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Bioefficiency

Comparison of treated and untreated fuels with regard to fuel properties, ash composition, ash properties, economics and resource efficiency (D2.3)

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Abbreviations and Acronyms

| | |
|-------|--|
| ABO | Åbo Akademi University |
| B/A | Base to acid ratio related to ash composition |
| BVOR | Dutch Association of Biowaste Processors |
| CFB | Circulating Fluidized Bed |
| d80 | Characteristic particle undersize |
| DONG | Danish Oil and Natural Gas, now is Ørsted A/S |
| DTU | Technical University of Denmark |
| ECN | Energy Research Centre of The Netherlands (now TNO) |
| Em | Grinding specific energy |
| FAO | Food and Agriculture Organization of the United Nations |
| FI | Fouling Index |
| HHV | High Heating Value |
| HTC | Hydrothermal carbonisation |
| LAB | Belgisch Laboratorium van de Elektriciteitsindustrie (LABORELEC) |
| LHV | Low Heating Value |
| MET | Metsä Fibre Oy |
| MHPSE | Mitsubishi Hitachi Power Systems Europe GmbH |
| NL | The Netherlands |
| ORS | Ørsted A/S – former DONG (Danish Oil and Natural Gas) |
| PF | Pulverized Fuel |
| PDI | Pellet Durability Index |
| PSD | Particle Size Distribution |
| RP | Receiving Partner |
| SE | Steam Explosion |
| SEP | Steam Exploded Pellets |
| SI | Slagging Index |
| TNO | the Netherlands Organization for Applied Scientific Research TNO (ECN part of TNO), former ECN – Energy Research Centre of The Netherlands |
| TUM | Technical University of Munich |
| VAL | Valmet Technologies Oy |
| VTT | Technical Research Centre of Finland, Ltd |

1. Biomass selection and final provision (all supplying partners and industrial users)

1.1 Availability potential (TUM,TNO)

The data gathered for this chapter include amounts of biomass produced, as well as current use of the waste streams divided in energy and non-energy applications (information retrieved where possible).

1.1.1 Spruce bark

One important biomass feedstock for the project has been spruce bark provided for the project by Metsä Fibre. Spruce bark in Finland is a side-stream of the forest industry that is used as a solid biofuel in biomass boilers. Out of the three main industrial wood species in Finland, Scots pine (*Pinus Sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula*), spruce bark has the highest ash content and was thus selected as a feedstock for the project. Bark comprises the outer part of woody stems and branches. The availability of spruce bark in Finland is around 1 Mt/a dry matter. It is produced in pulp mills, which employ wet debarking, and at saw mills, which employ dry debarking technology. Moisture content of the bark after debarking is in the range of 50-60% depending on the debarking technology and seasonal conditions. Bark is currently used in compost production, as boiler fuel, as wood replacement in panel production, etc.

1.1.2 Miscanthus

Field trials have been carried out to investigate the biomass potential of miscanthus across Europe since the 1980s.

Harvestable miscanthus worldwide yields have been estimated to be in the range of 2-44 t/ha (dry basis). However, yields of 27-44 t/ha (dry basis) have been reported in Europe and US Midwestern locations, where better technology and knowledge is available. The mass yield appears to depend on different factors: genotypes, soil types, nutrients used, crop age, location and weather during growth. An overview is given in [1].

Miscanthus is currently being cultivated as an energy crop and it is estimated that in The Netherlands its land use amounts up to 200 ha, 25% of which is being harvested for energy purposes. The mean annual increment is 15-20 tons dry miscanthus/ha/year, which is fully harvested. This can be calculated to a total of 3-4 ktons dry/year available miscanthus, 1 kton dry/year of which is being used for energy purposes. The rest is being used in other applications, such as animal bedding [2].

1.1.3 Natural grass and road side grass

Natural grass is defined as clippings originating from vegetation growing in natural landscapes and managed land areas with non-arable land. Clippings contain grass, herbs, shrubs as well as very young trees. The type of land where natural grass originates from can be natural landscapes, land in controlled-environment agriculture

or non-arable land. There is no clear difference in definition between grass from agricultural land and grass from non-agricultural land, because some farmers are also managing natural landscapes as well as road verges. Grass from non-agricultural land is normally harvested once a year, but this can occur also more often. Harvesting is done by grazing, pasturing or some type of land management. If the harvesting frequency is decreased the land becomes rugged or can develop into a forest land.

Road side grass is defined as clippings coming from strips of land adjacent to road infrastructure. The terms grass and clippings are used in this report for the grass and herbaceous biomass streams originating from natural landscapes and road verges [3]. The road verge is easily accessible and in most cases has to be maintained and cultivated.

Based on data for natural grass it is estimated that in 2011 ca. 5% of the total harvest is used in the energy sector. It is assumed that this fraction is used solely within The Netherlands. The volume of road-side grass harvested is based on a land surface area of 60,000 ha with a mean annual increment of 4 tons dry/ha/year.

In 2012, 0.1% of all processed green products were used by BVOR-members for energy production in co-digesters. The rest was composted or used in other non-energy applications. In this case, it is assumed that this percentage used by BVOR is representative for the processing of road-side grass in The Netherlands. This means that 0.1% of all harvested road-side grass (in total 240 ktons dry grass) was used in the energy sector in 2014. The data is obtained from ref [2] and are given in Table 1.

Even though road-side grass is a waste stream from landscaping activities specifically relevant for The Netherlands, it serves as a reference material for other types of “grassy” feedstocks.

Table 1. Availability of natural grass and road-side grass used in energy and non-energy applications.

| | Harvest | Energy Use NL | Non-Energy Use |
|------------------------|-------------------|--------------------------|---------------------------|
| | ktons dry/year | ktons dry/year | ktons dry/year |
| Natural grass | 476 | 24 | 452 |
| Road- side grass | 240 | 0.2 | 239.8 |
| Total | 716 | 24 | 692 |

1.1.4 Straw as agricultural residue

“Straw” is the collective term used for the dry stalks of cereal crops, such as rice and wheat. Straw is a biomass residue that remains on the fields after removal of the grain

during the grain harvesting process. Table 2 and Table 3 present the estimated rice straw and wheat straw production, respectively, in different regions of the world. Total rice straw production amounts to almost 730,000 ktons/a worldwide and total wheat straw production to almost 600,000 ktons/a [4].

Rice straw is currently used as fuel for cooking, as animal feed or bedding, in anaerobic digestion for the production of biogas and as roofing material. In some cases, straw is collected in piles on the field for composting.

Table 2. Cultivated agricultural area and rice production in different regions of the world, and estimate of rice straw production. Data based on FAO grain production data of 2009. Data are ranked by size of cropping area.

| | Area harvested | Production | Straw production |
|---------------------------|-----------------------|-------------------|-------------------------|
| | 1000 ha | kton of Rice/a | kton of straw/a |
| World | 158,511 | 684,595 | 727,400 |
| Southern Asia | 59,449 | 202,889 | 215,600 |
| South-Eastern Asia | 48,203 | 197,777 | 210,100 |
| Eastern Asia | 32,999 | 216,630 | 230,200 |
| Western Africa | 5,114 | 10,392 | 11,000 |
| South America | 5,253 | 25,568 | 27,200 |
| Eastern Africa | 3,147 | 6,701 | 7,100 |
| Northern America | 1,256 | 9,972 | 10,600 |
| Middle Africa | 691 | 663 | 700 |
| Northern Africa | 590 | 5,593 | 6,000 |
| European Union | 462 | 3,152 | 3,350 |
| Caribbean | 456 | 1,246 | 1,300 |
| Southern Europe | 418 | 2,906 | 3,100 |
| Central America | 326 | 1,228 | 1,300 |
| Eastern Europe | 225 | 1,183 | 1,250 |
| Central Asia | 193 | 696 | 740 |
| Western Asia | 153 | 927 | 990 |
| Western Europe | 24 | 138 | 150 |
| Oceania | 14 | 82 | 90 |
| Southern Africa | 1 | 3 | 3 |

Modernization of the rural areas where rice straw is being produced has led to other uses such as fiber production and combustion for electricity generation. Nevertheless, in many cases, rice straw is still disposed of by open field burning.

Unlike for rice straw, there are many current uses of wheat straw. Straw is currently used as: soil improver, supplement in animal feed, bedding for frost prevention (for example in flower bulb production), soil improvement for mushroom production and

building material. Straw has also been used for the production of energy. In some European countries (e.g. Denmark, Spain and UK) there are dedicated power plants that use wheat straw as feed. However, even with the many existing uses for wheat straw, in many regions around the world there is still a surplus of wheat straw. Open field burning of wheat straw is practiced as well, but not as often as rice straw.

Table 3. Cultivated agricultural area and wheat production in different regions of the world, and estimate of wheat straw production. Data based on FAO grain production data of 2009. Data are ranked by size of cropping area.

| | Area harvested | Production | Straw production |
|---------------------------|---------------------------|-------------------|-------------------------|
| | 1000 ha | kton of Wheat/a | kton of straw/a |
| World | 224,389 | 686,795 | 583,776 |
| Europe | 61,084 | 228,485 | 194,212 |
| Southern Asia | 47,113 | 125,458 | 106,639 |
| Eastern Europe | 42,387 | 114,626 | 97,432 |
| Northern America | 29,830 | 87,213 | 74,131 |
| European Union | 25,634 | 138,463 | 117,694 |
| Eastern Asia | 24,828 | 116,365 | 98,910 |
| Central Asia | 17,372 | 28,735 | 24,425 |
| Oceania | 13842 | 22,060 | 18,751 |
| Western Asia | 11853 | 30,029 | 25,525 |
| Western Europe | 9140 | 69,001 | 58,651 |
| Northern Africa | 7480 | 20,248 | 17,211 |
| South America | 7436 | 18,592 | 15,803 |
| Southern Europe | 5386 | 17,230 | 14,646 |
| Northern Europe | 4171 | 27,628 | 23,484 |
| Eastern Africa | 1882 | 3,220 | 2,737 |
| Central America | 835496 | 4126 | 3,507 |
| Southern Africa | 666 | 1978 | 1,681 |
| South-Eastern Asia | 105 | 183 | 156 |
| Western Africa | 48 | 77 | 65 |
| Middle Africa | 15 | 24 | 20 |

1.1.5 Empty Fruit Bunches

Empty Fruit Bunches (EFB) are a biomass waste stream from palm oil production. Palm oil is gained from fresh fruit bunches (FFB) in a palm oil mill. The milling process yields biomass wastes of which around 20 % consist of EFB. EFB is saturated with water due to the biological growth combined with the steam sterilization at the mill. Since the moisture content in EFB is around 67% pre-processing is necessary before EFB can be considered as a fuel.

The annual palm oil production volume is estimated to be at 63 M t. For producing 1 t of palm oil, 1.07 t of EFB is generated. Indonesia, Malaysia account for 85 % of the global palm oil production. Therefore, the amount of EFB waste every year in these countries adds up to ~50 Mt (475.000 TJ) (Amsterdam Research Project). Currently, 82 % of EFB is used in mulching, 10 % is incinerated on the fields, also leading to GHG emissions. Only 3 % is currently used as boiler fuels mainly due to its challenging fuel properties such as high alkaline and chlorine content (Malaysian Palm Oil Board).

1.1.6 Further moist Biomass for Hydrothermal Carbonisation

| Type | Description | Moisture content / wt% | Potential |
|--------------------|---|------------------------|-------------------------|
| Digestate | Left over indigestible material and dead micro-organisms | 98 | 20 Mt (Germany) |
| Horse Manure | Organic material consists primarily of a more or less homogenous mix of faeces and urine from horses, including bedding material, feed left overs | 40-80 | 7.6 Mt (Germany) |
| Urban leave litter | Leaves from the conservation of green urban areas | 60-80 | 1.18 Mt / 17 PJ (EU 27) |

1.2 Large-scale utilization experience (ORS, VAL, LAB, MET)

In ORS experience in PF power plants using wood pellets, the fuel price has a major impact on the production costs for power and heat and the incentive for substituting wood pellets with cheaper low-grade biopellets is strong. The share of low-grade pellets is limited by operational issues related to a high content of potassium, chlorine, ash etc. (slagging&fouling, SCR catalyst deactivation and corrosion) and is typically restricted to a low level (5-10% or similar). Pre-treatment of low-grade biomasses in order to reduce the content of potassium and chlorine will increase the share of low-grade biopellets significantly and will be commercially attractive, if the pre-treatment costs do not exceed the price difference between wood pellets and the low-grade pellets.

In LAB/ENGIE experience, large-scale application of wood as fuel started with co-combustion in pulverised coal-fired power plants. Purification of waste wood and

pulverisation of wood chips required much attention. With time, the co-combustion capacity expanded. Other biomass fuels were investigated and applied: residue from olive oil pressing, wood pellets, nutshells, etc. Conversion of pulverised coal-fired boilers to firing wood only was studied and implemented. Aspects of ATEX, safety and pulverisation and pneumatic transport required much attention. Moreover, the coal burners must be adapted, as the biomass produces longer flames than coal. Especially clean wood pellets were used as fuel, since lower grade biomasses contribute to faster slagging, fouling, corrosion in the boiler and poisoning of SCR catalysts.

With time, more customers of LAB were interested in conversion of coal-firing to wood firing, like the district heating company of the city of Paris, in France, and Volvo in Ghent as industrial customer, in Belgium. With these customers ENGIE gained experiences with grate-firing.

At the former ENGIE power station Polaniec in Poland, a new CFBC boiler firing wood and wood-like fuels only was constructed. In this way, the capacity of wood-fired boilers increased to about 250 MWe per unit. ENGIE Laborelec finds that now CFBC is the preferred technology for firing solid fuels, like wood. This CFBC technology has several advantages over PFC, like lower costs, better safety, reduced primary emissions, etc.

