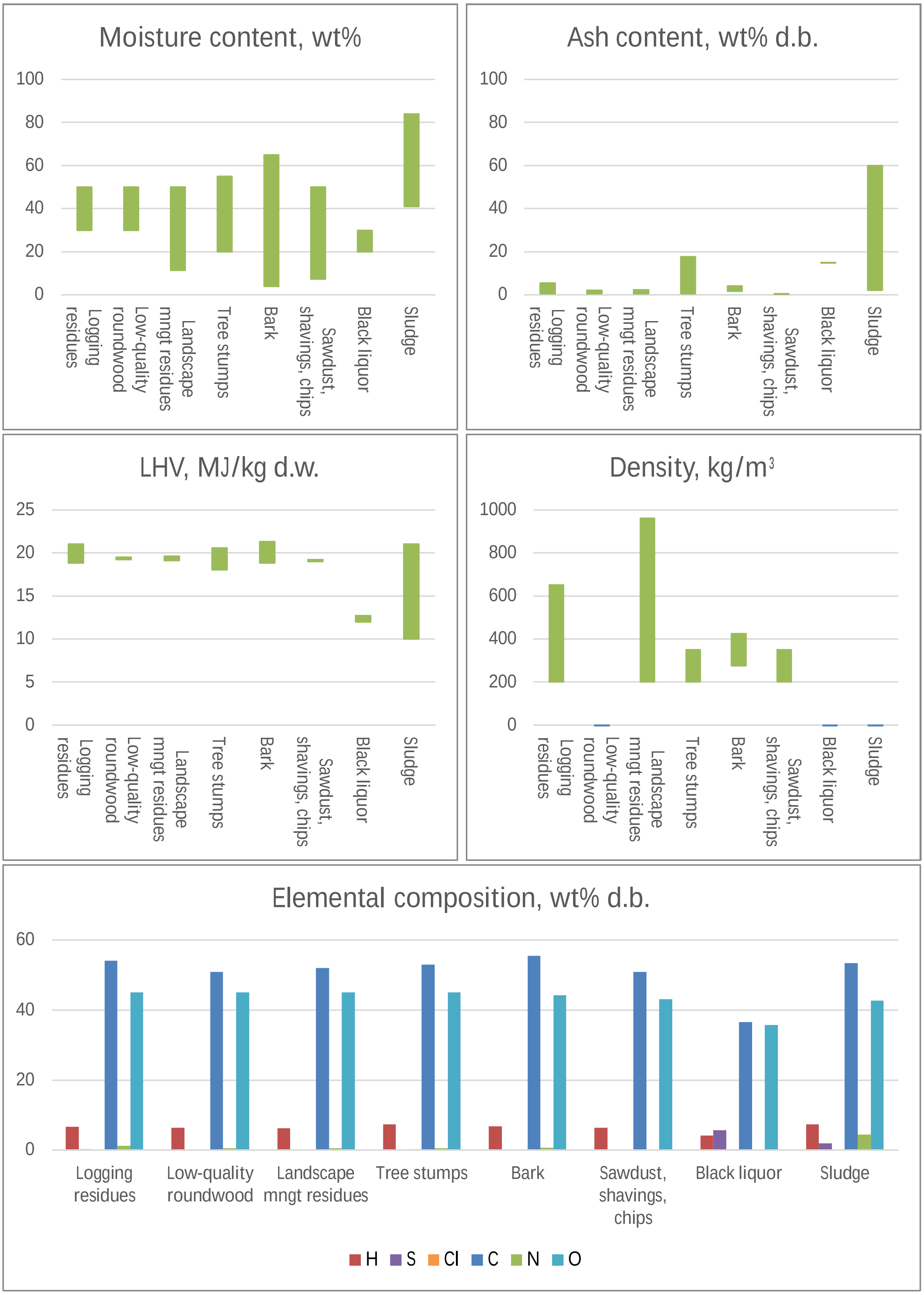
Sludge is the by-product from wastewater treatment at pulp and paper mills. Sludge has a high moisture content and must be dried, de-watered, or mixed with other dry assortments to meet combustion requirements. The dry part is similar to pure wood in elemental composition, but the ash content is higher. Some ash elements are of low-temperature sintering type, and there is a risk of heavy metals. The heating value is low due to the high moisture and ash content (Strömberg and Herstad, 2012).

Logging residues refer to treetops and branches generated in the forest at the time of harvest, **low-quality roundwood** to logs deemed unmerchantable due to defects, and **landscape management residues** to trees and brushwood removed at pre-commercial thinning or obtained from other silviculture operations, such as cleaning of roadsides and powerline corridors. These assortments are more divergent in moisture and ash content than the industry by-products, the handling of the material and the storage conditions playing important roles. For example, primary residues could dry under favorable conditions but also rewet during periods of heavy rainfall, and there is an obvious risk of contamination by soil during handling in the forest that affects both ash content and composition. Low-quality roundwood is in general not contaminated by soil; however, by definition, there could be other quality-affecting defects present such as root-rot and damages by insect infestations or forest fires. Moreover, the particle size distribution of primary residues depends, among other factors, on the stem diameters, which are subject to large variations. Methods exist to variate the chipper or crusher outputs towards finer or coarser particle sizes depending on end-user requirements, but the utilization of these techniques is still limited. Figure 2 shows a picture of the screening process which separates chips into fractions of different particle size (Eliasson et al., 2021). Logging residues and landscape management residues consist mainly of small-diameter trees or tree parts, for which the proportion of bark is higher with a possible effect on the quality. In addition, the presence of pine and spruce needles in these residues gives a higher nitrogen content.

Figure 2. Quality enhancement by separation through screening of logging residue chips into a coarser accept fraction and a finer reject fraction. (Photo: Eriksson, Anders)

Tree stumps refer to the trunk and roots below the felling cut, and removal requires specific stump harvesting processes. Given the inclusion of tree parts below ground, contamination by soil is inevitable. Tree stumps can still be of high quality and use if handled properly throughout the supply chain. Blunt tools such as grinders, shredders, and crushers are less sensitive to wearing effects of stones and gravel (Goldstein & Diaz 2005) and should therefore be considered before knife-equipped chippers. The difference in output between these two comminution techniques can be seen in Figure 3.

Figure 3. The result of two different comminution techniques: chipped roundwood (left) and grinded stump biomass (right). (Photo: Eriksson, Anders)


Moisture content, wt%
100
80
60
40
20
0
Logging residues
Low-quality roundwood
Landscape mngt residues
Tree stumps
Bark
Sawdust, shavings, chips
Black liquor
Sludge
Ash content, wt% d.b.
LHV, MJ/kg d.w.
25
15
10
5
Density, kg/m3
1000
800
600
400
200
Elemental composition, wt% d.b.
H
S
Cl
C
N
O

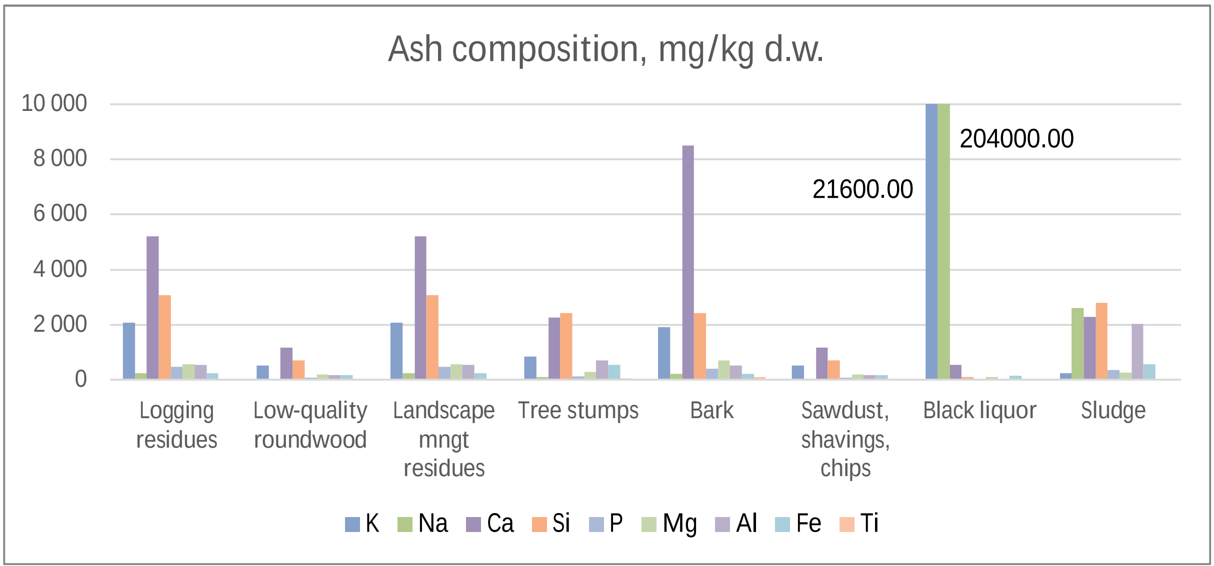


Figure 4. (incl. previous page) Characteristics and quality parameters for the included forest feedstock categories. Presented values are the ranges (for moisture and ash contents, LHV, and density) or averages (for elemental and ash compositions) of assortments identified within each category. Data sources are listed in Section 7.2.

3.2 Residues from the agricultural sector

Identified feedstocks from the agricultural sector include primary residues generated in the field, energy crops grown for energy production purposes, and various industry by-products generated during processing at industries. An overview of identified feedstock categories is given in Figure 5.