Within ENGIE, wood pellets are the main fuel. This fuel is expensive, and for boilers with high steam parameters special measures are required, like using suitable additives and steel alloys. So, the use of cheaper biomass fuels is of interest, but without causing big and costly problems. Besides, there are customers who are interested in using their or a local biomass fuel, which often is not wood but a residue from agriculture. The use of these lower grade biomasses at industrial scale would benefit if the fuel properties would be enhanced by upgrading methods that affordable could decrease the alkaline and chlorine contents, while simultaneously could increase the heating value of the biomass.

1.3 Provision of biomass materials (TUM, TNO, MET, ORS, VTT)

The biomasses were selected in agreement among all project partners. They were chosen in agreement with power plant operators (i.e. widely available and low-cost and currently in use). The biomasses supply chain within Bioefficiency project can be seen in Figure 1 and Table 4.

A quick overview on the fuels selected for combustion and grinding at the test rigs in the Bioefficiency project is given in Table 5.

An agriculture residue such as straw was chosen, as an example of problematic biomass in use, and was provided by ORS to TNO, where it was prewashed and torrefied at lab scale. TNO has used a different Dutch origin straw for pilot scale washing and torrefaction tests. The straw samples produced at pilot scale of both the original straw, as well as the prewashed and torrefied straw were sent to VTT for combustion tests at pilot scale CFB.

Residual spruce bark, as an example of available forestry residues, was also selected and provided by MET via VTT to TNO to be prewashed and torrefied. The washed and torrefied bark was sent to VTT for combustion tests. The spruce bark provided by MET

was also sent via VTT (after being dried and crushed) to VAL to produce steam exploded pellets (SEP) and later to MHPSE to perform grinding tests to enable the evaluation of the upgrading processes during milling operation. Furthermore, untreated and pre-treated biomass fuels were also sent to TUM and DTU to be tested in lab and pilot scale PF combustion installations (see Table 4).

Steam-exploded pellet is a new product which can be produced from various cellulose-based raw materials. In steam explosion treatment, the raw material is thermally treated to produce a pellet which is hydrophobic, more durable compared, and easier to grind compared to a conventional white wood pellet. This can be seen as a great advantage during transportation and storage of pelletized fuels. Large amounts of bark are assumed to be available in the near future as by-product from kraft pulping. This bark can be sold and used for heat and power production, but it could be necessary to dry and pelletize it to make it economically profitable for distant users. Pelleting will reduce transportation and handling costs of the biomass. Steam explosion treatment of residual spruce bark was delivered by Valmet Technologies Oy affiliate company Valmet AB in Sweden. Steam explosion treatment was carried out in March 2018. The bark used was residual from the debarking of pulp wood process from Joutseno Pulp mill (owned by Metsä Fibre) located in Finland. Metsä delivered the bark to VTT, Jyväskylä. After crushing, the material was sent to Valmet Fiber Technology Center located in Sundsvall, Sweden. After the steam explosion treatment, the material was sent back to VTT for pelletizing and further evaluation. Totally 2400 kg of steam exploded material was produced. The process has been described more in detailed in deliverable 2.2. VTT also crushed and pelletized 2.3 t untreated bark which properties can be compared with the SE bark pellets. The pellets were sent to MHPSE.



Figure 1: The biomasses supply chain within Bioefficiency project.

During the Bioefficiency-project, the needed amount of steam exploded bark was realised to be considerably larger than originally planned and budgeted. This was due to wider interest to study more fuel properties and milling behaviour by other project partners (TUM, MHPSE, ORS and MET). Budgetary changes were accepted within respective industrial project partners (ORS, MHPSE, Valmet and MET). Cost reporting for this steam explosion treatment has not been finished yet within this reporting period and it will be reported in the project final report. However, the steam explosion treatment work has been done and reported and the report has been delivered.

Miscanthus and road-side grass were also selected, as an example of herbaceous species, and used at TNO for prewashing and torrefaction tests as well as for lab scale combustion tests (PF) to evaluate the performance of the upgraded biomass fuels. TNO also tested spruce bark and straw, untreated and pre-treated samples.

Clean wood fuel was selected for base line data for industrial and pilot scale testing (supplied by ORS) and for blending with low grade biomasses and to study the effects of additives (supplied by VAL).

Among several biomass samples (Brewers' spent grains, empty fruit bunches, spruce bark, horse manure, lawn cuttings, digestate, miscanthus, olive pomace, urban leaf litter, fir brushwood), studied at preliminary lab scale tests, one high moisture residual biomass with no primary energetic use was selected - urban leaf litter - for HTC pre-treatment (TUM).

All selected fuels were characterized with standard fuel analysis and ash analysis methods, using EN standards. Standard fuel analysis encompassed proximate, ultimate and heating value analysis. Moreover, ash composition analyses were also done using XRF and ICP-OES. Ash fusion temperatures were determined using a melting microscopy. A detailed plan for the split of the analysis work was established in the beginning of the project among the partners to avoid duplicate work.

A short resume on the characterization activities performed by the Bioefficiency partners is presented in Table 6

Wheat straw samples (original, washed and washed/torrefied) as well as spruce bark samples (original, washed, washed/torrefied and steam exploded), produced at lab scale (TNO) and pilot scale (VAL), were characterized at ABO with the purpose of evaluation the corrosion potential of the original fuels and comparing with the upgraded biomasses, done based on the chemical fractionation method first developed for coal and then adapted for biomass by Abo Akademi (ABO). This work is presented in detail in D2.1 and the main conclusions are that the largest differences were observed in the samples that have been pre-washed before torrefaction.

After pre-washing and torrefaction, both the bark and the straw had a significantly lower Cl-concentration. Potassium was only removed by washing. In the case with steam exploded spruce bark, no obvious changes were observed, not even concerning the chlorine. It was concluded that the corrosion rate could be expected to be significantly lower due to the lower amounts of chlorine in the pre-washed and torrefied fuel samples. However, although pre-treated, the straw would still be expected to cause corrosion if fired alone. Steam explosion is not expected to reduce the corrosion and deposit formation. Other possible effects of pre-treatment on the fuel quality, such as on grindability, followability, etc. will be reported in the next section.

Table 4. Overview on fuel provision to partners. (RP = receiving partner).

| | Amount (kg) | 1. RP | Treatment | Amount (kg) | 2. RP | Treatment | Amount (kg) | 3. RP | Treatment | Amount (kg) | 4. RP | Treatment | Amount (kg) | 5. RP | Purpose |
|------------------------------------|-------------|-------|--|-------------|-------|------------------------------------|-------------|-------------------------|-------------|-------------|-------|-----------|-------------|-------|--------------------------|
| Wood Pellets (from ORS) | 2.000 | MHPSE | milling | 1.600 | TUM | | | | | | | | | | Grinding tests, PF tests |
| | 3.000 | VTT | | | | | | | | | | | | | VTT CFB tests |
| Spruce bark, batch 1 (from MET) | ~5.000 | VTT | Drying, crushing | 700 | VAL | none | 2 | TUM | | | | | | | Fuel analysis |
| | | | | | | pelletising | 2 | ABO | | | | | | | Fuel analysis |
| | | | | | | | 30 | MHPSE | | | | | | | Grinding tests |
| | | | | | | | 2 | TUM | | | | | | | Fuel analysis |
| | | | | | | | 2 | ABO | | | | | | | Fuel analysis |
| | | | | | | Steam explosion | 20 | TUT (subcontractor) | | | | | | | Fuel analysis |
| | | | | | | | 280 | Promill (subcontractor) | pelletising | 30 | MHPSE | | | | Grinding tests |
| | | | | | | | | | | 250 | TUM | | | | PF tests |
| | | | | | | 7 | TUM | Milling, HTC | | | | | | | HTC pretests |
| | | | | | | 70 | TNO | Washing, torrefaction | 70 | TNO | | | | | Torrewash pretests |
| | | | | 1.000 | TNO | Washing, torrefaction, pelletising | 330 | VTT | | | | | | | CFB tests |
| Spruce bark, batch 2 (from MET) | 23.500 | VTT | crushing | 6.000 | VAL | Steam explosion | 2.600 | VTT | pelletising | 2.200 | MHPSE | milling | <2.200 | TUM | Grinding tests, PF tests |
| Spruce bark, batch 3 (from MET) | 20.000 | VAL | | 2.300 | VTT | pelletising | 2.300 | MHPSE | <2300 | TUM | | | | | Grinding tests, PF tests |
| | | | | | | | | | | | | | | | CFB tests |
| Wheat straw (from ORS) | 1.630 | TNO | crushing, washing, torrefaction, pelletising | 380 | TNO | | | | | | | | | | Torrewash pilot |
| | | | | 300 | VTT | | | | | | | | | | CFB tests |
| | | | | | | | | | | | | | | | |
| EFB pellet, batch 1 (from VAL) | 900 | VTT | crushing, pelletising | 300 | VTT | | | | | | | | | | CFB tests |
| EFB pellet, batch 2 (from VAL) | 100 | VTT | none | 70 | TNO | | | | | | | | | | Torrewash tests |
| | 3000 | VTT | | 7 | TUM | | | | | | | | | | HTC tests |
| | 90.000 | VAL | | | | | | | | | | | | | CFB tests |
| Russian bituminous coal (from VAL) | 1.000 | VTT | crushing | 900 | VTT | | | | | | | | | | CFB tests |
| | 25.000 | VAL | crushing | 24.000 | VAL | | | | | | | | | | CFB tests |
| Leaves (TUM) | 55 | TUM | HTC | 25 | TUM | | | | | | | | | | CFB tests |
| | | | HTC | 6 | DTU | | | | | | | | | | HTC pilot |
| Miscanthus (TNO) | 1.500 | TNO | washing, torrefaction | 325 | | | | | | | | | | | PF test |
| Road-side grass | 1.000 | TNO | washing, torrefaction | 215 | | | | | | | | | | | Torrewash pilot |

Table 5. Overview of fuels selected for further investigations at the different test rigs.

| | Test Rig | Raw fuels | Pre-Treated fuels | Additives |
|---------------|-----------------------|-----------------|-----------------------|---------------------|
| FB combustion | 50 kW CFB VTT | Wood pellets | Torr bark | Asnaes coal fly ash |
| | | Bark pellets | Torrawash bark | Hofer coal fly ash |
| | | Bituminous Coal | Torr straw | Kaolin |
| | | | Torrawash straw | Elemental Sulfur |
| | 4 MW FB VAL | EFB pellets | - | - |
| | Bark | | | |
| | Bituminous Coal | | | |
| PF combustion | EFR DTU | Wood pellets | SE bark | Asnaes coal fly ash |
| | | | HTC urban leaf litter | Hofer coal fly ash |
| | Pilot Scale PF TUM | Wood pellets | SE bark | Asnaes coal fly ash |
| | | Bark | HTC biomass | Hofer coal fly ash |
| | | | | Kaolin |
| | Grinding MHPSE | Wood pellets | SE bark pellets | Coal ash |
| | | Bark pellets | | |

Table 6. Planned biomass fuels and additives characterization carried out by partners.

| Feedstock | Proximate | Ultimate | Heating value | Ash composition | Ash fusion temperature | Ash chemical fractionation | Grinding tests (pellets) | Particle size |
|--------------------------------------|-----------|----------|---------------|-----------------|------------------------|----------------------------|--------------------------|---------------|
| White pellets | TUM | TUM | TUM | TUM | TUM | | MHPSE | |
| White pellets + grinding aid | TUM | TUM | TUM | TUM | TUM | | MHPSE | |
| Herbaceous biomass | | | | | | | | |
| Wheat straw | TNO | ABO/TNO | TNO | ABO/TNO | - | ABO | TNO | - |
| Wheat straw washed | TNO | TNO | TNO | TNO | - | - | - | - |
| Wheat straw torrefied | - | ABO | ABO | ABO | - | ABO | - | - |
| Wheat straw washed and torrefied | TNO | ABO/TNO | ABO/TNO | ABO/TNO | - | ABO | TNO | - |
| Miscanthus | TNO | TNO | TNO | TNO | - | - | TNO | - |
| Miscanthus washed and torrefied | TNO | TNO | TNO | TNO | - | - | TNO | - |
| Agricultural residues | | | | | | | | |
| Empty fruit bunches | TUM | TUM | TUM | TUM | - | - | - | - |
| HTC Empty fruit bunches | TUM | TUM | TUM | TUM | - | - | - | - |
| Brewery spent grains | TUM | TUM | TUM | TUM | - | - | - | - |
| HTC Brewery spent grains | TUM | TUM | TUM | TUM | - | - | - | - |
| Olive pomace | TUM | TUM | TUM | TUM | | | | |
| HTC olive pomace | TUM | TUM | TUM | TUM | | | | |
| Forestry residues | | | | | | | | |
| Spruce bark | TNO | ABO | ABO | ABO | TUM | ABO | MHPSE | - |
| SE spruce bark | - | ABO | ABO | ABO | TUM | ABO | MHPSE | - |
| Spruce bark torrefied | - | ABO | ABO | ABO | - | ABO | - | - |
| Spruce bark washed | TNO | TNO | TNO | TNO | - | - | - | - |
| Spruce bark washed and torrefied | TNO | ABO/TNO | ABO/TNO | ABO/TNO | - | ABO | - | - |
| HTC spruce bark | TUM | TUM | TUM | TUM | TUM | | | |
| Fir brushwood | TUM | TUM | TUM | TUM | TUM | | | |
| HTC fir brushwood | TUM | TUM | TUM | TUM | TUM | | | |
| Low-grade residual derived biomasses | | | | | | | | |
| Road-side grass | TNO | TNO | TNO | TNO | - | - | TNO | - |
| Road-side grass washed and torrefied | TNO | TNO | TNO | TNO | - | - | TNO | - |
| Urban leaf litter | TUM | TUM | TUM | TUM | TUM | - | - | - |
| HTC urban leaf litter | TUM | TUM | TUM | TUM | TUM | - | - | - |
| Digestate | TUM | TUM | TUM | TUM | TUM | | | |
| HTC digestate | TUM | TUM | TUM | TUM | TUM | | | |
| Lawn cuttings | TUM | TUM | TUM | TUM | TUM | | | |
| HTC lawn cuttings | TUM | TUM | TUM | TUM | TUM | | | |
| Horse manure | TUM | TUM | TUM | TUM | TUM | | | |
| HTC horse manure | TUM | TUM | TUM | TUM | TUM | | | |
| Additives | | | | | | | | |
| Asnaes coal fly ash | - | - | - | VTT/TUM | TUM | - | - | VTT |
| Hofer coal fly ash | - | - | - | VTT/TUM | TUM | - | - | VTT |
| Kaolin | - | - | - | VTT/TUM | - | - | - | VTT |

2. Comparison of treated and untreated fuels (TUM, ECN, VAL, ABO, MHPSE)

2.1 Prewash and torrefaction (TNO)

In the scope of Bioefficiency project, ECN part of TNO has conducted a lab-scale upgrading study by prewashing and torrefaction of several low-grade biomasses. Among the different biomass streams studied, wheat straw, miscanthus, road side grass and spruce bark revealed significant potential to be scalable to an industrial process. The other investigated biomass species (e.g. tomato foliage, chicken litter, sunflower husks) were found not in enough quantities, or have led to great mass losses during the washing process and does not justify the investment in a large upgrading unit. Therefore, four materials were selected to proceed to pilot scale level, as reported in Deliverable 2.2 – wheat straw, miscanthus, road side grass and spruce bark. All the steps from lab to pilot scale testing is presented in more detail in ref. [5].

2.1.1 Biomass analyses results

These four materials including original, pre-washed and torrefied have been analysed on proximate, ultimate and ash composition. The results are shown in Table 7.

After the pre-treatment, it is possible to observe that the ash content tended to decrease for the biomasses with high ash content (straw and grass) and to increase slightly for the low ash content biomasses (bark and miscanthus). The volatile content decreased and the heating value increased after torrefaction as expected, due to the increased content in C and decreased content in O, while washing did not affected these values significantly. The Cl and the S contents decreased significantly after washing and slightly after torrefaction, bark being the exception due to the low levels of these elements, already in the original bark material. The P and K decreased after washing but were not significantly affected by torrefaction. The Na content of these biomasses was low (< 300 mg/kg) and after washing it increased slightly, most probably due to a higher Na content in the tap water. The exception was the grass, which originally had a higher Na content (1600 mg/kg) and after washing it decreased to 1000 mg/kg at which level it remained after torrefaction. The pre-treatments did not affect the trace elements (heavy metals) contents. The exception was for Hg, for which a decreasing tendency was observed with torrefaction without any major change after the prewash step.

In order to assess the technical feasibility of the results, a comparison was made between the lab-scale and pilot scale results. The comparison is Figure 2 for the cases of road side grass and miscanthus, as an example. The effect of washing separately and the combined effect of pre-wash plus torrefaction is presented on an energy basis, for the most problematic elements for combustion (Cl, K, P and S), as well as for total ash.

Table 7. Raw and pre-treated biomass fuels characterization at TNO (proximate, ultimate and ash composition).

| (Dry basis) | Wheat straw | | | Spruce bark | | | Road-side grass | | | Miscanthus | | |
|---------------|-------------|--------|-----------|-------------|--------|-----------|-----------------|--------|-----------|------------|--------|-----------|
| | Original | Washed | Torrefied | Original | Washed | Torrefied | Original | Washed | Torrefied | Original | Washed | Torrefied |
| Ash (550) (%) | 10.3 | 10.2 | 9.3 | 3.4 | 4.8 | 4 | 18.1 | 14.2 | 14.8 | 2.1 | 2.4 | 3.1 |
| Volatiles (%) | 71.8 | 74 | 70.9 | 74.5 | 74.7 | 69.2 | 66.1 | 72.1 | 61.5 | 81.7 | 82.5 | 75.7 |
| HHV (MJ/kg) | 17.5 | 17.7 | 19.2 | 19.9 | 20.0 | 21.5 | 16.5 | 17.3 | 20 | 19.3 | 19.2 | 20.4 |
| Cl (mg/kg) | 2800 | 790 | 540 | 100 | 130 | 88 | 9500 | 2000 | 1300 | 1300 | 550 | 420 |
| C (%) | 42.9 | 42.9 | 47.7 | 49.4 | 49.9 | 54.3 | 41.4 | 43.1 | 49.9 | 47.7 | 47.3 | 50.1 |
| H (%) | 5.6 | 5.6 | 5.5 | 5.8 | 5.9 | 5.6 | 5.3 | 5.6 | 5.3 | 5.9 | 5.9 | 5.6 |
| N (%) | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 1.8 | 1.4 | 1.7 | 0.3 | 0.25 | 0.25 |
| O (%) | 38.6 | 40.2 | 35.9 | 40.2 | 41.3 | 36.2 | 35.4 | 37.4 | 30.7 | 43.3 | 43.4 | 38.9 |
| Al (mg/kg) | 45 | 120 | 180 | 470 | 560 | 580 | 1700 | 2000 | 1400 | 79 | 71 | 160 |
| As (mg/kg) | <1 | <1 | <1 | <1 | <1 | <1 | 1.5 | <1 | <1 | <1 | <1 | <1 |
| B (mg/kg) | 1.8 | 1.3 | 2 | 12 | 11 | 11 | 40 | 15 | 15 | 1.9 | <0.7 | <0.7 |
| Ba (mg/kg) | 7.3 | 2.5 | 6.8 | 220 | 220 | 250 | 25 | 29 | 33 | 8.2 | 1.5 | 4.4 |
| Ca (mg/kg) | 2800 | 3600 | 3800 | 11000 | 12000 | 14000 | 18000 | 11000 | 13000 | 1000 | 1100 | 1700 |
| Cd (mg/kg) | 0.14 | 0.13 | 0.14 | 0.36 | 0.37 | 0.41 | 0.12 | 0.13 | 0.15 | <0.1 | <0.1 | 0.11 |
| Co (mg/kg) | <0.3 | <0.3 | <0.3 | 0.65 | 0.49 | 0.43 | 0.44 | 0.46 | <0.3 | <0.3 | <0.3 | <0.3 |
| Cr (mg/kg) | 1.8 | 1.6 | 4.8 | 3.4 | 2.1 | 1.7 | 3.9 | 6.3 | 11 | 1.4 | 1.4 | 2.4 |
| Cu (mg/kg) | <2 | 2.7 | 3.1 | 3.7 | 4.3 | 14 | 4.7 | 7 | 9.1 | <2 | 2.4 | 3.9 |
| Fe (mg/kg) | 140 | 150 | 250 | 280 | 340 | 370 | 1800 | 1500 | 1400 | 160 | 230 | 330 |
| K (mg/kg) | 8400 | 3100 | 3400 | 2000 | 1000 | 1000 | 17000 | 4600 | 4400 | 2300 | 1200 | 1800 |
| Li (mg/kg) | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | <0.3 | 1.1 | 1.1 | 0.87 | <0.3 | <0.3 | <0.3 |
| Mg (mg/kg) | 560 | 540 | 560 | 810 | 790 | 850 | 2000 | 1100 | 1600 | 360 | 320 | 420 |
| Mn (mg/kg) | 17 | 15 | 42 | 650 | 620 | 680 | 130 | 160 | 140 | 22 | 11 | 15 |
| Mo (mg/kg) | 1.3 | <0.8 | <0.8 | <0.8 | <0.8 | <0.8 | 1.8 | 2.1 | 2.6 | <0.8 | <0.8 | <0.8 |
| Na (mg/kg) | 140 | 410 | 440 | 160 | 430 | 500 | 1600 | 1000 | 1000 | 260 | 390 | 470 |
| Ni (mg/kg) | 1.3 | 0.79 | 1 | 2.6 | 1.8 | 1.9 | 2 | 2.9 | 3.7 | 0.66 | 0.74 | <0.6 |
| P (mg/kg) | 830 | 640 | 610 | 510 | 440 | 430 | 4000 | 1600 | 2200 | 220 | 150 | 250 |
| Pb (mg/kg) | <0.6 | 0.62 | <0.6 | <0.6 | 0.7 | 1.6 | 3.3 | 2.7 | 1.9 | <0.6 | <0.6 | <0.6 |
| S (mg/kg) | 820 | 600 | 520 | 330 | 340 | 310 | 3400 | 1700 | 1400 | 480 | 310 | 360 |
| Sb (mg/kg) | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 | <3 |
| Se (mg/kg) | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Si (mg/kg) | 36000 | 38000 | 34000 | 1900 | 3800 | 2300 | 45000 | 54000 | 46000 | 6500 | 9400 | 14000 |
| Sn (mg/kg) | <0.9 | <0.9 | <0.9 | <0.9 | <0.9 | <0.9 | 1.5 | <0.9 | <0.9 | <0.9 | <0.9 | <0.9 |
| Sr (mg/kg) | 11 | 20 | 23 | 44 | 46 | 55 | 91 | 51 | 55 | 5.3 | 6.6 | 10 |
| Ti (mg/kg) | 50 | 60 | 41 | 90 | 94 | 87 | 230 | 250 | 220 | 50 | 40 | 18 |
| V (mg/kg) | <0.2 | <0.2 | 0.3 | 0.39 | 0.78 | 0.45 | 3 | 2.4 | 1.9 | <0.2 | <0.2 | 0.35 |
| W (mg/kg) | <1 | <1 | <1 | 1.3 | 1.6 | 1.7 | <1 | <1 | <1 | <1 | <1 | <1 |
| Zn (mg/kg) | 6.4 | 25 | 29 | 140 | 160 | 170 | 39 | 70 | 78 | 9.1 | 24 | 50 |
| Hg (mg/kg) | 0.0067 | 0.0074 | <0.002 | 0.033 | 0.034 | 0.0075 | 0.011 | 0.015 | <0.002 | 0.0023 | <0.002 | 0.0024 |

For the road-side grass, the data from the lab scale matches the data from the pilot scale within a margin of error of 10%, showing that it is possible to reproduce the results in a representative manner, at a significantly less expensive small scale. The exception was the element P, for which a significant discrepancy was observed. Probably this was related to the fact that the grass sample used for the pilot scale tests had a two times higher P content than the sample used for the lab-scale, facilitating its removal. Nevertheless, the tendency was the same, and the P was extracted only at the washing step, being concentrated during torrefaction due to the global mass loss of the evolved volatile material during this step. The Cl global extraction efficiency was 90%, with 80% achieved by the washing step and a 10% extra during the torrefaction step, as can be seen Figure 2. The K global extraction efficiency was between 70 and 80% and the removal occurred solely during the washing step. The S extraction was about 50% during washing and plus 10 to 15% during torrefaction. The total ash content was reduced significantly during washing (25-30%) and remained unchanged during torrefaction. These results showed the importance of the washing step in the pre-treatment method. The torrefaction brings further benefits in terms of Cl and S decrease, added to its major advantages related to the energy densification, enhanced homogeneity, water resistance and grindability.

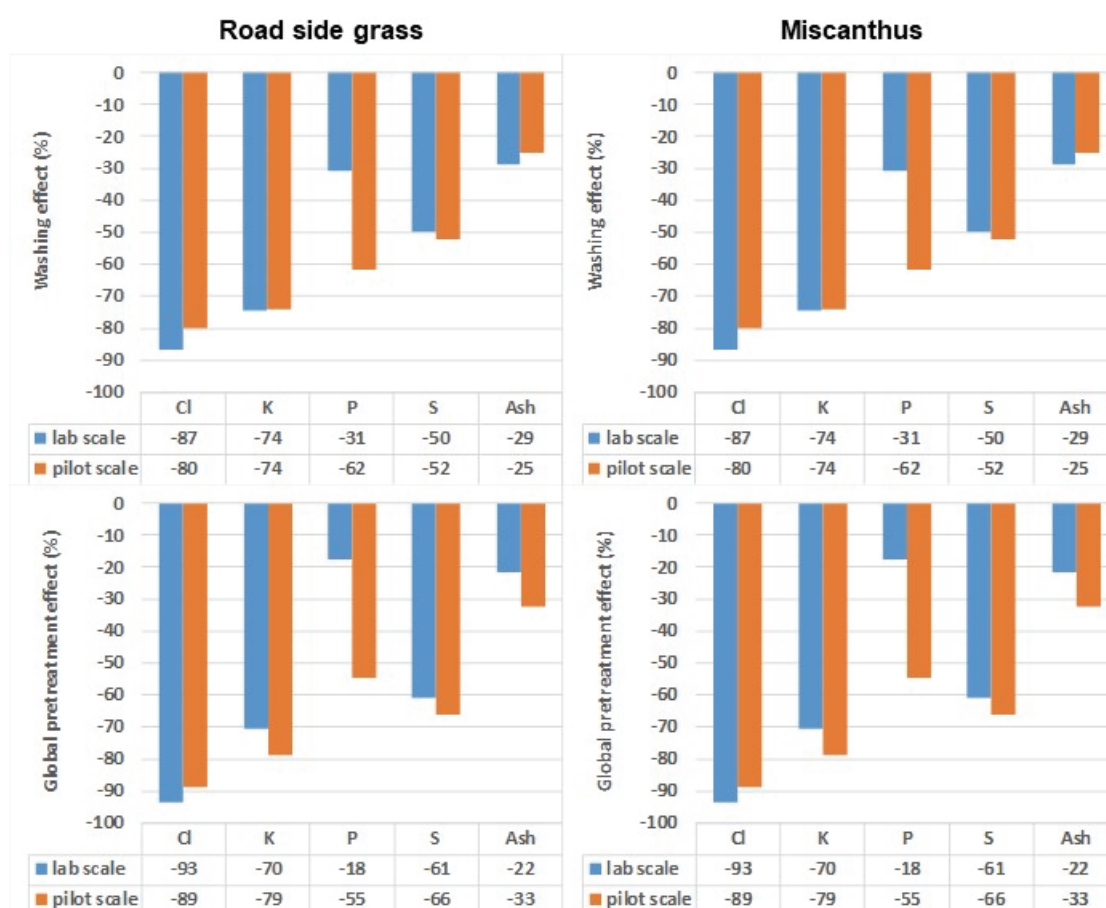


Figure 2: The changes in concentration for some pernicious elements in road-side grass and in miscanthus, as a result of the washing treatment (top graphs) and combined treatment (bottom graphs), for both lab and pilot scale.