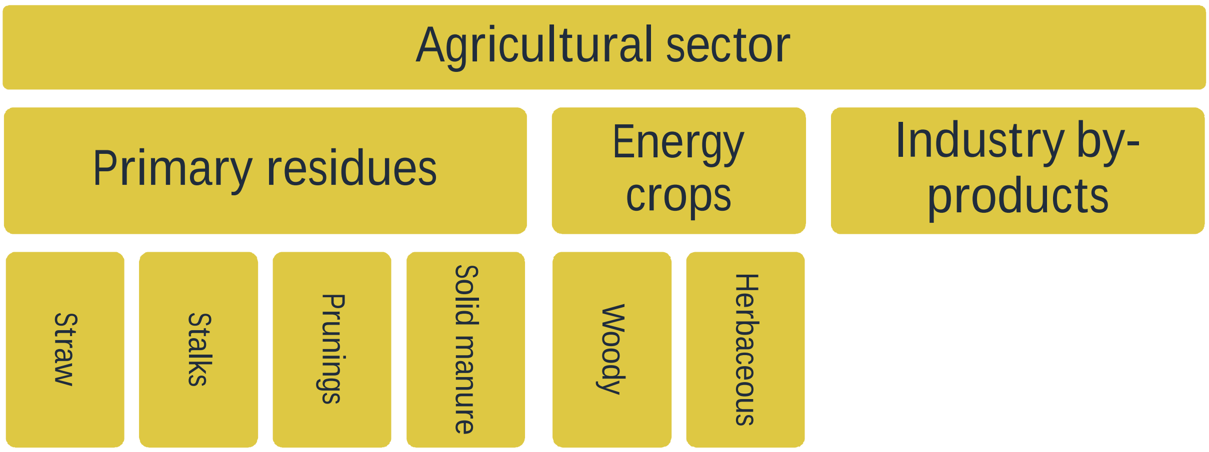


Figure 5. Categories of identified feedstocks within the agricultural sector.

Figure 6 shows the ranges of moisture and ash content, heating value (LHV), and density, and averages of elemental and ash compositions of the identified feedstocks.

Straw is the dry stalks of cereals with characteristics depending on both natural variations between cereal species and outer conditions such as weather and soil type. The ash content is high with high levels of chlorine and potassium, but a substantial reduction can be obtained if stored outside (Strömberg and Herstad, 2012). The thermochemical challenges associated with a high ash content can also be dealt with by co-combustion (Martinsson, 2003). Cleaning from soil particles can still be needed, as well as pre-treatments to handle the large content of lignocellulose. The low energy density and the particle shape are often challenging in many aspects (e.g., with respect to transportation or feeding system requirements), but pelletization or briquetting is possible.

Stalks refer to the stalks of non-cereal plants such as e.g. maize and cotton.

Prunings refer to woody residues from agricultural pruning operations, such as branches of fruit trees or grapevine. Prunings have similar characteristics as forestry biomass, but levels of calcium, magnesium, and potassium are in general higher (Strömberg and Herstad, 2012).

Solid manure is a mixture of excrements and bedding materials and is often directly used at the farms as fertilizer, but utilization as a biogas feedstock is possible. A clear advantage of solid manure is its continuous availability throughout the year, but on the other hand, the high water content makes it expensive to transport and sets requirements for pre-drying, especially of the solid manures from pigs and cattle. The ash content is high with important levels of sulfur and chlorine, implying risks of fouling, sintering, or corrosion in combustion applications. The exact characteristics are dependent on the bedding material, where straw, sawdust, peat, or even recycled paper is seen. For example, different bedding materials result in different levels of alkali, and the low ash melting temperature in straw can cause problems if solid manure from straw beddings is used (Strömberg and Herstad 2012).

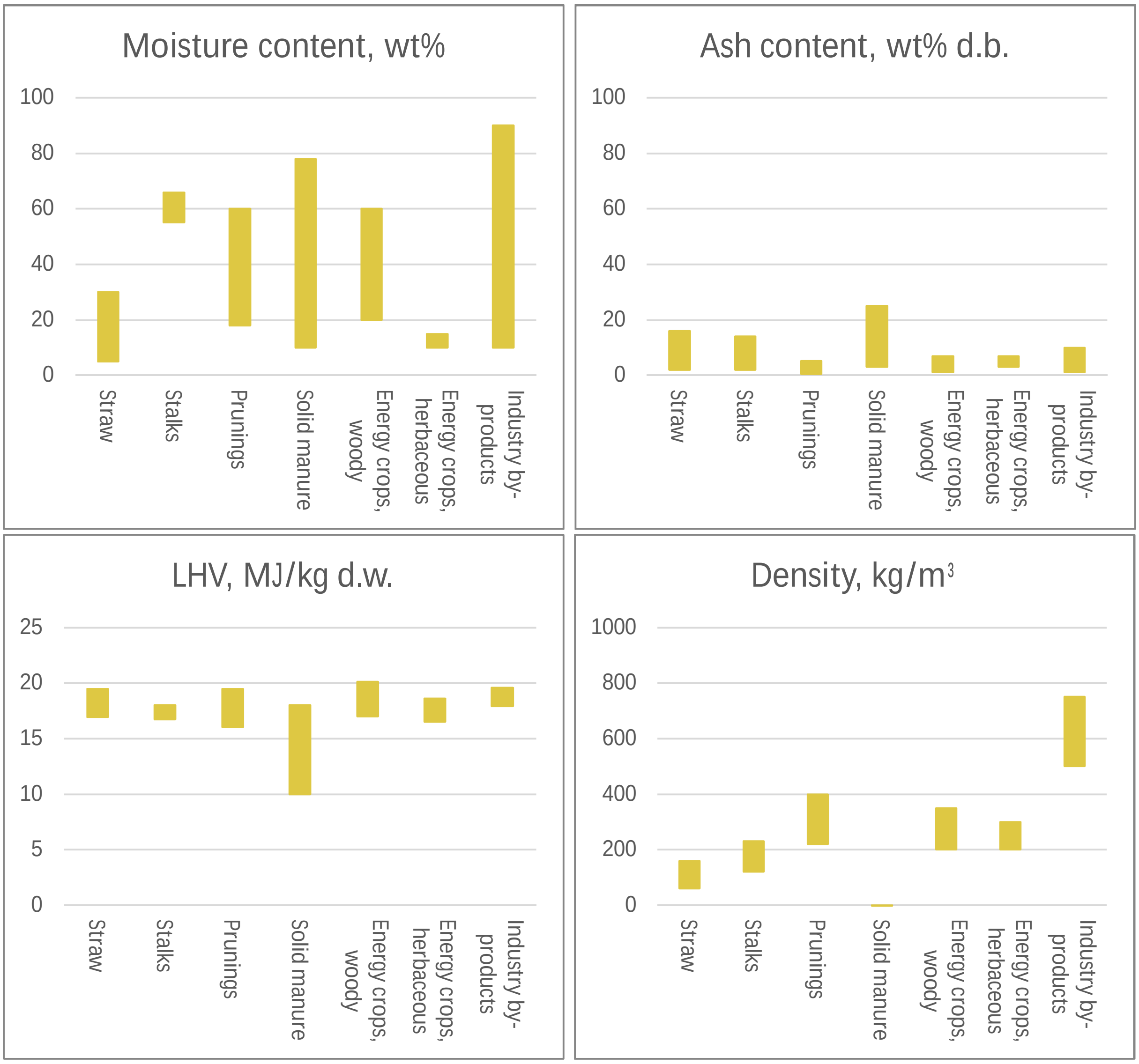
Woody energy crops are fast-growing trees grown for energy production purposes. Willow in particular is associated with high levels of heavy metals and low ash melting temperatures, the latter causing a risk of fouling. The levels of nitrogen, sulfur, and chlorine are higher than in pure wood which can affect emissions. The particle size distribution is homogeneous with few fine particles as a result of the evenly shaped small stems. The moisture content in unprocessed willow is subject to little variation thanks to the bark acting as a barrier, however, the variation between two different batches can be large depending on storage time (Strömberg and Herstad, 2012).

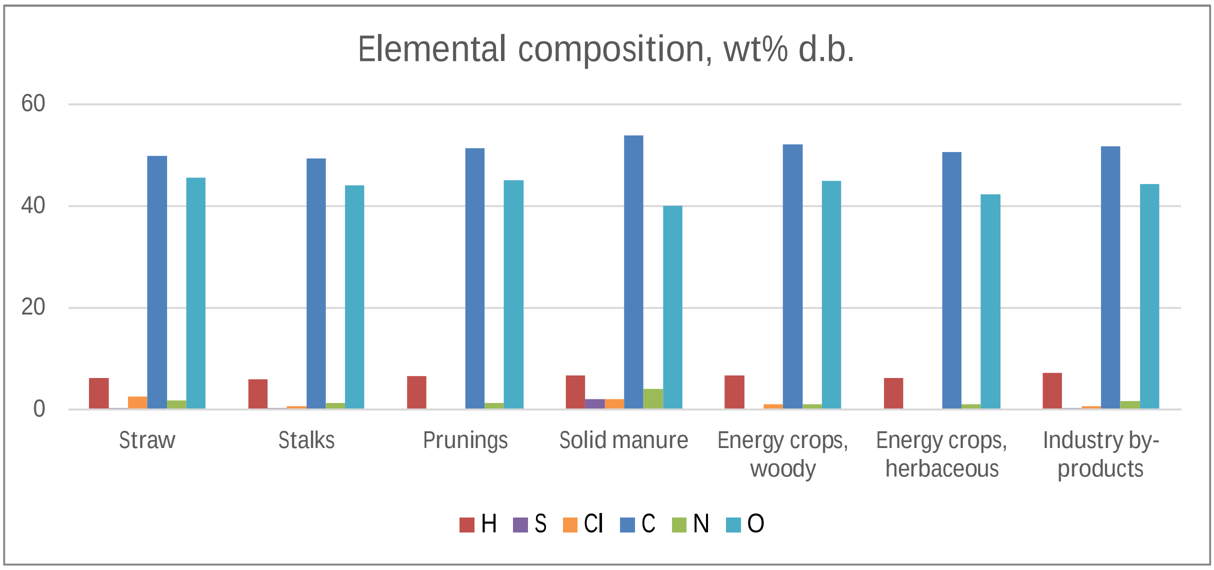
Table 1. Metal content in willow, straw, and forest chips (Hjalmarson and Ingman, 1998).