The ash content, as well as the pernicious ash elements concentration, is significantly lower in the case of miscanthus when compared to the road-side grass (see Table 7). Moreover, the samples used at lab-scale and at pilot scale were different. Therefore, in the case of miscanthus, the relative error levels during quantification are expected to increase and the results presented in Figure 2 are affected somehow by this, especially comparing the P and total ash contents from lab and pilot scale experiments. Apart from this, the data from the lab-scale matches the data from the pilot scale within a margin of error of 15%. For miscanthus, the Cl global extraction efficiency was between 70 and 80%, with at least 60% removal at the washing step. The final sulphur extraction was quantified between 30 and 35%, almost all extracted during washing. During washing, the K content was decreased between 40 to 50%, but during torrefaction there was a concentration effect, decreasing the final removal to between 25 to 40%. The same was observed with P which could be removed by 30% during washing although during torrefaction the final decrease was probably lower, since the pilot test showed a net increase of 10%, diverging from the lab-scale result that remained at 30% removal. This last effect was due to the fact that at the lab-scale the final ash content was decreased by about 20%, while during the pilot test a final ash

increase of 40% was registered. The low ash content of the miscanthus contributed to this high relative error.

Post-wash (washing after torrefaction) was also tested with wheat straw. The conclusions were similar to the pre-wash process in terms of washing removal efficiency. However, a significant reduction in the total organic matter content in the waste water was found, which could indicate a significant cost saving in terms of water treatment needs. Moreover, comparing the mechanical dewatering efficiency after washing, the water content of the washed raw straw cake was about 70 %(wt) while for the washed torrefied straw cake a value of 30 %(wt) was found. Therefore, post-wash seems to be a viable and preferable route to upgrade dry-type biomasses, since it produced equivalent salts extraction efficiencies, compared to pre-wash, while allows decreasing the costs of water treatment and of energy related to drying the washed dewatered cakes.

2.1.2 Pre-evaluation of emissions, high temperature corrosion and ash melting tendency (fuel indexes)

The alkali indexes of the individual fuels is shown in Figure 3. The alkali index is a measure commonly used for biomass to predict the fouling propensity of a fuel originating from alkali salt deposition on heat exchangers [6]. It can be seen that all fuels profit greatly from the potassium removal during the pre-washing. Spruce bark shows only a marginal fouling propensity before and after pre-washing if only the alkali index is concerned. While miscanthus also shows a low alkali index, both wheat straw and road side grass are probably causing fouling problems even after upgrading. However, it should be noted that the alkali index is a very specific alkali salts deposition oriented index that makes no statements about fine particulate matter induced fouling for instance induced due the presence of sub-micron calcium oxide particles commonly experienced in woody biomass combustion. Moreover, the two levels indicating “probable” and “certain” fouling problems in Figure 3 are only indicative references, since fouling is related not only to the fuel composition, but more significantly to the combustion system, boiler design and operating conditions. Therefore combustion tests simulating the real process conditions should always be considered to provide more reliable data. More certain data on this will be presented in WP3 and WP4.

The potential reduction in the pollutant gaseous formation through pre-treatment can be evaluated by the achieved reduction in the contents of N, S and Cl for the formation of NO_x, SO₂ and HCl respectively. The change in the sum of the contents of K, Na, Pb and Zn can also provide an indication related to the aerosol formation [7]

The specific nitrogen contents per unit energy content decrease for all fuels due to upgrading. On the other hand, also the volatile matter of the fuels is reduced by torrefaction which in general reduces the ability of the volatiles to reduce NO_x formation in situ. Evidently, all fuels fall in the same range of specific nitrogen content of approximately between 100 and 250 mg/MJ with the exception for road side grass which contains - even when upgraded - 850 mg/MJ. The commonly observed NO_x reduction when (co-) firing biomass is not to be expected for this fuel.

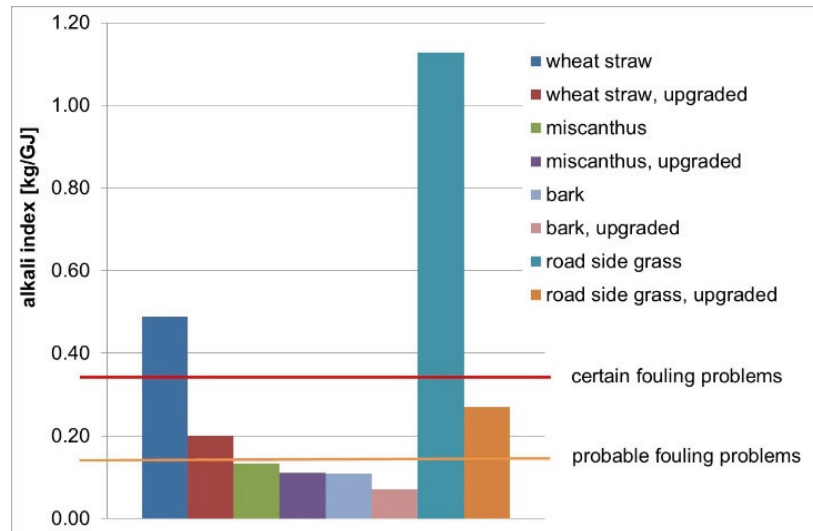


Figure 3: Alkali indices of the investigated fuels and limits as proposed in [6].

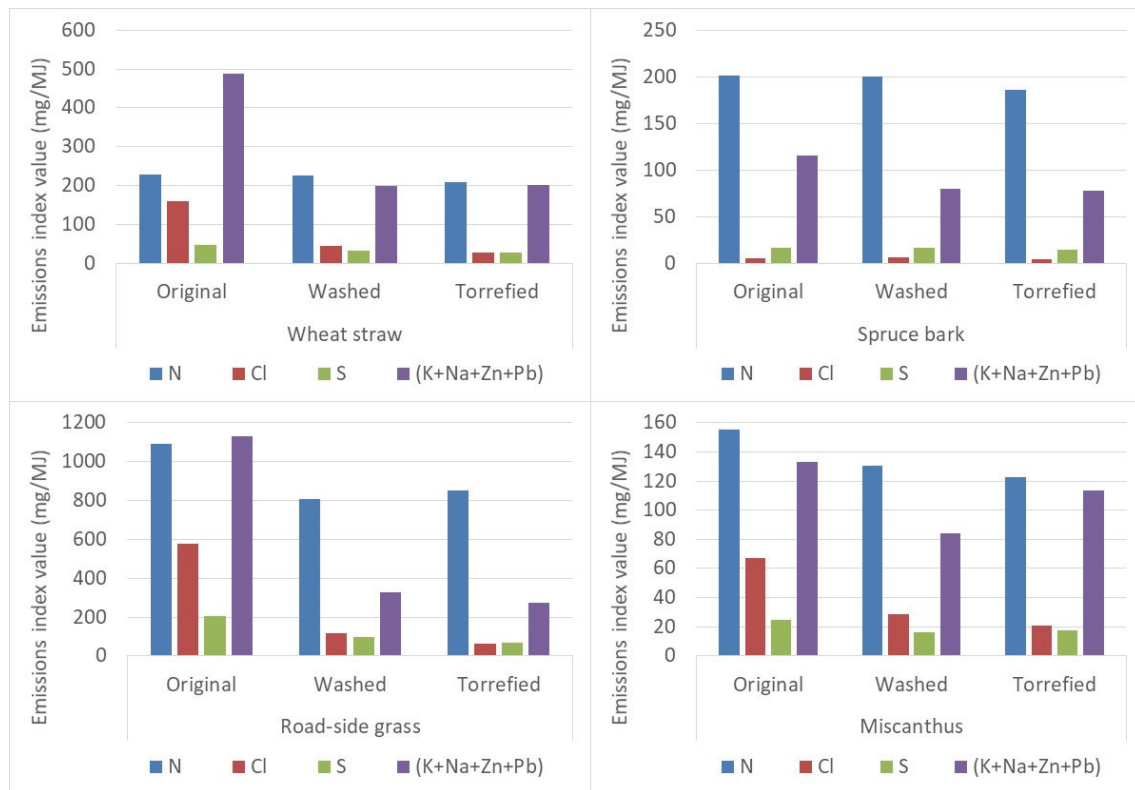


Figure 4: The changes in the emissions fuel indexes obtained during upgrading by washing and torrefaction.

Sulphur conversion to SO_x is usually not a problem during the combustion of this kind of biomasses, due to the low amounts of S present ($< 50 \text{ mg/MJ}$). However, during the upgrading a decrease in the S content was observed for all fuels and specially for the road side grass, which decreased from 206 to 70 mg/MJ.

Chlorine reduction both due to pre-washing and torrefaction yields for wheat straw and miscanthus very similar specific chlorine contents of 30 and 22 mg/MJ, respectively, while spruce bark yields very low values of 4 mg/MJ of specific chlorine content. Even the very chlorine rich road side grass yields a value of 69 mg/MJ after upgrading. Obviously, these high removal yields are due to the fact that chlorine is very well water-soluble and can hence be removed efficiently. The achieved values indicate that no significant high temperature chlorine corrosion is expected for the upgraded materials, with the exception of road side grass. The molar ratio S/Cl is also often used to evaluate the risk for Cl-containing deposits on superheaters. Usually with a S/Cl ratio higher than 2 minor corrosion risk is expected and a value of 4 is normally assumed to achieve a negligible chlorine level in the boiler deposits [7,8]. By upgrading the road-side grass and the miscanthus, the risk of corrosion is significantly reduced, as shown in Table 8. This means a reduction from a severe corrosion potential to an acceptable risk if the heat exchange surface temperature is limited to 550 °C. The values presented in Table 8 still indicate that even if the grass and the miscanthus are both pre-washed and torrefied there is a risk for alkali chloride formation, although the amounts will be significantly smaller when compared to untreated materials.

The potential for aerosol formation, direct related to the formation of submicron particles, is also decreased by the upgrading process mainly due to the removal of alkalis. This effect is more pronounced in the cases of road side grass and wheat straw. For spruce bark a small impact is expected.

For the slagging and fouling evaluation, there are still no widely accepted indexes that could cover the behaviour of all the biomass types with a good correlation to actual observations, in the combustion systems. However, as a first indication the indexes proposed in [9] and usually applied for coal will be used here. In Table 8 it can be seen that with the grass and especially with miscanthus, the slagging index (SI) presents a relatively low value due to the high Si content of the original materials. A SI value < 0.6 already points to a low slagging inclination. The pre-treatment improves this value further for both fuels.

The fouling index (FI) of both original grass and miscanthus is relatively high (23.3 and 19.2 respectively). Values between 0.6 and 40 means high tendency for sintering. With the pre-treatment the FI was significantly reduced to 4 and 6 for the grass and the miscanthus respectively. However, these reduced values are still indicative of significant fouling issues. Moreover, the applicability of this indexes to biomass combustion is rather limited as mentioned previously.

Table 8. The changes in high temperature corrosion (S/Cl, molar) fuel index and slagging (SI) and fouling (FI) fuel indexes, obtained after upgrading of road-side grass and miscanthus at pilot scale.

| Fuel index | Road-side grass | | | Miscanthus | | |
|----------------------------|-----------------|--------|-----------|------------|--------|-----------|
| | Original | Washed | Torrefied | Original | Washed | Torrefied |
| S/Cl (molar) | 0.4 | 0.9 | 1.2 | 0.4 | 0.6 | 0.9 |
| Slagging index (SI) | 0.32 | 0.06 | 0.06 | 0.03 | 0.01 | 0.01 |
| Fouling index (FI) | 23.3 | 3.3 | 4.2 | 19.2 | 5.8 | 6.4 |

$$SI = B/A \times S\%, \quad B/A = (K_2O + CaO + Na_2O + MgO + Fe_2O_3 + P_2O_5) / (SiO_2 + TiO_2 + Al_2O_3)$$

$$FI = B/A \times (Na_2O + K_2O)$$

Although fuel indexes could present a first view on the expected improved behaviour during combustion, as a result of the upgrading processes, performing actual combustion testing will be essential to definitely confirm the improved combustion properties of the upgraded fuels. Combustion tests are programmed to confirm this and the results will be presented in Deliverable D4.1.

In terms of gaseous pollutants formation and ash behaviour, on the contrary to the others fuels tested, spruce bark seems not to be improved significantly by the upgrading process. As a matter in fact, the original spruce bark seems to be already a reasonable quality biomass fuel and therefore upgrading by washing/torrefaction is pointless from this point of view.

2.1.3 Grindability

The three materials that were in pellet form – grass, miscanthus and straw – were subjected to grindability studies and the results on the required specific energy consumption (E_m) and the characteristic particle correspondent to 80% (wt) undersize (d_{80}) of the milled material are presented in Table 9.

The photos and the main characteristics of the pellets are presented in appendix A. A determined quantity of pellets is milled using several bottom sieves (1.5 -0.25 mm). The energy required for milling is measured and the quantity of milled pellets is recorded for each mill sieve individual test. After the milling, the particle size distribution (PSD) is measured. An example of how the parameter d_{80} was determined is presented in Figure 5.

In Figure 5 it is possible to see that the d_{80} is obtained by intercepting the 0.8 fraction line (black dashed horizontal line) with the respective PSD curve lines and reading the corresponding value from the particle size axis. The milling tests showed that among the original materials, the grass was the most easy material to grind presenting the lower specific energy consumptions for the same reference size (d_{80}). The miscanthus followed closely the grass and the straw was undoubtedly the material that required more energy to be milled.

Table 9. The milling specific energy consumption and the characteristic particle undersize d_{80} for the three biomasses tested.

| Material | Milling sieves | | | | | | | | | |
|------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | 1.5 mm | | 1.0 mm | | 0.75 mm | | 0.50 mm | | 0.25 mm | |
| | d_{80} [μm] | E_m [kWh/t] | d_{80} [μm] | E_m [kWh/t] | d_{80} [μm] | E_m [kWh/t] | d_{80} [μm] | E_m [kWh/t] | d_{80} [μm] | E_m [kWh/t] |
| Grass | 875 | 5 | 661 | 6 | 627 | 10 | 420 | 19 | 303 | 50 |
| Miscanthus | 886 | 15 | 654 | 17 | 610 | 19 | 373 | 49 | 259 | 80 |
| Straw | 1069 | 15 | 961 | 19 | 935 | 26 | 600 | 60 | 362 | 168 |
| Torr.Grass | 775 | 2 | 594 | 4 | 563 | 6 | 386 | 9 | 290 | 25 |
| Torr.Miscanthus | 889 | 5 | 663 | 6 | 624 | 9 | 417 | 16 | 290 | 36 |
| Torr.Straw | 971 | 10 | 812 | 11 | 691 | 17 | 476 | 32 | 305 | 69 |

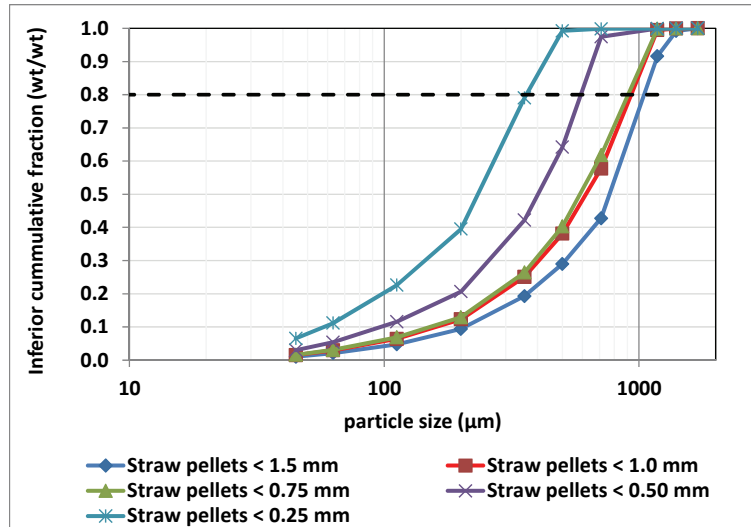


Figure 5: The PSD curves obtained for the milled products from the straw pellets, using different bottom sieves (0.25, 0.50, 0.75, 1.0 and 1.5 mm).

In Figure 6 it is possible to observe that the upgraded materials required significant less energy to be committed to a particular particle size, when compared to the respective original material. However, the specific energy demands follows the same order of materials as the original, being the straw the more demanding and the grass the lower. Moreover, it was observed a significant decrease in attrition of the moving parts of the mill and in the final temperature of the mill, while milling the upgraded materials. The values in Figure 6 were used to derive trend line curves representing the specific energy required to achieve any desired undersize particle diameter, characteristic of each fuel pellet material. This curves are presented in Figure 6 and Figure 7. The energy demands follows an exponential increase as de comminution diameter is decreased and the differences in the required specific energy for milling the different materials can be well visualized. For instance if a particle undersize diameter (d_{80}) of 500 μm is desirable to be obtained, the energy requirements are about 299, 107 and 51 MJ/ton (or 83.2, 29.7, 14.3 kWh/ton) for the straw, miscanthus and grass pellets respectively.

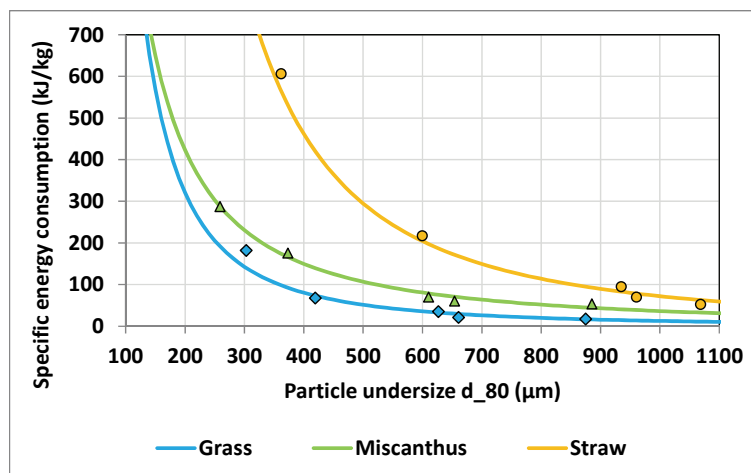


Figure 6: The specific energy consumption (E_m) obtained for the three original biomasses tested.

If we consider the upgraded materials and the same required particle undersize ($d_{80} = 500 \mu\text{m}$), the energy requirements are significantly lowered to about 106, 45 and 23 MJ/ton (or 29.4, 12.4, 6.5 kWh/ton) for the straw, miscanthus and grass pellets respectively.

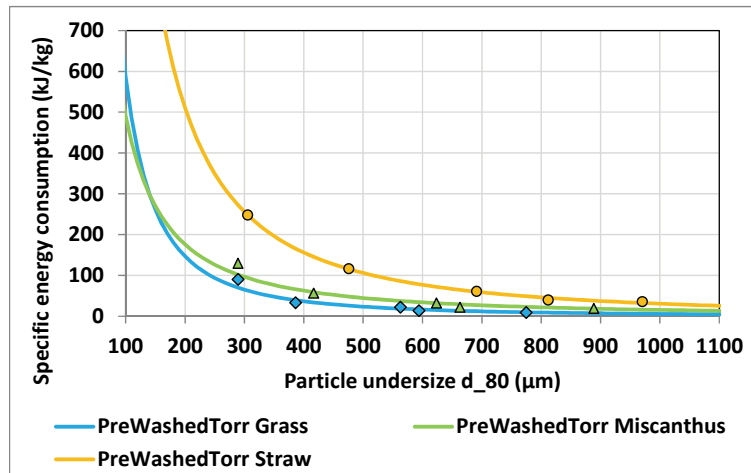


Figure 7: The specific energy consumption (E_m) obtained for the three upgraded biomasses tested.

2.1.4 Flowability

The results of the flowability measurements are presented in Figure 8 and Figure 9. The original biomasses were found impossible to fluidize. As the air flow was increased, channelling within the bed was observed and therefore a proper flow of these materials out from the bottom of the tube tester was not achieved.

In Figure 8 we can observe the decrease in the material height with time, after opening the solids exit at the bottom of the tube tester. For the original miscanthus and straw materials no significant changes in height were measured and accordingly, no significant mass was measured to flow out of the tube (less than 10% in Figure 9). Even increasing the fluidization air flow showed to be ineffective. For the original grass it was slightly better, however, no proper fluidization was attained at 7 l/min, the standard flow used, and the material flow out of the tube tester in two impulses as the flow was increased from 7 to 9 and then to 11 l/min. At the end only about 30% of the initial mass could be transported. The practical result is that this materials will offer some resistance to pneumatic transport and will behave totally different from coal, the reference material, requiring higher velocities and thus presenting lower efficiencies and higher operation costs at the plant.

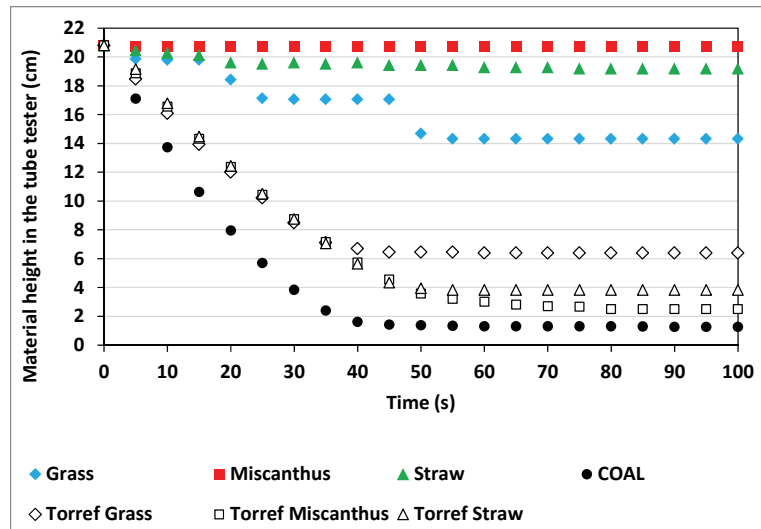


Figure 8: The evolution of the biomass materials height inside the tube tester along time.

The upgraded materials showed a significant different behaviour, showing clearly the benefits of the upgrading process (mainly due to torrefaction). Using an air flow of 7 l/min, all the upgraded materials could be fluidized and were observed to flow continually at the bottom of the tube tester. However, there were some differences observed within the materials. Contrary of what was observed with the original materials, the upgraded grass seemed to be the worst to flow and at the end only 70% of the initial mass was transported. On the other end was the upgraded miscanthus, which presented about 90% of the initial mass transported and the upgraded straw was in between (about 80%). The expected final value should be around 95% since the exit at the bottom was at a height of 1.0 cm from the bottom distributor plate, as it was observed with a good quality South African coal as used in a Dutch coal power plant.

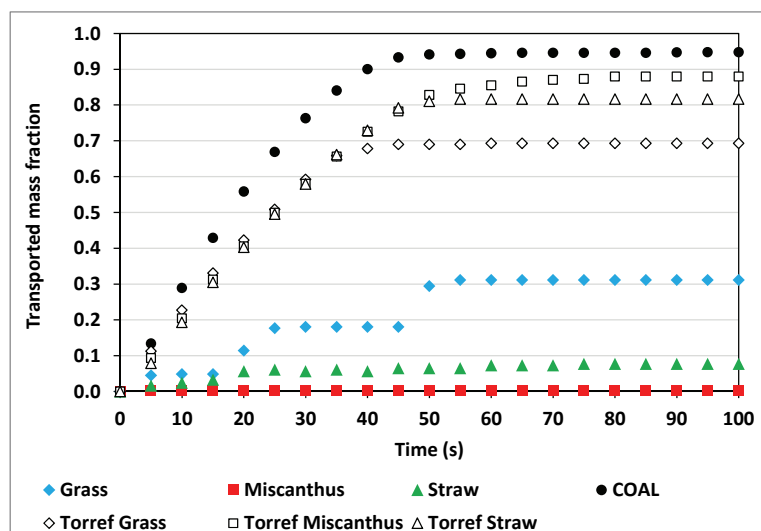


Figure 9: Fraction of the initial mass transported out of the tube tester along time.

Table 10. Bulk density of the dried materials used for flowability tests ($63 < d_p < 355 \mu\text{m}$).

| Material: | Original | | | Upgraded | | | SA Coal |
|---|------------|-------|-------|------------|-------|-------|------------|
| | Miscanthus | Grass | Straw | Miscanthus | Grass | Straw | |
| Bulk density (kg/m³): | 332 | 324 | 277 | 457 | 390 | 413 | 890 |

The particles shape and bulk density have a significant impact on pneumatic transport. The bulk density of the milled materials is presented in Table 10. The milled particles shape before and after torrefaction can be evaluated in Figure 10 and Figure 11, where it can be seen that the shape of the milled particles didn't change significantly after torrefaction, even comparing two different particle sizes – in Figure 10 the particles were milled below 0.5 mm and sieved below 355 μm ; in Figure 11 the particles were milled below 1.5 mm.