	Willow mg/kg dw	Straw mg/kg dw	Forest chips mg/kg dw
Cadmium	0.8-2.9	0.1-0.5	< 0.15
Nickel	0.5-0.7	0.3	0.5
Lead	1-2	0.2-0.3	1.1
Zink	50-100	5-12	20
Mangan	30-80	20-35	347
Cupper	3-5	1	13

Herbaceous energy crops refer to non-woody plants including, for example, reed canary grass, miscanthus, and hemp. The ash content is strongly dependent on the soil type, but the level can be high and risks of sintering should be considered in a combustion application. As with straw, handling of the material could be a challenge due to the low bulk density. The levels of nitrogen, sulfur, and chlorine are higher than in pure wood which affects emissions. The bulk density is also low and is associated with a challenging handling (Strömberg and Herstad, 2012).

Industry by-products from the agricultural sector are assortments of various origins, such as olive stones and olive cake obtained from olive oil production and rice husks obtained at rice mills. Although the characteristics can vary by large amounts between these assortments, individual streams are generally homogeneous as an effect of being the by-product of an industrialized process. Rice husks, olive stones, and olive cake have low or even near-zero moisture content, but by-products at the other end of the spectrum can also be found. Olive residues have a problematic ash composition which indicates large potential problems with fouling and corrosion. The general high ash content and high levels of alkali is challenging. As for other biomass assortments, storage of dry olive residue is uncomplicated but storage related problems for more moist residues have been reported. (Strömberg and Herstad 2012). Although *Rice husks* is an industry-byproduct as olive stones and cake, it has more similarities to straw and stalks in a chemical perspective. The ash composition is also similar as for straw and stalks, which indicates that similar challenges as described for straw can be expected. The ash composition in olive stones and olive cake with high levels of alkali implies a risk of fouling and corrosion. As for rice husks, the composition is similar to that of straw.


Moisture content, wt%
100
80
60
40
20
0
Straw
Stalks
Prunings
Solid manure
Energy crops, woody
Energy crops, herbaceous
Industry by-products
Ash content, wt% d.b.
100
80
60
40
20
0
Straw
Stalks
Prunings
Solid manure
Energy crops, woody
Energy crops, herbaceous
Industry by-products
LHV, MJ/kg d.w.
25
20
15
10
5
0
Straw
Stalks
Prunings
Solid manure
Energy crops, woody
Energy crops, herbaceous
Industry by-products
Density, kg/m3
1000
800
600
400
200
0
Straw
Stalks
Prunings
Solid manure
Energy crops, woody
Energy crops, herbaceous
Industry by-products



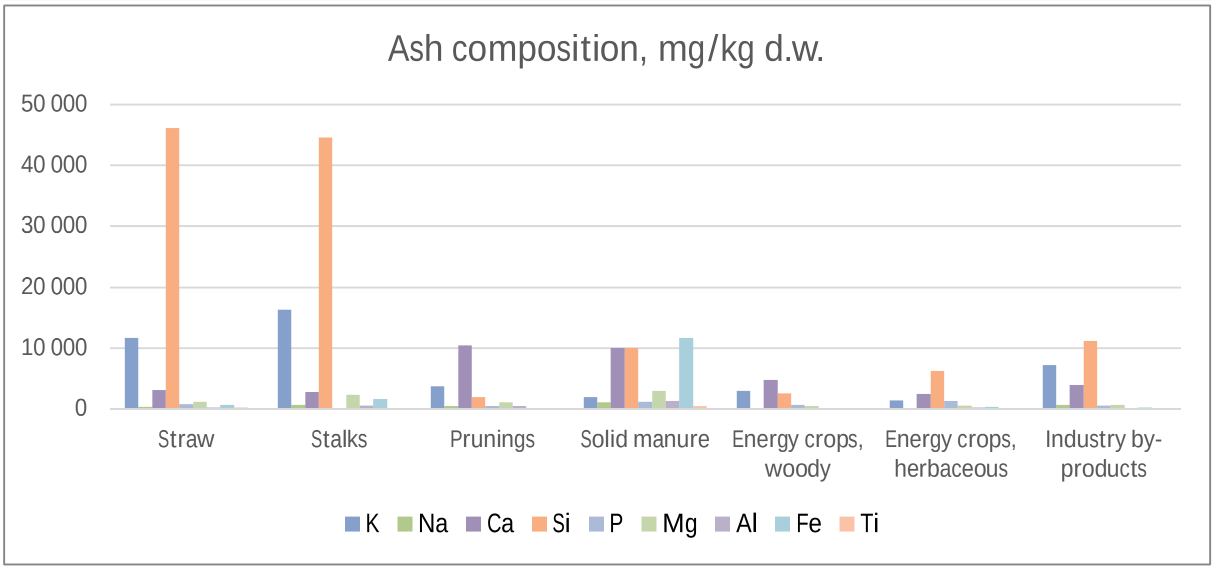


Figure 6. (incl. previous page) Characteristics and quality parameters for the included agricultural feedstock categories. Presented values are the ranges (for moisture and ash contents, LHV, and density) or averages (for elemental and ash compositions) of assortments identified within each category. Data sources are listed in Section 7.2.

3.3 Biogenic waste streams

According to the definition set by the Waste Framework Directive, bio-waste comprises “biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises, and comparable waste from food-processing plants”. An overview of identified feedstocks from biogenic waste streams is given in Figure 7.

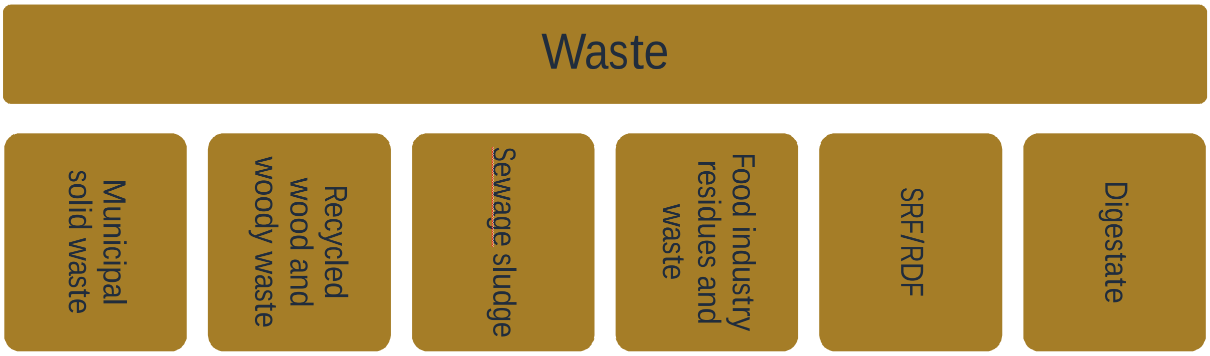


Figure 7. Categories of identified feedstocks from biogenic waste streams.

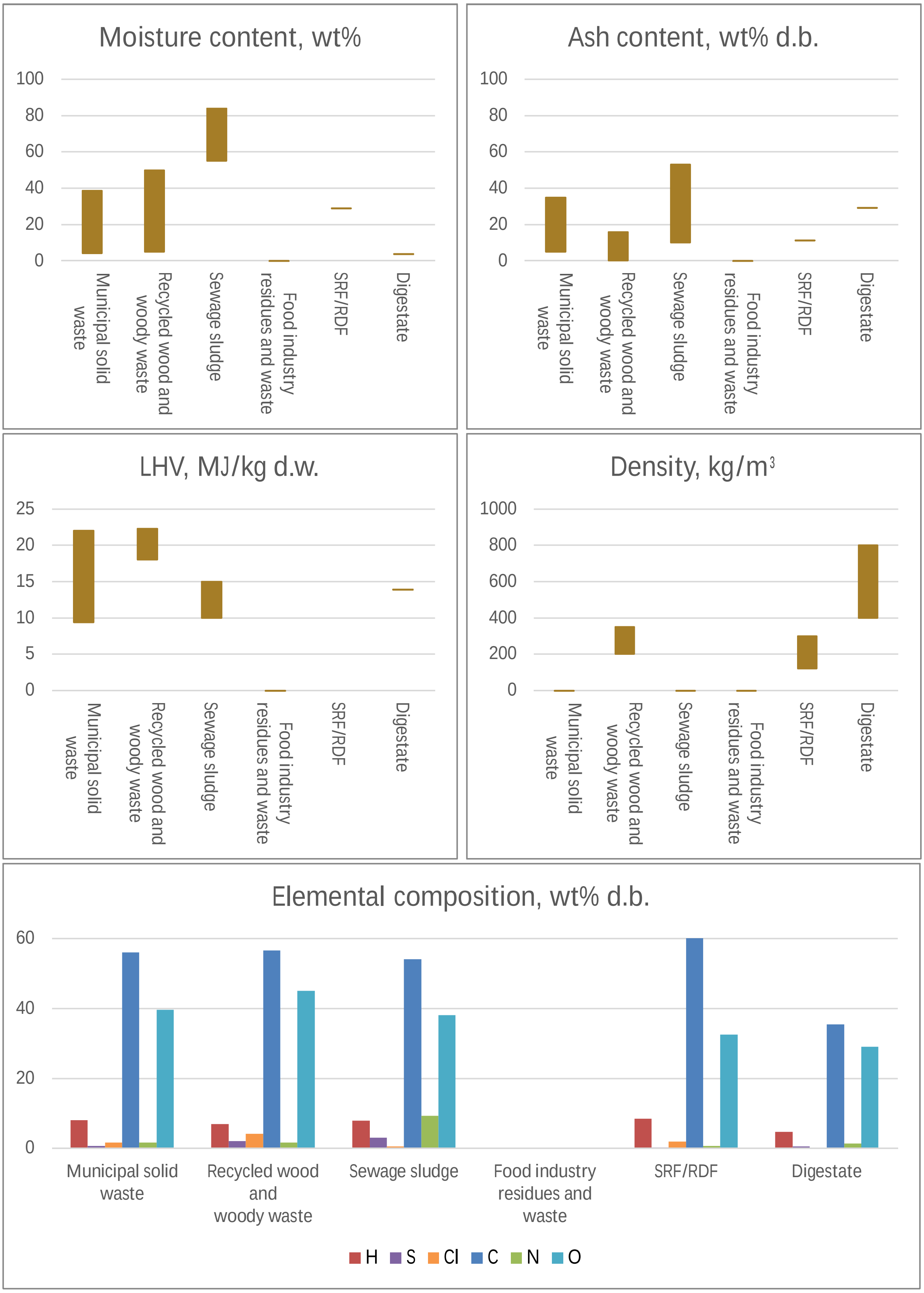
Figure 9 shows the ranges of moisture and ash content, heating value (LHV), and density, and averages of elemental and ash compositions of the identified feedstocks. The biogenic waste sector offers a wider spectrum of feedstocks compared to the forestry and agricultural sectors. The feedstock characteristics differ between waste streams but are also highly dependent on the choice of collection, sorting, and other processing methods. Available and frequently used methods vary by country or region.