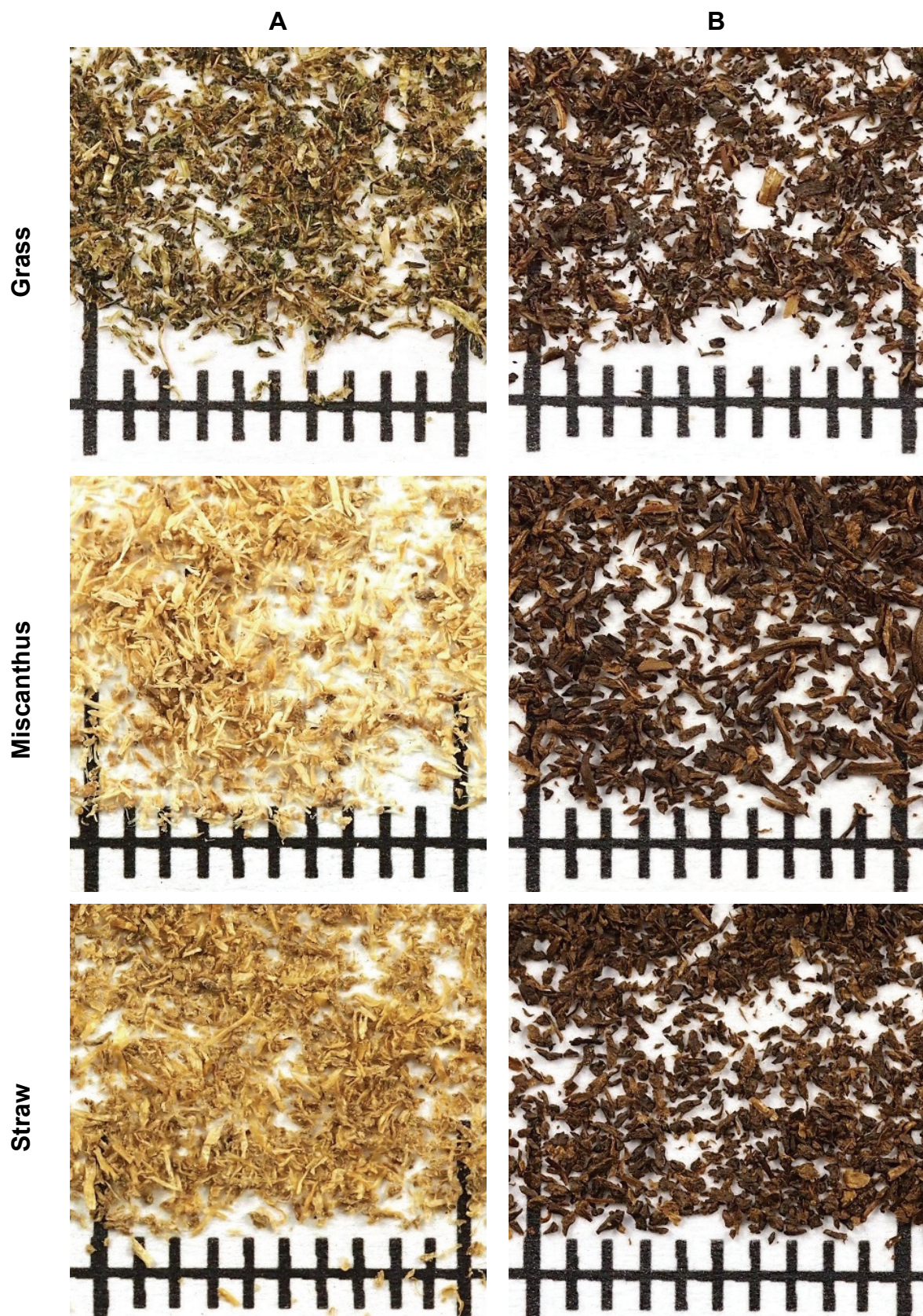


Figure 10: The milled particles shape before (A) and after torrefaction (B). Major gridlines – 1 cm; minor gridlines – 1 mm. Particles milled < 0.5 mm and sieved below 355 μm .

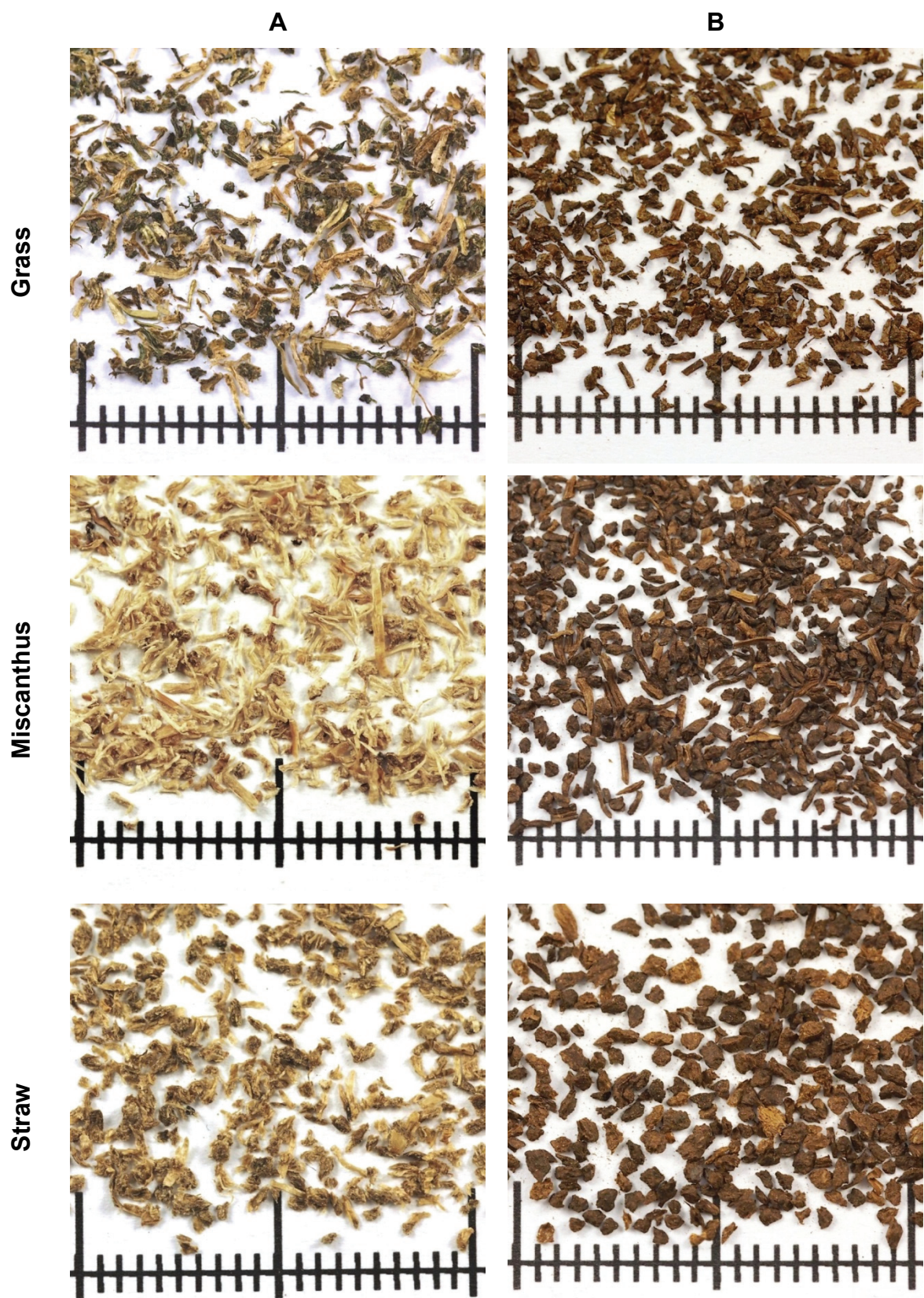


Figure 11: The milled particles shape before (A) and after torrefaction (B). Major gridlines – 1 cm; minor gridlines – 1 mm. Particles milled < 1.5 mm.

In previous studies ECN part of TNO has shown that wood torrefaction had a beneficial effect on the pneumatic transport of particles, when compared to the raw wood materials, by increasing slightly the bulk density of the milled particles maintaining the sphericity almost unchanged. However, when pelletization was done after torrefaction of the wood material, an extra increase on both the sphericity and the bulk density of the milled particles was observed. The same phenomena should also occur for this non-woody biomass materials. However, in the current study the pellets of the raw materials were used for torrefaction and directly milled for this tests, i.e. no pelletization was performed after torrefaction.

The results presented in Figure 12, where the pressure drop in the tube tester is correlated with the mass flow, shows that under the tested conditions a pressure drop of at least 3 mbar is required to fluidize and transport the upgraded materials in a continuous process. For the raw materials, even increasing the pressure drop to 7 mbar was not enough to start transporting the material in a continuous and smooth process. However, if the upgraded materials are compared with a standard coal, for the same pressure drop value the mass flow of the upgraded materials is about a half of the transported mass of the coal. In Table 10 it is possible to confirm that the density of the coal is about the double of the upgraded materials and therefore the bulk density of the material must play a fundamental role in pneumatic transport processes.

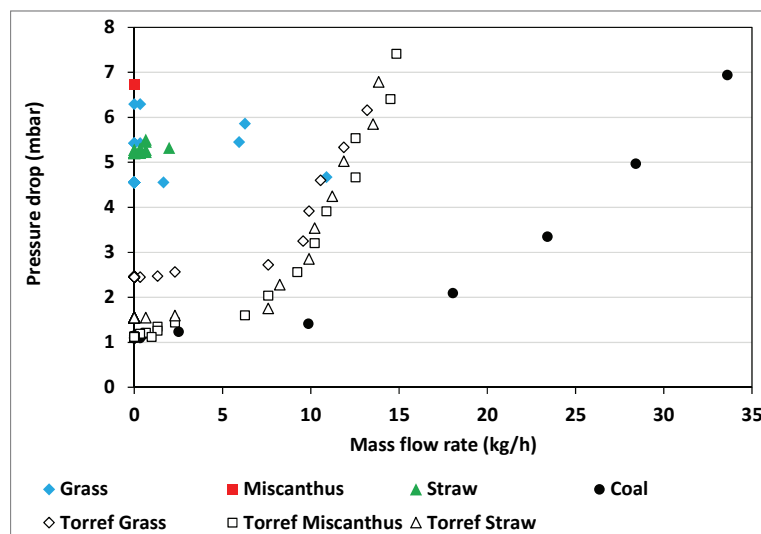


Figure 12: The relationship between the pressure drop inside the tube and the material flow.

The results presented both on Table 10 and in Figure 12, clearly shows the major role that the bulk density plays on pneumatic transport. Of course that the particle shape cannot be ruled out of this question, it is somehow interconnected with it since the increment in the sphericity of a particle will contribute to an increase in the bulk density of its powder. However, we can see from Table 10 that biomass raw materials (particles with low sphericity) with a density around 300 kg/m³ will be difficult to be pneumatically transported. However, the upgraded materials with the density increased to 400 kg/m³ but maintaining a similar particle sphericity, as compared to the raw material, can

already perform much better. However, for pneumatic transport optimization it is strongly advised to pelletize the torrefied biomass materials to obtain an extra gain and optimize both the bulk density and sphericity of the milled particles, in order to shift the curves of the torrefied biomasses towards the coal line in Figure 12.

2.1.5 Economics of the process

Based on the upgrading experimental results obtained at lab and pilot scale, three feedstocks were studied in a preliminary techno- economic analysis to evaluate the feasibility of the biomass upgrading routes. These feedstocks were roadside grass, wheat straw and miscanthus. The spruce bark has low alkalis and chlorine contents and upgrading by washing and torrefaction only increases its price with small improvements in its quality as a fuel. Therefore the spruce bark was left outside this evaluation.

Depending on the moisture content of the original materials two lines were explored. Washing followed by torrefaction (prewash) was chosen when the moisture content of the available raw biomass stream was higher than 30 wt.%. This was the case of roadside grass, which has about 75 wt.% of moisture content. When the moisture content was lower than 30 wt.%, torrefaction followed by washing (postwash) was also explored as an option. This was the case for the straw and miscanthus (both with about 15 wt.% moisture). To support the decision criteria and to validate the best route to follow, the prewash option was compared with the postwash option for the case of straw. Mass and energy balances were performed for each material, supported by the lab and pilot scale test results. Based on this, a preliminary economic analysis was performed to generate decision criteria, based on calculated internal rates of return (IRR), total annuities and payback times (PB) and sensitivity analysis based on the most critical input parameters for profitability.

All the tested materials could be technically upgraded on large scale to commodity fuels, with some limitations on the quality, due to still significant alkali content in case of the roadside grass. However, since a gate fee of about 20 € can be charged, the price at which the upgraded roadside grass can be offered (4.7 €/GJ) is very attractive leading to IRR in the range of 14%, which can be further increased to 18% if sludge disposal costs could be reduced from 60 to 40 €/t. Capital costs, consumables and sludge disposal were the most critical parameters for the economics profitability. Postwash was the most profitable option in the case of dried biomasses upgrading (straw and miscanthus). Wheat straw upgrading is not profitable unless a similar gate fee can be charged as well. This can be the case of residual straws from rice and sugar cane crops, upgrading the material locally and exporting it. A competitive price of 6.2 €/GJ can be applied for the upgraded straw giving a IRR of 7%. Detailed description of the methods and the obtained results are presented in reference [10].

2.2 Hydrothermal carbonization – HTC (TUM)

This section will provide insights to the results of lab-scale and pilot scale HTC experiments carried out within the scope of the Bioefficiency project: For lab-scale experiments a number of moist biomass streams were treated at temperatures ranging from 180-280 °C at a constant residence time of 4h. At pilot-scale urban leave litter was treated at 180 °C for 2h.

In D2.2 a general introduction to HTC was provided: Hydrothermal Carbonization (HTC) is a biomass pre-treatment method, which converts a solid biomass into a lignite-like fuel. In HTC, biomass is suspended in water and treated at elevated temperatures (180-300 °C). To keep water in the liquid phase throughout the treatment, pressure above the respective vapour pressure of water (20-100 bar) is applied.

In comparison to other thermal treatment methods, HTC allows direct conversion of wet biomass without any pre-drying of the feedstock. Another advantage arises from a pre-treatment in water: Species active in corrosion as well as slagging and fouling such as chlorine and alkali metals are often present as water-soluble compounds that can be removed with the process water.

2.2.1 Results of lab-scale HTC treatment

At lab-scale the following biomass types were investigated: EFB, grass cuttings, leave litter, horse manure, digestate and spruce bark. The experimental procedure is described in D2.2. The raw biomass samples were treated in the temperature range from 180-280 °C covering mild to harsh HTC conditions at a constant residence time of 4 h. All raw materials and HTC treated biomass have been analysed by proximate, ultimate and ash composition analysis.

Mass Yield and Heating Value

During hydrothermal carbonisation a manifold of different reactions occurs leading to an increasing degree of coalification (i.e. lower H/C and lower O/C ratios) and consequently yielding a solid with higher C-content and higher heating values by removal of oxygen and hydrogen through dehydration and decarboxylation reactions.

Mass yield (Y_m , the ratio of solid product to the original raw biomass from which it was produced) and lower heating value (LHV) are two important characteristics of HTC treated biomass, and are reported in Figure 13: Mass yield decreases for all biomass types with increasing HTC reaction temperature, while LHV increases with HTC temperatures.

Higher treatment temperature leads to lower mass yields due to dissolution of organic material in the process water. At temperatures of 150 °C it is assumed that carbon dioxide is released from the biomass matrix via elimination of unstable carboxyl groups. Significant reactions occur at temperatures above 180 °C where hemicellulose (180 °C), cellulose (220 °C) and lignin (180 °C-220 °C) are hydrolysed. Consequently with higher reaction intensity, i.e. higher treatment temperature the mass yields decrease. For mild reaction conditions mass yields lie between 54-74 %. At higher treatment temperature, more biomass is liquefied and mass yields decrease to 25-30 %. Simultaneously, at low HTC treatment temperature the heating values of the HTC

biomasses are found to be in the range of 17.81-21.32 MJ kg⁻¹ increasing to up to 29.35 MJkg⁻¹ for HTC treated EFB at 270 °C.

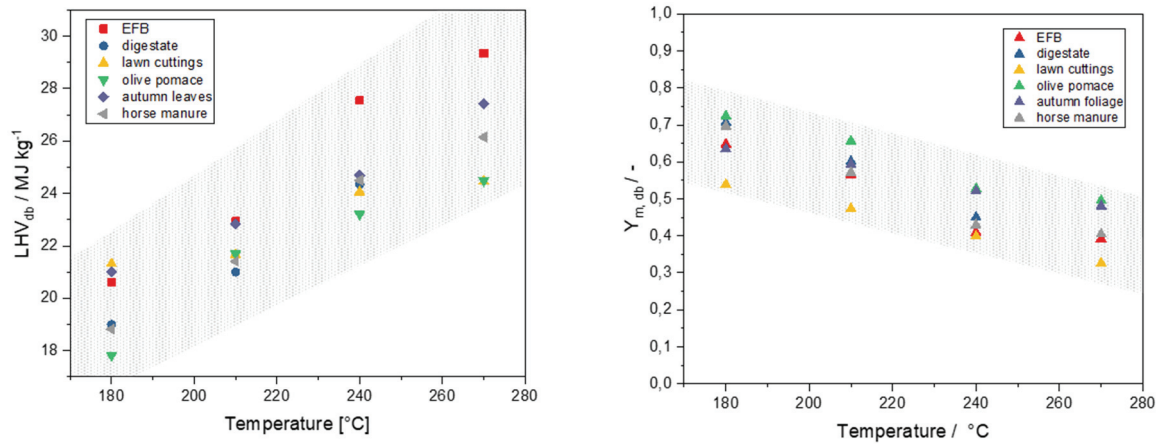


Figure 13: Lower heating value (left) and mass yield (right) for various biomass types and treatment temperatures at a constant residence time of 4 h.

To assess the recovered chemical energy in the HTC treated biomass, the energy yield (Y_e), defined as the mass yield multiplied by the energy densification (the ratio of the LHV of the HTC biomass divided by the LHV of the raw biomass) can be used. Despite the large mass losses the energy yield is found to only slightly decrease over the examined temperature region. Large differences can however be observed for the different biomass types. Horse manure showed the lowest energy yield of all investigated biomass, while the highest recovered chemical energy was found for olive pomace (Figure 14).

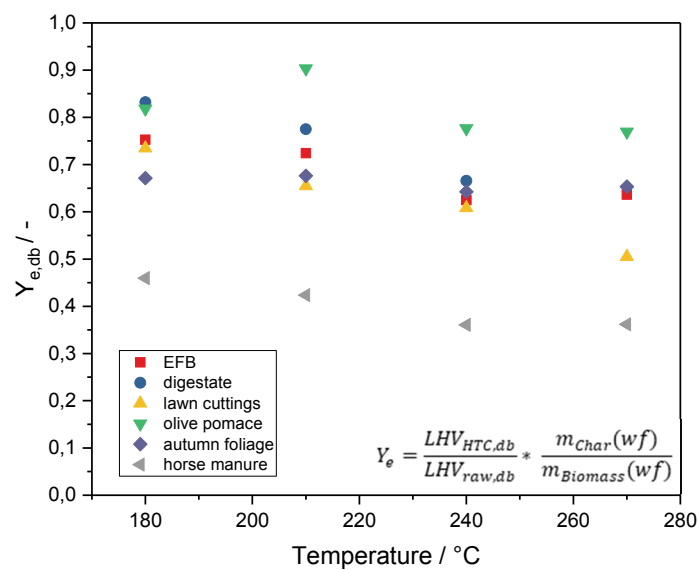


Figure 14: Energy yield of different biomass samples versus the HTC treatment temperature

Impact of HTC on concentration of pernicious elements

The effect of hydrothermal carbonisation on the concentration of the most problematic elements for combustion (Cl, K, P and S), as well as for total ash amount was assessed. Figure 15 provides an overview on the fraction of the elements removed from the biomass after an HTC treatment at different temperatures.

The results show that with higher HTC treatment temperature the concentration of pernicious elements is decreasing. The trend pronounces most for Chlorine and Potassium that are both present as water-soluble ion species in biomass. For EFB, grass cuttings, digestate and spruce bark > 50% of the initially present chlorine are removed already at a treatment temperature of 180 °C. In case of horse manure and leave litter, 50 % reduction is only achieved for the highest HTC temperature of 270 °C. For the reduction of potassium, similar trends are observed: For all biomass types, except from grass cuttings, potassium concentrations are reduced by 50% already at the lowest HTC treatment temperature, further decreasing up to 78-97 % at the highest examined treatment temperature of 270 °C.

In contrast, sulfur extraction was much lower than for chlorine and potassium and showed higher variability among the different biomass types. For instance in case of EFB over 80% of the originally present sulfur was removed from the biomass matrix, in other cases e.g. grass cuttings the sulfur concentration was decreased by about 40% at all treatment temperatures.

Phosphor reduction in the fuel by HTC also varied strongly. HTC treatment could only remove about 20 % of the initial present phosphor in case of EFB, digestate and leave litter, indicating that most phosphor species are present in form of water insoluble salts. Higher phosphor extraction is observed for spruce bark (up to 70 %). In many cases for higher temperatures a the phosphorous concentration increase again for higher treatment temperatures. Possibly, this is a consequence of the precipitation of salts.

The final ash amount was decreased by about 20-67% by HTC. Higher reduction was reached for biomass types that are rich in (well soluble) alkali metals.

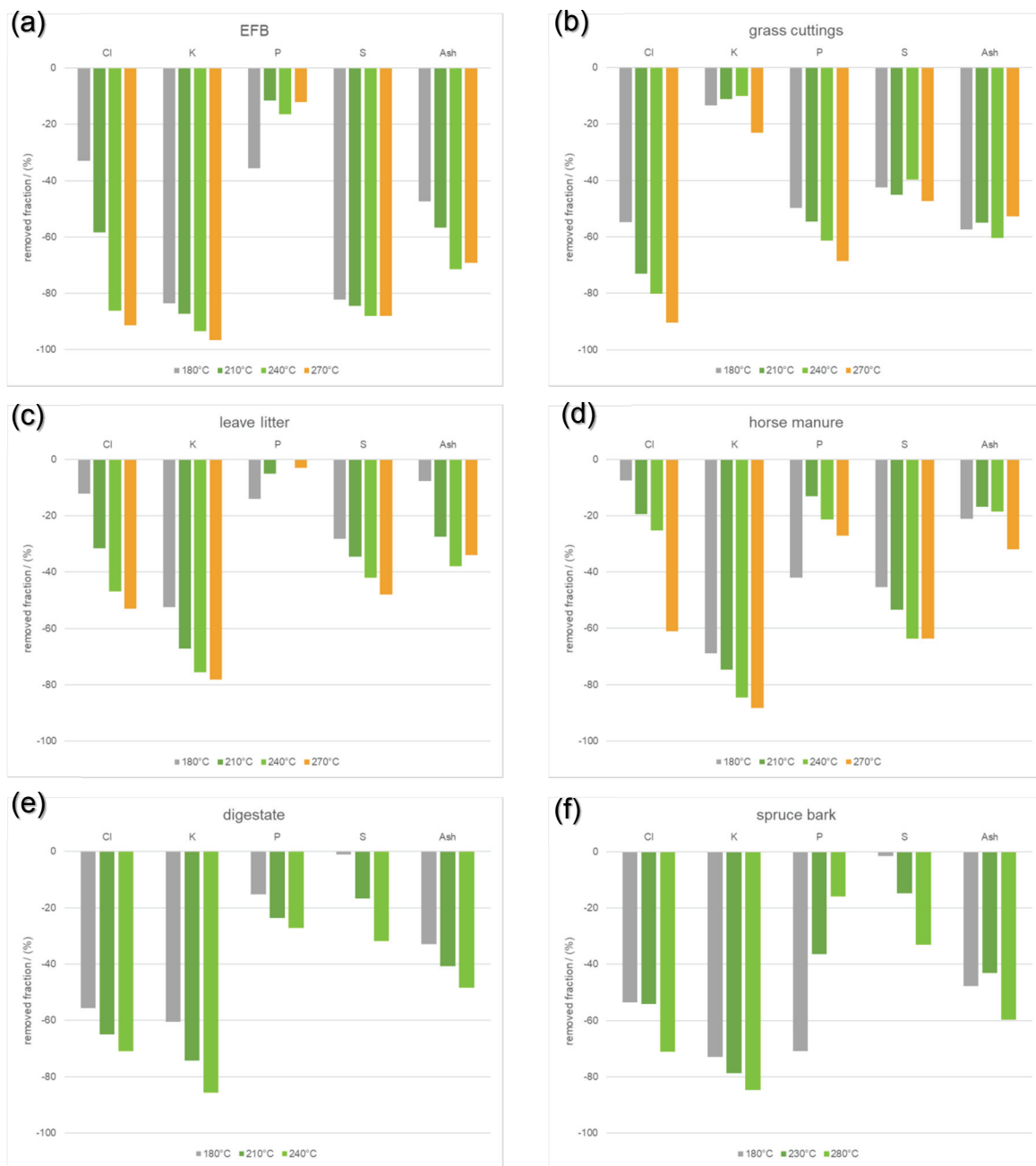


Figure 15: The changes in concentration for some pernicious elements in HTC biomass treated at varying temperatures at a residence time of 4h.

Pre-evaluation of emissions, high temperature corrosion and ash melting tendency (fuel indexes)

The alkali indexes of the individual fuels is shown in Figure 16. The alkali index is a measure common used for biomass to predict the fouling propensity of a fuel originating from alkali salt deposition on heat exchangers.

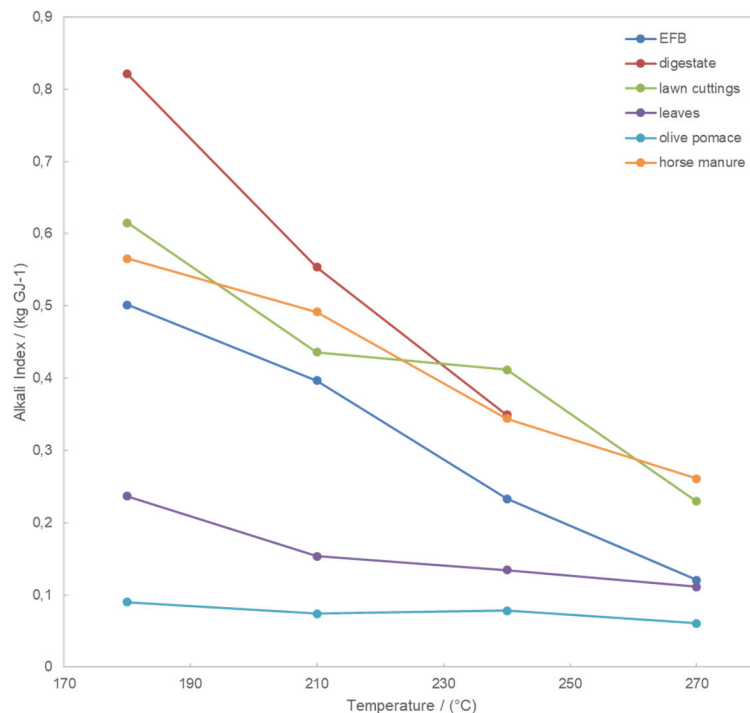


Figure 16: Alkali index for HTC treated biomass samples as a function of treatment temperature

The alkali index decreases with increasing HTC treatment temperature. Two different effects of HTC lead to this development:

1. The heating value of the fuel increases with increasing HTC treatment temperature
2. The amount of leached alkali metals increases with increasing HTC treatment temperature

Especially the fallen leaves and olive pomace show only a marginal fouling propensity after HTC if only the alkali index is considered. For EFB the highest reduction in alkali index could be achieved through HTC pre-treatment, which can already be anticipated from the high potassium reduction by HTC presented in Figure 15. Horse manure, digestate and lawn cuttings are still likely to cause fouling problems even after HTC upgrading. However, for all biomass types HTC lowers the alkali index significantly compared to the raw biomass as the values presented in Table 11 show. Therefore overall a positive effect of an HTC treatment on the fouling propensity can be expected.

Table 11: Alkali indices of raw and HTC treated fuels.

| | EFB | digestate | lawn cuttings | leaves | olive pomace | horse manure |
|-----|------|-----------|---------------|--------|--------------|--------------|
| raw | 2.18 | 1.71 | 2.02 | 0.39 | 0.68 | 0.80 |
| 180 | 0.50 | 0.82 | 0.62 | 0.24 | 0.09 | 0.57 |
| 210 | 0.40 | 0.55 | 0.44 | 0.15 | 0.07 | 0.49 |
| 240 | 0.23 | 0.35 | 0.41 | 0.13 | 0.08 | 0.34 |
| 270 | 0.12 | - | 0.23 | 0.11 | 0.06 | 0.26 |

As already done in Section 2.1 for torrefied fuels, the potential reduction in the pollutant gaseous formation by a HTC pre-treatment is evaluated by the achieved reduction in the contents of N, S and Cl for the emissions of NO_x, SO₂ and HCl respectively. The change in the sum of the contents of K, Na, Pb and Zn can also provide an indication related to the aerosol emission impact. Figure 17 provides an overview of the changes in content of N, S, Cl and sum of the contents of K, Na, Pb and Zn for raw biomass and HTC biomass treated at 210 °C for 4 h.