Municipal solid waste consists of garbage from a number of sources that is discarded by the public (i.e., not industries). The composition varies by region for previously mentioned reasons.

Recycled wood and woody waste consists mainly of demolition and recycled construction wood and is similar to dry forestry residues in composition, but contamination is by natural causes more pronounced. High levels of zinc and lead are found in surface treated wood, whereas the levels of cupper, chromium, and arsenic are high in impregnated wood. Mechanical contaminants are also found, such as plastics, metals, stones, and minerals (Strömberg, 2012), as well as inorganic items such as clay bricks and plasterboard pieces. The particles are highly irregular and sizes ranging from dust to long slivers are seen, as pictured in Figure 8. The garden waste fraction of municipal waste, consisting of brush wood and small trees from public or private cleaning and pruning, is another type of wood waste stream.

Figure 8. Waste wood chips at a Swedish district heating plant. (Photo: Eriksson, Anders)

Sewage sludge is sludge from sewage treatments plants. In Sweden, sewage sludge is often digestated after mechanical, biological, and chemical treatment. Experiments with sewage sludge have indicated successful use as an additive in co-combustion with other biomass assortments to avoid sintering and agglomeration in fluidized beds. The moisture and ash contents are high, the latter amounting to 40-50 percent in some cases. The exact ash composition is dependent on the chemical treatments.


Moisture content, wt%
Ash content, wt% d.b.
LHV, MJ/kg d.w.
Density, kg/m3
Elemental composition, wt% d.b.
Municipal solid waste
Recycled wood and woody waste
Sewage sludge
Food industry residues and waste
SRF/RDF
Digestate
H
S
Cl
C
N
O

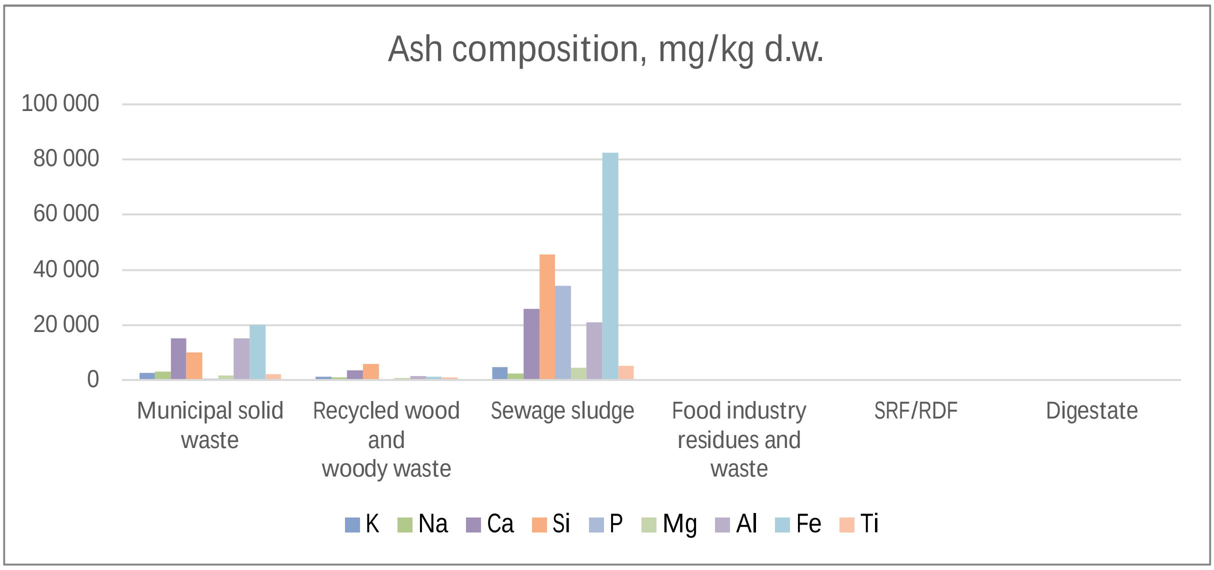


Figure 9. (incl. previous page) Characteristics and quality parameters for the included biogenic waste categories. Presented values are the ranges (for moisture and ash contents, LHV, and density) or averages (for elemental and ash compositions) of assortments identified within each category. Data sources are listed in Section 7.2.

4 Availability and market price of identified feedstocks

Many factors influence the potential and availability of different biomass assortments. The two terms potential and availability are used in the following sense. The *potential* includes all biomass within a certain region that fulfill sustainability requirements such as ecological, economical, or technical limitations. The *availability* of the potential for new industry applications depends on market conditions, such as price and competitive current use. Important factors when assessing the biomass potential is the land composition (e.g. arable land, forest land), the existing forest and agricultural industry sector, the population and the existing waste handling systems.

For the **forest-based streams**, national/regional biomass potential and feedstock availability is dependent on the available forest land, size of the forest industry sector and present biomass use. Larger volumes can be found in countries with larger annual fellings, due to more by-products being produced. The Nordic countries stands out, but also large countries as Germany and France have a strong forest industry sector, whereas the volumes being cut in the Southern Europe are, in comparison smaller. Canada has, similar to the Nordic countries, also a strong forest industry sector.

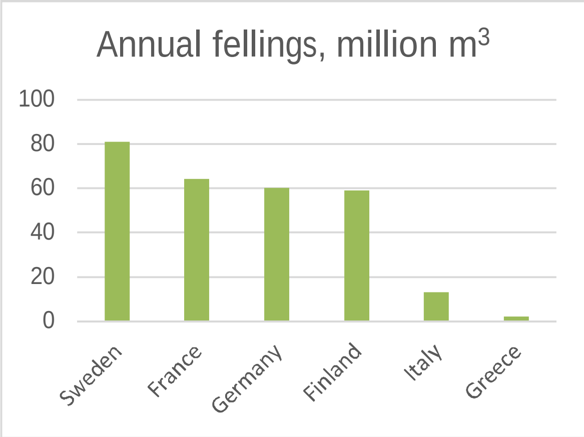


Figure 10. Annual fellings in targeted regions in Europe (Eurostat, 2011).

The feedstock potential from forest-based biomass is affected by this fact, but also by the absolute values of forest land and roundwood production which often generates the by-products.

A forest cover map can give a rough indication of forest biomass potential but the actual fellings are a better proxy when assessing the available forest biomass residues and by-products. Sweden has the largest forest land area (31.2 M ha) in the EU followed by Spain (27.7 M ha), Finland (23.23 M ha), France (17.6 M ha), Germany (11.1 M ha) and Italy (10.9 M ha). Sweden is in the top with an annual fellings of 81 M m^3 over bark, followed by France (64 M m^3), Germany (60 M m^3) and Finland (59 M m^3). The Mediterranean country such as Greece (2 M m^3) and Italy (13 M m3) is found lower down in the list of annual fellings (Figure 10). Less forest land, lower annual fellings and a less developed forest industry sector implies more challenges to mobilize considerable amounts of forest biomass for new industry applications in Greece and Italy (Eurostat, 2011).

Even though the **sawmills and pulp and paper industry** generate by-products, such as bark, saw dust, shavings, dry and fresh chips, sludge and black liquor, most of it is often already used today. However, there is still a potential to redirect a part of these residues to more value-added applications. Forest raw material is being supplied to the forest industries where the by-products arise. This means that the biomass has been concentrated and transported to a single point. The forest industry circulates by-products and internally use them to a large extent.

The price for the discussed possible feedstock if often related to the quality and characteristics. The use today is often for heat and steam production in the forest industry itself or in the district heating sector. The market price reflects the suitability for those purposes.

In a general level, there is a larger possibility to expand deliveries by utilizing more **primary forest residues**, i.e. biomass residues today left in the forest or with no existing high-value industrial use.

For the **agricultural-based streams**, the potential includes a wide range of different biomasses and assortments which is highlighted in the quality and characteristics section 4.2.1. Many of these have quality challenges, which bioindustry applications must cope with. This influences the market price for these potential feedstocks which also have a wide range. Countries with a large agricultural sector, such as Germany and France, have larger possibilities to mobilize more primary residues and have a large agricultural industry sector that generates considerable amount of by-products. Larger countries can also produce more dedicated energy crops which could be valuable feedstocks. In contrast to the forest industry, which is quite homogenous, the agricultural industry sector is more divers where each country has their own unique agroindustry landscape.

Within EU about 5,2 billion tonnes of **waste** was produced during 2016. 36.4 % from construction industry, 25.3 % from mining, 10.3 % from different production industries, 8.5 % municipal waste, 0.8 % from forest and agriculture and 18.7 % from other sources. The biogenic part of the municipal solid waste was 34% in 2017, which adds up to 86 million tonnes in the EU-28 (Brusselaers, J. and Van Der Linden, 2020).

From 2005 to 2018, the average amount of municipal waste per capita in the EU decreased. But the trends vary from country to country (Table 2). Richer states tend to produce more waste. Tourism also contributed to the higher numbers in countries with a lot of tourism. However, it is difficult to compare statistics within the EU because the countries apply different concepts and measurement methods. The latest statistics, which refer to 2019, show that the amount of municipal waste in the EU then amounted to 502 kg per person.

Table 2. Municipal waste generation per capita in 2018 for the targeted EU countries (Eurostat, 2022)

	Municipal waste, kg/capita	Share of reuse or composting, %	Share use as landfills, %
Germany	615	68	1
France	527	43	22
Greece	497	19	80
Italy	499	48	26
Sweden	434	47	0
Finland	551	41	1

The goal within EU for reuse or composting has been set as minimum 55 % to 2025 and the maximum share for landfill as 10 % to 2035. This will influence the waste situation in Europe. There is a very distinct trend towards less landfilling as countries move steadily towards alternative ways of treating waste. Landfill is almost non-existent in countries such as Belgium, the Netherlands, Denmark, Sweden, Germany, Austria and Finland. Here, waste incineration plays an important role alongside recycling. Germany and Austria are also the EU's leading recycling countries. Landfill is still popular in Eastern and Southern Europe. Ten countries dispose of half or more of their municipal waste. In Malta, Cyprus and Greece, this is more than 80 percent.

Municipal waste accounts for only about 10 % of total waste generated when compared with the data reported according to the Waste Statistics Regulation. However, it has a very high political profile because of its complex character, due to its composition, its distribution among many sources of waste, and its link to consumption patterns. 48 % of municipal waste in the EU was recycled (material recycling and composting) in 2020.

The market for waste is different from other markets. Since there is a need for waste treatment options, there can be compensation paid to those who can offer the waste treatment solutions. This can imply negative prices, meaning that the waste generator needs to pay to the one that offer the waste treatment service.

4.1 Northern Europe

The Swedish and Finish **forest industries** generates large volumes of by-products. However, most of these by-products is used internally or sold elsewhere, e.g. heating sector or pellets producers. Still there is a potential to allocate more biomass to new industry applications. Bark is an example of a by-product that could be used in new applications. A price of 16.8 €/MWh is reported for forest industry by-products (Energimyndigheten, 2022). The Swedish pulp and paper industry also generates some 560 000 odt biosludge annually which corresponds to 2 TWh/y. Approximately 50% is being used internally and a large share sent for costly external handling.

The largest forest-based unutilized potential is in the **primary forest residues**, e.g. logging residues, small-diameter trees and tree stumps. In Sweden, logging residues have the greatest potential, 6 M odt/year after considering the Swedish Forest Agency's environmental considerations (e.g. leaving some residues) and only extract from final fellings. Logging residues are at the same time an assortment that is partly used to today (1.7 M odt). There is also a large potential from tree stumps extraction, 5.7M odt/year, which today is an unutilized assortment in Sweden (Claesson et al., 2015). The yearly potential for removing small trees in very small thinning is also large, 2.2 M odt, but the harvest is often not carried out as the income from the extracted material only partially covers the cost of carrying out this forest management measure. The potential to extract volumes of brush wood from overgrown agricultural land is also relatively large, 0.98 M odt/year, but this harvest is also not carried out on a large scale, mostly due to lack of knowledge, tradition and the current low demand for these volumes. In general, we can state that domestic extraction and use of primary forest fuels can be developed if new industries demand more biomass. In **Sweden**, chipped logging residues can be delivered to a heating plant at 19.4 €/MWh. Tree stumps are not commercial in Sweden, and they will be more expensive since there is a need to mechanically uproot them before being forwarded to roadside landings. Small-diameter trees are also often somewhat more costly then logging residues.

The situation in Finland is similar, however, one important difference is that tree stump is being harvested and a larger share of the available logging residues is being utilized. Still there is an untapped potential that could be used for new industry applications without competing with existing use. In Finland, tree stumps can be delivered to a price of 11.3 €/m^3, logging residues 16.9 €/m^3 and energywood 24.2 €/m^3 (LUKE, 2021).

In countries such as Finland and Sweden where forest land can be found irrespective of region, the primary forest fuels can also be found in all regions. However, since only a part of all potential volumes of primary forest is being extracted and utilized a large surplus can be found. Today, the fuel is used in various CHP and district heating plants, which creates a large demand in regions with a large need for heat. Today there is surplus areas in less populated regions and deficit areas in highly populated regions. In Sweden, large volumes of primary forest fuels are being used in the southern half of Sweden, whereas the Northern part has little primary forest fuel outtake.

The residual with the greatest potential from **agricultural sector** is grain straw, with an estimated potential of 1.9 M tonnes/year in Sweden and 1 M tonne in Finland. In, Sweden the estimated amount of manure on dairy farms is 1.1 M odt/year and other residual sums up to a potential of just over 0.3 M odt/year. In Sweden, straw can be found at a price of 16.9 €/MWh and in Finland at price levels of 30 to 50 €/odt (10 to 15 €/MWh) can be expected for straw collected at fields.

Today, straw is mainly used as a bedding and as feed in animal production, but also for mushroom, strawberry, and carrot cultivation. Straw is used as fuel in heating plant, about 100,000 tonnes per year. Farmers can be concerned about the soil quality if removing too much organic matters from poor soils. This might jeopardize the long-term harvest levels and the farmers sometimes want to keep the straw in the field.

Growing dedicated energy crops has been done in both Sweden and Finland in the last decades. The northern parts of the countries have grown Reed canary grass and there has also been established Salix plantations in both countries during the last decades. In 2009, read canary grass was paid around 20 €/MWh for large bales in Sweden. In 2000, a price of 12 to 16 €/MWh can be found (Bränslehandboken).

Discarded silage is an unused resource and often consists of small quantities, spread over large areas and with varying availability over years. The discarded silage is mainly spread on arable land as fertilizer today, but is also used to some extent for biogas production.

Stable manure is mainly used as fertilizer on the farms today. To a certain extent, the manure is digested into biogas, and the digestate can then be spread as manure. Annually, approximately one million tonnes of animal manure is used in Sweden to produce biogas. The amount of manure used for digestion is slowly increasing but the potential is great. Today less than 5% of the total amount of manure is used for biogas production.

In the Nordic countries, different **biogenic waste streams** are commonly used in the heating sector. Domestic waste wood and municipal solid waste is used, but large volume is also imported. Waste wood is a popular wood fuel due to its low price. The price has historically been about half of the one for forest chips. At present, wood waste to a district heating plant, is around 10 €/MWh (Energimyndigheten, 2022). Recycled waste wood in Finland can be found at a price of 38.5 €/tonnes for an energy production plant.

Sweden and Finland generates annually some 2 to 3 M tonnes of solid waste. In addition to that, the Nordic countries also import municipal solid waste from other European countries. In Sweden, a compensation is paid to the heat and power plant that handles waste, which means that they are traded to a negative cost. For municipal waste incineration the compensation, or negative price, has raised from -16 to -17 Euro per MWh during 2021. For operational waste, the raise during 2021 was from -16 to -18 Euro per MWh and the compensation for accepting imported waste was raised from -17,5 to -20 Euro per MWh.

Table 3. Annual potential, current use and market price for each identified feedstock in Sweden and Finland. Blank fields indicate lack of data and not a zero number. The references for the data can be found in the reference list – section B.

	Category	Origin	Assortment	Annual potential	Current use	Market price
Agro	Energy crops, woody	Finland	*Willow (willow farm in Finland)*			
Agro	Energy crops, woody	Sweden	*Salix/willow*			
Agro	Industry by-products	Sweden	*Other agro residues*	577 000 odt		
Agro	Prunings	Sweden	*Brush woods*	986 000 odt		
Agro	Solid manure	Finland	*Solid manure (total amount)*	1 200 000 t		
Agro	Solid manure	Sweden	*Solid manure*	1 080 odt		
Agro	Straw	Finland	*Straw (general)*	1 000 000 t	1 000 000 t	30-50 €/odt
Agro	Straw	Sweden	*Straw*	1 873 000 odt		16,9 €/MWh
Forest	Landscape mngt residues	Finland	*Forest waste residue (Forest thinnings of pine and spruce)*	500 000 t	7 600 000 m³	
Forest	Logging residues	Finland	*Logging residue (spruce, pine)*	2 380 000 m³	2 200 000 m³	3-17 €/m³
Forest	Logging residues	Sweden	*Logging residue*	6 005 000 odt	1 716 400 odt	19,40 €/MWh
Forest	Low-quality roundwood	Sweden	*Low-quality roundwood*	5 000 GWh		
Forest	Sawdust, shavings, chips	Finland	*Saw dust*		2 200 000 m³	
Forest	Sawdust, shavings, chips	Sweden	*Saw dust*	8 000 GWh		16,80 €/MWh
Forest	Sludge	Sweden	*Forest industry sludge*	560 000 odt		

Forest	Bark	Finland	*Bark - a mixture of soft wood bark and birch bark*		6 800 000 m³	
Forest	Bark	Sweden	*Bark*	11 000 GWh		16,80 €/MWh
Forest	Landscape mngt residues	Sweden	*Small diameter trees*	2 195 000 odt	180 360 odt	
Forest	Landscape mngt residues	Sweden	*Brush woods*	367 000 odt		
Forest	Tree stumps	Finland	*Tree stumps*	17 000 000 m³	1 000 000 m³	2,50-11,50 €/m³
Forest	Tree stumps	Sweden	*Tree stumps*	5 748 000 odt	19 380 odt	
Forest	Sludge	Sweden	*Forest industry sludge*	2 TWh	1 TWh	
Waste	Municipal solid waste	Finland	*Municipal solid waste*	3 000 000 t		
Waste	Municipal solid waste	Finland	*Household &mixed waste / REF*	2 600 000 t		
Waste	Municipal solid waste	Sweden	*Municipal solid waste*	2 240 000 t	2 240 000 t	-16,40 €/MWh
Waste	Recycled wood and	Finland	*Recycled waste wood*	3 200 000 t		38,50 €/t
Waste	Recycled wood and	Finland	*Used wood (Class B)*	1 600 000 t		
Waste	Recycled wood and woody waste	Sweden	*Recycled waste wood*		4 003 GWh	9,70 €/MWh
Waste	Sewage sludge	Sweden	*Sewage sludge*			

4.2 Central Europe

France and Germany have, like the Nordic countries, a considerable **forest biomass feedstock** potential due to large forest areas and a well-developed forest sector. Their forestry and forest industries will generate similar by-products as the Nordic countries. However, the exact output is off course influenced by the tree species and forest industry processes. In Germany, logging residues have an indicative price of 30-80 €/odt and woody biomass from landscape management 15-80 €/odt. In France, the indicative price of logging residues is 49-83 €/tonnes, energywood logs 51-67 €/tonnes, woody biomass from landscape management 32 €/tonnes, wood industry residues 26-55 €/tonnes, bark 7-26 €/tonnes and sawdust 29-43 €/tonnes.

The **agricultural feedstock** potential in France and German has similar feedstocks as the Nordic countries. However, prunings from vineyards and residues from parfume plants is a difference. The straw potential is larger in these countries compared to the Nordic countries.

The cost for straw in Germany varies between 60-160 €/odt. For woody biomasses from vineyards, the authors estimate that the cost can range from 0 up to 35 €/odt. Solid manure and different agro residues can be found for free at some farms. For digestate, the cost is occasionally negative, and the range found in the literature ranges from -30 €/odt up to 10 €/odt. In France, straw costs between 15 and 30 €/tonnes and solid manure is available at a cost of 12 to 45 €/tonne.

Among the target countries, Germany and France have the largest volumes of municipal solid waste, due to more inhabitants. Both of them generate approximately 40 million odt of municipal solid waste annually. Germany also has large other waste streams including some 10.9 M odt of wood waste byproducts, 6-9 M odt of recycled waste wood, 2.4 M odt of roadside/railway wood waste, 20 k odt of driftwood, 5.3 M odt of mechanically dried sewedge sludge, 14.6 M tonnes of residues from the food industry, 3.9 M tonnes of leaves and 0.9 M odt of kitchen/food wastes. In France, the class B wood waste is around 6.8 M odt annually.

In Germany, wood waste by-products can be found at 20-40 €/odt, driftwood at no cost, recycled waste wood from –10 to 25 €/odt and road side/railway woody wastes from zero to 35 €/odt. The residues from the food industry and kitchen/food waste varies widely between zero up to 200 €/odt. Mechanically dried sewage sludge is available at a negative costs between 30 to 10 €/odt. Municipal solid waste is available from a negative cost of 30 €/odt up to a free of charge situation for some waste streams. In France, wood waste (class B) have an indicative price of some 35-70 €/odt.

Table 4. Annual potential, current use and market price for each identified feedstock in German and France. Blank fields indicate lack of data and not a zero number. The references for the data can be found in the reference list – section B.

	Category	Origin	Assortment	Annual potential	Current use	Market price
Agro		France	*Agro residues from silos (cereals, rice, maize…)*	377 000 odt	166 610 odt	
Agro		France	*Agro residues from parfum plants (lavender, lavandin…)*	61 780 odt	58 700 odt	
Agro		Germany	*Agro residues*	660 000 odt		0 €/odt
Agro		Germany	*Digestate*	13 500 000 odt		(-30)-10 €/odt
Agro	Energy crops, herbaceous	France	*Energy culture (miscanthus, hemp, flax…)*	915 000 odt	740 200 odt	
Agro	Energy crops, woody	France	*Short rotation coppice*	41 000 odt	41 000 odt	
Agro	Prunings	France	*Woody biomass from vineyards and fruit trees*	7 346 000 odt	7 346 000 odt	
Agro	Prunings	Germany	*Woody biomass from vineyards*	410 000 odt	410 000 odt	0-35 €/odt
Agro	Solid manure	France	*Solid manure*	98 076 000 odt		12-45 €/t
Agro	Solid manure	Germany	*Solid manure*	10 000 000 odt	1 850 000 odt	0 €/odt
Agro	Stalks	France	*Straw from maize*	1 728 000 odt	0 odt	
Agro	Straw	France	*Straw from cereals*	13 303 000 odt	10 245 000 odt	15-30 €/t
Agro	Straw	Germany	*Straw*	25 300 000 odt	9 500 000 odt	60-160 €/odt
Forest	Logging residues	France	*Logging residue (wood chips)*		3 135 000 m³	48,6-83 €/t
Forest	Logging residues	Germany	*Logging residue*	14 800 000 odt	3 900 000 odt	30-80 €/odt
Forest	Low-quality roundwood	France	*Logging residue (woodlogs commercialized, for domestic use)*		5 227 000 m³	50,7-67,4 €/t

Forest	Low-quality roundwood	France	*Logging residue (woodlogs not commercialized, for domestic use)*		9 800 000 m³	
Forest	Bark	France	*Bark*		783 000 odt	6,7-25,6 €/t
Forest	Bark	Germany	*Bark*	2 100 000 odt	2 650 000 odt	
Forest	Black liquor	Germany	*Black Liquor*	1 900 000 odt	1 900 000 odt	
Forest	Landscape mngt residues	France	*Woody biomass from landscape management: roadside, prunning residues, green waste…)*	1 000 000 odt		31,5 €/t
Forest	Landscape mngt residues	France	*Woody biomass from landscape management: roadside, prunning residues, green waste…) (not commercilized, for domestic use)*		5 000 000 m³	
Forest	Landscape mngt residues	Germany	*Woody biomass from landscape management*	5 600 000 odt	4 600 000 odt	15-80 €/odt
Forest	Sawdust, shavings, chips	France	*Wood industry residues (sawmill, timber…)*		7 057 000 odt	26-55 €/t
Forest	Sawdust, shavings, chips	France	*Saw dust*		2 478 000 odt	28,6-42,6 €/t
Waste		Germany	*Leaves*	350 000 odt	140 000 odt	0 €/odt
Waste	Food industry residues and waste	Germany	*Residues from food industry*	14 500 000 odt	14 500 000 odt	0-200 €/odt
Waste	Food industry residues and waste	Germany	*Kitchen/food wastes*	900 000 odt	650 000 odt	0-200 €/odt
Waste	Municipal solid waste	France	*Municipal waste*	38 900 000 odt	31 898 000 odt	
Waste	Municipal solid waste	Germany	*Municipal solid waste*	40 000 000 odt	31 000 000 odt	(-30)-0 €/odt
Waste	Recycled wood and woody waste	France	*Waste wood (class B)*	6 800 000 odt	5 440 000 odt	35-70 €/t
Waste	Recycled wood and woody waste	Germany	*Wood wastes byproducts*	10 900 000 odt	10 900 000 odt	20-40 €/odt
Waste	Recycled wood and woody waste	Germany	*Recycled waste wood*	6 900 000 odt	6 900 000 odt	(-10)-25 €/odt
Waste	Recycled wood and woody waste	Germany	*Roadside/railway woody wastes*	1 200 000 odt	1 200 000 odt	0-35 €/odt
Waste	Recycled wood and woody waste	Germany	*Driftwood*	16 000 odt	16 000 odt	0 €/odt
Waste	Sewage sludge	Germany	*Sewage sludge (mech. dried)*	5 300 000 odt	2 500 000 odt	(-30)-(-10) €/odt

4.3 Southern Europe

Italy has, in contrast to Greece, a potential to mobilize larger amounts of forest biomass for industry applications. Forest industry by-products are available, logging residues and landscape management residues and woody biomasses from coppice systems are available. Italy also has an agricultural based feedstock potential which constitute of prunings, solid manure, straw and stalks, and agroindustry by-products.

Most of the identified feedstock potentials in Greece comes from the agricultural sector where multiple different streams including prunings, straw and stalks, and industry by-products contribute to the potential. In Greece, which has a wide range of agricultural streams, straw can be found at 35 to 115 €/odt and rice husks at an indicative cost of 60 to 80 €/odt. Olive stones can be found at 150 €/odt and olive cake at 50 to 80 €/odt. For prunings, an indicative cost for olive tree pruning of 45 €/odt can be found in the literature. Corn stalks in Italy has a market price of 30-50 €/odt and cereal straw 60-100 €/odt.

Both Greece and Italy have waste stream of SRF/RDF which could be utilized to more high value applications, such as the FlexSNG process. The waste is available at a negative price of -20 to -10 €/odt in Greece.

Table 5. Annual potential, current use and market price for each identified feedstock in Greece and Italy. Blank fields indicate lack of data and not a zero number. The references for the data can be found in the reference list – section B.

	Category	Origin	Assortment	Annual potential	Current use	Market price
Agro		Italy	*Fruit peel*	287 500 odt	115 000 odt	
Agro		Italy	*Cattle manure liquid*	80 624 000 m³		
Agro		Italy	*Pig manure liquid*	17 140 000 m³		
Agro	Industry by-products	Greece	*Rice Husks*	41 000 odt		60-80 €/odt
Agro	Industry by-products	Greece	*Exhausted Olive Cake*	392 000 odt		50-80 €/odt
Agro	Industry by-products	Greece	*Olive Stones*	165 000 odt		150 €/odt
Agro	Industry by-products	Italy	*Agroindustry*	1 420 000 odt	1 130 000 odt	
Agro	Prunings	Greece	*Olive tree pruning*	1 552 000 odt		45 €/odt
Agro	Prunings	Greece	*Vine pruning*	49 000 odt		
Agro	Prunings	Greece	*Pomefruit tree prunings (apples, pears)*	180 000 odt		
Agro	Prunings	Greece	*Stonefruit tree pruning (peaches, nectarines, cherries, apricots)*	225 000 odt		
Agro	Prunings	Greece	*Citrus tree prunings*	242 000 odt		
Agro	Prunings	Greece	*Nut tree prunings*	105 000 odt		
Agro	Prunings	Italy	*Olive tree pruning*	1 547 917 odt	743 000 odt	
Agro	Prunings	Italy	*Vine pruning*	1 122 917 odt	539 000 odt	
Agro	Prunings	Italy	*Other tree prunings*	768 750 odt	369 000 odt	
Agro	Solid manure	Italy	*Cattle manure solid*	10 203 000 m³		
Agro	Solid manure	Italy	*Pig manure solid*	752 000 m³		
Agro	Stalks	Greece	*Maize residues*	802 000 odt		
Agro	Stalks	Greece	*Cotton Residues (stalks)*	991 000 odt		
Agro	Stalks	Italy	*Corn residues*	4 582 500 odt	1 833 000 odt	30-50 €/odt
Agro	Stalks	Italy	*Sunflower Stalks*	215 000 odt	86 000 odt	
Agro	Straw	Greece	*Rice Straw*	216 000 odt		
Agro	Straw	Greece	*Cereal Straw*	897 000 odt		35-115 €/odt
Agro	Straw	Italy	*Residues from rice*	650 000 odt	270 000 odt	
Agro	Straw	Italy	*Cereal Straw*	4 557 500 odt	1 823 000 odt	60-100 €/odt

Forest	Landscape mngt residues	Italy	*Woody biomass - Forest coppice*	9 984 035 m³	1 996 807 m³	
Forest	Landscape mngt residues	Italy	*Woody biomass - small forest coppice (<0,5 ha)*	20 000 000 m³	441 977 m³	
Forest	Logging residues	Italy	*Woody biomass residue from forest*	8 638 827 m³	6 225 067 m³	
Forest	Low-quality roundwood	Italy	*Woody biomass - High forest (Wild)*	14 094 200 m³	4 228 260 m³	
Forest	Sawdust, shavings, chips	Italy	*Forest industry (wood)*	4 400 000 odt	1 800 000 odt	
Waste	Digestate	Greece	*Compost Like Output-CLO/ Digestate*	360 000 odt		-1 €/odt
Waste	Recycled wood and woody waste	Italy	*Paper recycling*	270 000 odt	150 000 odt	
Waste	SRF/RDF	Greece	*Solid recovered fuel/Refused derived fuels*	402 000 odt	126 000 odt	(-20)-(-10) €/odt
Waste	SRF/RDF	Italy	*Solid recovered fuel/Refused derived fuels*	8 000 000 odt	4 000 000 odt	

4.4 Canada

Canada which is a large and forest-dense country with a well-developed forest industry sector generates large volumes of residues. The presented data is for five identified regions in different provinces previously identified as possible locations for biorefinery operations. The industry by-products, bark and chips, have the largest potential in the targeted area. Logging residues and slash also have a considerable potential. The values are a net commercial and economical viable potential after current sawmills and pulp mills have allocated their volumes. The bark is associated with the lowest market prices among the identified resources (38-63 Canadian CA$/odt). Logging residues and slash has roughly double the price (88-113 CA$/odt). Hardwood (88-150 CA$/odt) and softwood chips (113-150 CA$/odt) has the highest price range.

Table 6. Annual potential, current use and market price for each identified feedstock in the five targeted regions in Canada. Blank fields indicate lack of data and not a zero number. The references for the data can be found in the reference list – section B. Market price is given in Canadian dollars per odt (CA$/odt).

	Category	Origin	Assortment	Annual potential	Current use	Market price
Forest	Bark	Saguenay - Quebec	*Bark*	45 000 odt		38-63 CA$/odt
Forest	Bark	Terrace - British Columbia	*Bark*	100 000 odt		38-63 CA$/odt
Forest	Bark	Cornerbrook - New Foundland	*Bark*	37 000 odt		38-63 CA$/odt
Forest	Bark	Belledune - New Bruinswick	*Bark*	22 500 odt		38-63 CA$/odt
Forest	Bark	Kapuskasing - Ontario	*Bark*	112 500 odt		38-63 CA$/odt
Forest	Logging residues	Saguenay - Quebec	*Hardwod/Softwood Slash*	350 000 odt		88-113 CA$/odt
Forest	Logging residues	Terrace - British Columbia	*Hardwod/Softwood Slash*	30 000 odt		88-113 CA$/odt

Forest	Logging residues	Cornerbrook - New Foundland	*Hardwod/Softwood Slash*	100 000 odt		88-113 CA$/odt
Forest	Logging residues	Belledune - New Bruinswick	*Hardwod/Softwood Slash*	75 000 odt		88-113 CA$/odt
Forest	Logging residues	Kapuskasing - Ontario	*Hardwod/Softwood Slash*	200 000 odt		88-113 CA$/odt
Forest	Sawdust, shavings, chips	Saguenay - Quebec	*Hardwood chips*	100 000 odt		88-150 CA$/odt
Forest	Sawdust, shavings, chips	Cornerbrook - New Foundland	*Hardwood chips*	50 000 odt		88-150 CA$/odt
Forest	Sawdust, shavings, chips	Belledune - New Bruinswick	*Hardwood chips*	100 000 odt		88-150 CA$/odt
Forest	Sawdust, shavings, chips	Kapuskasing - Ontario	*Hardwood chips*	700 000 odt		88-150 CA$/odt
Forest	Sawdust, shavings, chips	Saguenay - Quebec	*Softwood chips*	300 000 odt		113-150 CA$/odt
Forest	Sawdust, shavings, chips	Terrace - British Columbia	*Softwood chips*	300 000 odt		113-150 CA$/odt
Forest	Sawdust, shavings, chips	Cornerbrook - New Foundland	*Softwood chips*	250 000 odt		113-150 CA$/odt
Forest	Sawdust, shavings, chips	Belledune - New Bruinswick	*Softwood chips*	50 000 odt		113-150 CA$/odt
Forest	Sawdust, shavings, chips	Kapuskasing - Ontario	*Softwood chips*	50 000 odt		113-150 CA$/odt

5 Feedstock suitability assessment for FlexSNG

5.1 Feedstock quality attributes relevant for gasification

Although gasification can be used to convert virtually any carbon-containing feedstock to syngas, in practice, the gasification process and the selected reactor type set certain constraints for the feedstock quality. The feedstock characteristics ultimately dictate whether, or under which conditions, the feedstock is suitable for gasification and what type of pre-processing is required. The most relevant feedstock quality attributes in this context are particle size, moisture, ash content, and more specifically ash composition and ash melting behaviour. The physical properties can be adjusted by applying properly selected feedstock pre-treatments prior to gasification. Challenging ash behaviour that is associated with high alkali fuels, on the other hand, needs to be addressed when specifying the gasification conditions for the feedstock.

High alkali feedstocks can cause ash sintering and agglomeration in the reactor if operated above ash melting temperature. Part of the ash-forming elements are also volatilised in gasification and need to be removed from syngas to prevent fouling in downstream units and also to meet the stringent gas quality requirements in end use applications. Several methods for leaching alkali metals from biomass feedstocks have been proposed as a means to separate these challenging species prior to the conversion process and thus minimize ash-related issues in gasification. The FlexSNG project, however, has taken the approach to keep the feedstock pre-processing steps and thereby also related costs to a minimum. Instead, ash-related issues are mainly managed within the gasification process itself by tuning the process conditions accordingly. Ash sintering can be inhibited in the gasifier by lowering the gasification temperature, introducing additives (e.g. kaolin, dolomite), and/or mixing the feedstock with low ash containing fuels, such as wood, or biochar. The majority of vaporized alkali metals, heavy metals and chlorine species, on the other hand, are captured downstream the gasifier by filtration. These species are first condensed on top of the solid particulates by cooling the gas down to 300-500 °C, after which they can be easily removed on the filter. Only mercury has been shown to remain in the gas phase at these temperatures and therefore needs to be removed in the final gas cleaning section. Also part of chlorine is retained in gaseous form as HCl after filtration. Chlorine retention in the filter can be induced with sorbent feeding (e.g. calcium hydroxide) prior to the filter unit. The residual chlorine (HCl) is handled in the scrubbing step where alkaline scrubbing solution is used for removing these trace amounts.

5.2 Feedstock pre-treatment requirements in FlexSNG

In general, the fluidised-bed gasification technology employed in FlexSNG is not as sensitive to feedstock properties, such as particle size, bulk density or moisture, as many other conversion technologies. Thus, the quality specifications for the gasifier feedstock are fairly low and intensive pre-processing, such as torrefaction or pulverizing the feedstock to very small particle size, is not required. Feedstock pre-processing typically involves at least drying as well as some type of mechanical handling, such as crushing, to adjust the particle size.

The feedstock moisture content plays a key role in the gasification process as water evaporation consumes energy in the gasifier. High moisture feedstocks may also cause malfunction in the feeding systems. To prevent consuming an excess amount of energy for vaporizing water, the feedstock needs to be dried to below 15-20 wt-% moisture content prior to entering the gasifier. The feedstock drying step is typically integrated within the gasification plant to exploit the surplus heat produced at the plant for heating up the drying medium. Belt dryers are one of the most common dryer types used in drying of biomass feedstocks due to their simple design, easy control of final moisture and the possibility to use low-temperature heat sources. Other dryer types applicable for biomass feedstocks are e.g. rotary drum dryers, pneumatic conveying steam dryers and perforated floor dryers. While most woody residues can easily contain around 50 wt-% moisture as they arrive at the gasification plant, certain feedstocks, like straw, can take advantage of natural drying on the harvest site and might not require additional drying at the gasification plant.

Particle size is another key factor that will both influence the gasification performance but also the reliability of feeding systems. For an industrial-scale FlexSNG fluidised-bed gasifier, the feedstock particle size should be in the range of 5-50 mm. The amount of fines (< 1 mm) in the feedstock should be below 20% and particles larger than 100 mm are not tolerable.

The pre-treatment requirements generally increase with increasing heterogeneity in the feedstock. Woody residues available from the forest sector are the least demanding in this respect and typically require only crushing/chipping and drying prior to gasification. Agricultural residues, such as straw or other herbaceous biomass, are often fluffy, low density feedstocks that also require compacting (e.g. pelletisation or briquetting) after crushing to enable fluent feeding to the gasifier. The pre-processing requirements for waste-derived feedstocks vary depending on the origin of the waste. Municipal solid waste is the most demanding within this category. Its composition may vary to great extent between different countries depending on the source separation practices applied in each country but there is also high quality variation within each batch. Municipal solid waste or similar commercial wastes need to undergo the Solid Recovered Fuel (SRF) production process to qualify as gasifier feedstock. This includes a series of processing steps that separate metals, inert materials like stones, glass and concrete, as well as soil material from the feed. As the final step, the SRF is dried and pelletised.

5.3 Feedstocks suitable for FlexSNG

The FlexSNG gasification process can tolerate a wide spectrum of biomass residues and waste-derived feedstocks ranging from easy-to-handle clean woody feedstocks up to challenging high alkali and waste fractions, such as sewage sludge or municipal solid waste. Feedstock flexibility is one of the key benefits of the FlexSNG concept over state-of-the-art gasification technologies. It originates from the two key features of the gasification process: (1) the gasifier is operated at lower temperature (well below 800 °C) when co-producing biochar and biomethane, which reduces the risk for ash melting, and (2) the gasification performance of particularly challenging high alkali and waste feeds can be improved by co-feeding with biochar. The presence of char in the gasifier bed and in the recycling loop has been shown in the past to prevent ash sintering as well as induce tar decomposition and improve gas quality.

This section now focuses on evaluating the results of the feedstock potential assessment presented in this report in terms of which feedstock resources are suitable for the FlexSNG process and under which conditions. The evaluation considers all three feedstock categories: (1) residues and by-products from the forestry sector, (2) agricultural residues and by-products, and (3) biogenic waste streams.

5.3.1 Woody residues from the forestry sector

A considerable share of the biomass potential especially in the Nordic countries and Canada comes from the forestry sector. Within this category, we only consider to utilise woody residues that have no competitive use in the mechanical or the pulping industry. These include e.g. branches, tree tops, stumps, wood from thinnings, landscape management residues, bark and other industrial side streams from the forestry sector, as described in section 3.1. Among the feedstocks reported in this category, all woody residues can be considered as suitable feeds for the FlexSNG gasification process with the exception of black liquor. Being a liquid feed, black liquor would be best suited for entrained-flow gasification instead, while only solid feedstocks are considered applicable for the FlexSNG process.

Amongst the feedstocks presented in this report, woody residues are the easiest to handle and pose no major challenges for the gasification process due to their relatively low ash content. Owing to the low ash level, woody biomasses are also considered to be well suited for biochar production particularly for applications, like soil amendment, where the quality specifications are more stringent. The pre-treatment requirements for typical woody residues involve crushing to 5-50 mm particle size followed by drying to below 15-20 wt-% moisture. Sawdust should be pelletised to enable feeding to the gasification process.

As described earlier, the ash content varies within this feedstock category depending on the level of soil contamination during harvesting or storage, tree species and whether the assortment contains mostly clean wood or also bark etc. The ash content of woody residues was generally found to be below 6 wt-%. The only exception is sludge derived from pulp and paper mills that can contain up to 20 wt-% of ash. Such high ash content could be problematic for gasification. Therefore, sludges should be mixed (after drying) and co-gasified with more clean woody fuels to make them more manageable in gasification.

5.3.2 Residues from the agricultural sector

Agricultural residues are another important feedstock category for the FlexSNG process. Especially in South European countries where forest resources are fairly limited, agricultural residues and by-products are the most abundant biomass resource. For example in Greece, the biggest potential lies in prunings from fruit trees that are currently poorly utilised (mostly burned in open fires or chipped/mulched and left on the soil) as well as in straw and stalks. Other feedstocks identified in this category are herbaceous (e.g. miscanthus, reed canary grass) and woody energy crops (e.g. willow, poplar) and manures.

Agricultural residues, especially straw, stalks, herbaceous energy crops and manures, have generally higher alkali content than woody fuels and therefore require more careful control of gasification conditions to prevent ash sintering. Straw is also rich in chlorine. Nevertheless, the FlexSNG process is able to tolerate also these high alkali feeds owing to the low gasification temperature and the possibility for biochar co-feeding (if needed). The alkali metals and most of chlorine released from the feedstock are captured already in the filter unit and not passed on to the final biomethane product. Also manures can be used as co-feed in the gasifier after drying. Depending on the ash composition, some of the agricultural residues may also be well suited for biochar production, but for example straw-derived biochar may have limited application potential in soil amendment due to the high level of chlorine.

As mentioned earlier, certain agricultural residues, such as straw, stalks and herbaceous crops, have low bulk density and are typically stored in bales after harvesting. Such fluffy materials are challenging from the logistics and fuel feeding point of view and require further densification prior to being fed to the gasification process. These feedstocks should be compressed into briquettes or pellets prior to gasification. They should also be dried if the moisture content exceeds 20 wt-%.

The fruit tree prunings are expected to behave in gasification in somewhat similar way to other woody residues and are thus not expected to cause any major issues. The pre-processing requirements are similar to those presented for woody biomass.

One critical aspect that concern certain agricultural residues is that they are not produced throughout the year but are often only seasonally available. Consequently, the FlexSNG plant should not rely on such agricultural residues as the only feedstock source but other complementary feedstocks are also needed.

5.3.3 Biogenic waste streams

The most potential feedstocks in this category are municipal solid waste, processed Solid Recovered Fuel (SRF) or Refuse Derived Fuel (RDF), paper/wood/plastic waste and demolition wood. These feedstocks, except for demolition wood, are the most challenging from the gasification perspective as they are heterogeneous, have high ash content and typically produce raw syngas that has particularly high tar loading. However, after proper pre-processing, they become suitable feeds for the FlexSNG process provided that they are co-fed with biochar. Biochar co-feeding is needed to manage ash melting behaviour in the gasifier but also to suppress tar formation and therefore ensure trouble-free cooling and filtration of the raw syngas. One of the key benefits of waste feedstocks from the process economics point of view is that they can even come with a negative price (gate fee).

As described earlier, the pre-treatment requirements for municipal solid waste or comparable commercial/industrial waste are more demanding than those applied for woody or agricultural residues. These waste fractions need to be processed into SRF/RDF in a series of mechanical treatment and sorting processes prior to gasification. These typically include shredding, separation of metals with magnetic/eddy current separators, and drum screening and air classification to remove heavy objects (e.g. stones or other inert material) as well as fines (e.g. soil, sand, glass). After final shredding, the SRF product still needs to be dried to below 20 wt-% moisture and pelletised.

Demolition wood is another highly potential feedstock within this category. The composition of demolition wood can be close to that of primary woody residues, depending on the wood grade ranking, but the price is typically lower - in Sweden even half of that of forest chips. Higher grade demolition wood could even be considered as a source for biochar production if the contaminant levels are low enough. Prior to gasification, most metals, stones, concrete and glass need to be removed from the waste wood fraction but other minor contaminants, such as paint, are not problematic for gasification. Most of the alkali and heavy metals and chlorine volatilized in gasification are removed from the raw syngas by filtration. Demolition wood can also be used as a co-feed when gasifying more challenging wastes, such as municipal solid waste, sludges and manures.

Sewage sludge is not directly suitable for gasification but needs to be first dried to below 20 wt-% moisture. Moreover, due to its high ash content (roughly 40-50 wt-%), it can be only considered as a co-feed with more clean fuels, such as woody residues.

6 Conclusions

There is available and suitable potential feedstock for the FlexSNG process in sufficient amounts in each of the targeted areas. In general, forest feedstocks are non-complicated, agricultural feedstocks more complicated but also more divers, and the waste feedstocks the most divers and challenging one. However, the variations between different streams and also within a specific stream is large. In general, a more challenging fuel is often associated with a lower market price, and for waste fractions sometimes negative costs. In the further analyses, the forest biomasses will be the core in the Nordic cases, a palette of different bio-based streams as well as urban wastes will be considered in the Central European cases, and agricultural residues together with waste streams will be considered in Southern Europe.

7 References

7.1 Section A

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7.2 Section B

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