By HTC the specific nitrogen contents per unit energy content can be decreased for all fuels. Nitrogen compounds are released by hydrolysis in HTC and dissolved in the process water. The range of specific nitrogen content per unit energy for raw fuels are varying between 240-1445 mg/MJ. Grass cuttings were found to contain most nitrogen which is in accordance with the findings for the torrefied fuels in Section 2.1. The HTC treated fuels contained between 206-1027 mg/MJ reducing the specific nitrogen content per unit energy by 24 % in average. The large variation can be explained by the large variety in starting material that have been selected in this study. An exception is the HTC treated horse manure, which is the only sample that shows an increase in specific nitrogen content. An explanation for this could be the low mass yields that were achieved after HTC. Presumably, the loss of other organic material for this biomass is higher than the extraction of nitrogen from the fuel, leading to a relatively higher specific nitrogen content per unit energy.

The specific chlorine content by unit energy is reduced by 57 % in average by HTC pre-treatment. Chlorine in plants is mostly present in form of the chloride ion which is well water soluble and therefore well extractable by HTC. After HTC treatment at 210 °C for 4h the specific chlorine content by unit energy ranges between 12-250 mg/MJ. Again, the large range reflects the manifold of different biomass types investigated.

All investigated biomass types contain rather low levels of sulfur (50-120 mg/MJ). HTC further decreases the sulfur content to a range of 30-88 mg/MJ.

A common indicator for aerosol formation and deposit built up is the sum of K, Na, Zn and Pb. As shown in Figure 17 the potential for aerosol formation decreased by the upgrading process mainly due to the removal of alkalis.

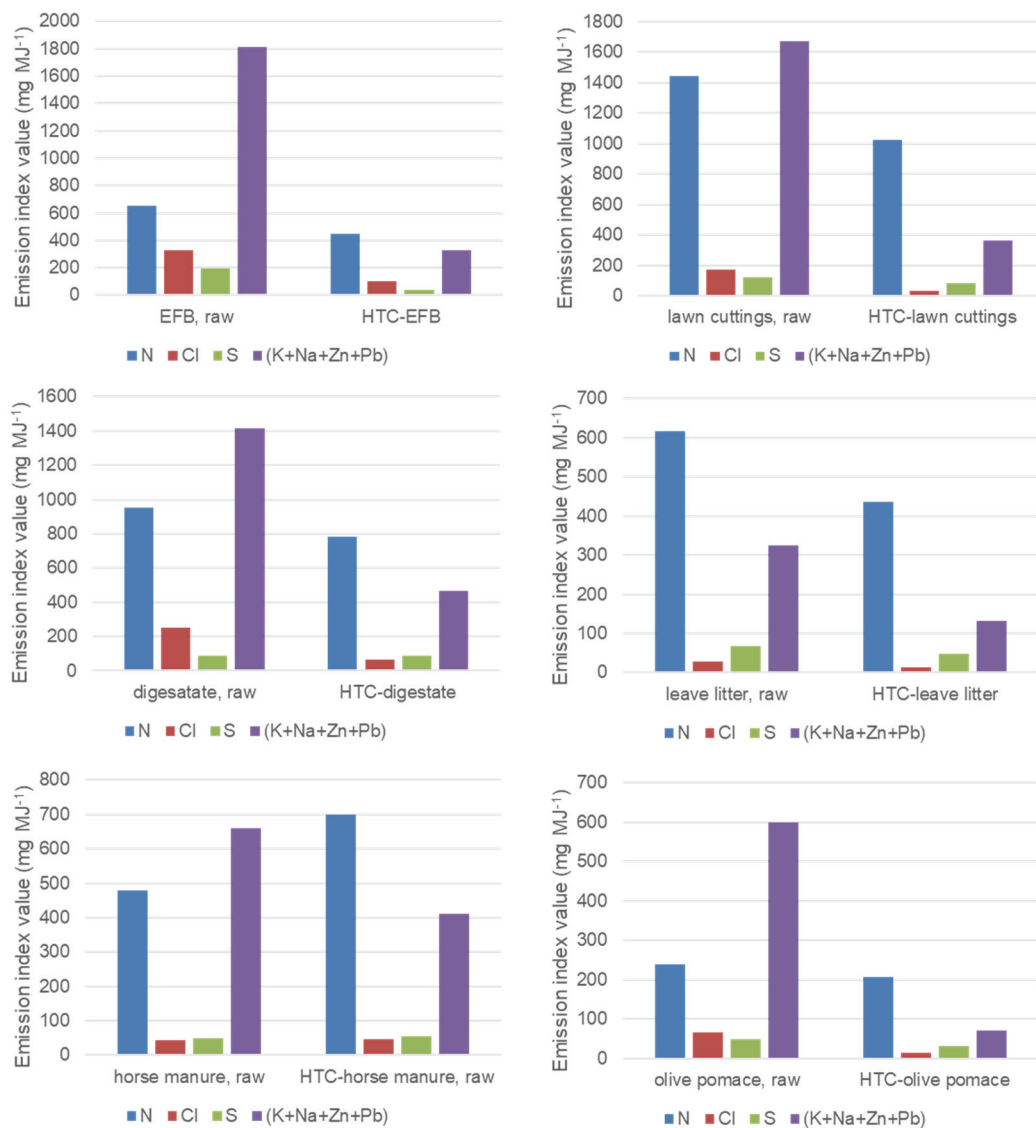


Figure 17: The changes in the emissions fuel indexes obtained during upgrading by HTC at 210°C for 4h.

As in section 2.1 for the slagging and fouling evaluation the indexes proposed in [9] will be used. The molar ratio S/Cl is also often used to evaluate the risk for Cl-containing deposits on superheaters. Usually with a S/Cl ratio higher than 2 minor corrosion risk is expected [7,8]. Table 12 contains the molar S/Cl ratios for untreated and HTC treated fuels. For untreated fuels the molar S/Cl ratio is below the critical value of 2, thus indicating that there is a risk of alkali chloride formation. After hydrothermal carbonisation the molar S/Cl ratio is increased and exceeds the value of 2 in case of lawn cuttings, autumn foliage and olive pomace. The improvements for this index are not as high as for others since during HTC not only chlorine is removed from the biomass but also inorganic sulphur species are removed from the biomass matrix. Still the amounts of harmful species will be significantly smaller for HTC treated samples when compared to untreated materials.

In Table 12 it can be seen that the slagging index (SI) presents a relatively low value already for the untreated fuels due to the high Si content of the original materials. A SI

value < 0.6 already points to a low slagging inclination. The only problematic biomass is EFB with a SI value of 1.66. The pre-treatment by HTC further improves the SI value further all fuels.

Table 12. Slagging and fouling indices for untreated and HTC treated biomass.

| Biomass | EFB | Digestate | Lawn cuttings | Autumn foliage | Olive pomace | Horse manure |
|----------------------|-----------------------|------------------|----------------------|-----------------------|---------------------|---------------------|
| <i>raw</i> | | | | | | |
| Molar S/CI | 0.53 | 0.31 | 0.36 | 2.18 | 0.68 | 1.03 |
| Slagging Index | 1.66 | 0.22 | 0.43 | 0.22 | 0.63 | 0.12 |
| Fouling Index | 69.85 | 45.97 | 68.75 | 9.71 | 426.12 | 20.23 |
| <i>Pre-treatment</i> | <i>HTC, 210°C, 4h</i> | | | | | |
| Molar S/CI | 0.35 | 1.21 | 2.23 | 3.18 | 2.18 | 1.04 |
| Slagging Index | 0.07 | 0.25 | 0.30 | 0.19 | 0.37 | 0.06 |
| Fouling Index | 9.44 | 16.10 | 13.24 | 4.22 | 294.25 | 3.89 |

The fouling index (FI) of all starting materials are relatively high. Values between 0.6 and 40 means high tendency for sintering. The value for olive pomace is exceptionally high (426.12), since the ash contains 59 % potassium. However the total ash content is also very low ($a = 2.08$ wt%), so the actual fouling propensity might overestimated with this index.

By hydrothermal carbonisation, the FI was significantly reduced for all biomass types: 86 % reduction for EFB, 65 % reduction for digestate, 81 % reduction for lawn cuttings, 57 % reduction for autumn foliage, 31 % reduction for olive pomace and 81 % reduction for horse manure. However, these reduced values are still indicative of significant fouling issues.

2.2.2 Results of pilot-scale HTC treatment

Urban leaf litter was also HTC treated on pilot-scale. Pellets produced from urban leaf litter served as feedstock for the pilot test. Leaves, shrubs, grass from the conservation of green urban areas, park and leisure facilities have a potential of 1.18 Mt / 17 PJ in the EU27+CH⁶. In the city area of Munich annually 6000 m³ of leaf litter are collected. Figure 18 shows the leaf litter pellets used for the pilot test as well a typical leaf litter pile as it can be seen often in urban city areas during fall.



Figure 18: Leaf litter in the urban area of Munich. (left). Leaf litter pellets used for HTC pilot test (right).

For the pilot HTC experiment, 55 kg of biomass was poured into the reactor filled with 500 L of fresh water, leading to a solid concentration of 10 wt%. The reactor was heated at an average heating rate of 0.6 Kmin⁻¹. During heating up, the system was gradually pressurized using Argon until a final pressure of 20 bar was reached. The final temperature of 180 °C was held for 2h. The reactor was cooled down with the aid of an installed cooling coil and the slurry filled into 200 L barrels. The separation of HTC char and process water was done using filtering bags. Figure 19 shows the obtained slurry, separation of the HTC Char with filter bags as well as the final product HTC char.

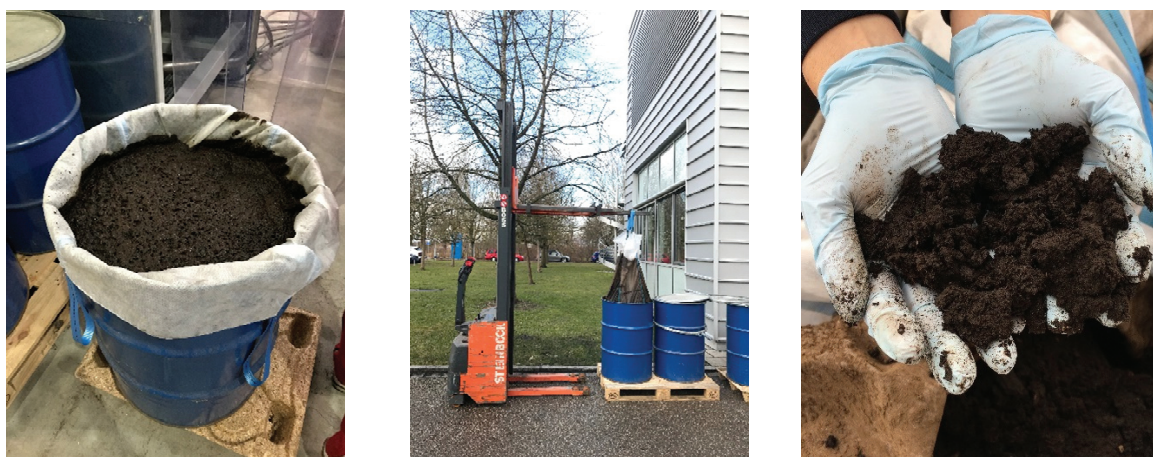


Figure 19: HTC Char slurry (left). Separation of the HTC Slurry with aid of filter bags (middle). Obtained, wet HTC Char (right).

To investigate scalability of the process the experiment was repeated in lab-scale with the same reaction severity. The reaction severity R_0 of hydrothermal processes, which combines temperature and time can be calculated as follows:

$$R_0 = \sum_{i=1}^n \int_{t_{i-1}}^{t_i} \exp \left[\frac{T_i(t) - 100}{14.75} \right] dt$$

where i denotes the i -th period, and n denotes the numbers of the periods including heating, holding, and cooling periods. t_{i-1} (min) and t_i is the initial and end time for the i -th period, respectively. $T_i(t)$ (°C) stands for the temperature profile of the i -th period.

Taking into account heating and cooling times the same reaction severity in lab-scale was reached at a residence time of 2.6 h. Table 13 shows the results of proximate- and ultimate analysis as well as the heating values for the HTC chars produced in pilot- and in lab-scale at the same reaction severity.

Table 13. Heating value, proximate- and ultimate analysis of HTC-urban leaf litter.

| Sample | Moisture (wt% _{ar}) | Ash (wt% _{db}) | Volatiles (wt% _{db}) | Fixed C (wt% _{db}) | N | C | S | H | O | Cl | LHV _{wf} MJ kg ⁻¹ | HHV MJ kg ⁻¹ |
|--------------------------------|----------------------------------|-----------------------------|-----------------------------------|---------------------------------|------|-------|-------|------|-------|-------|--|----------------------------|
| HTC pilot (sample 1) | 6.12 | 14.77 | 64.62 | 20.61 | 0.89 | 51.71 | 0.098 | 5.10 | 27.44 | 0.033 | 19.64 | 19.47 |
| HTC pilot (sample 2) | 4.31 | 13.46 | 64.49 | 22.04 | 0.93 | 54.44 | 0.110 | 5.14 | 25.91 | 0.021 | 20.24 | 20.43 |
| HTC lab | 4.44 | 12.21 | 65.59 | 22.20 | 0.86 | 55.39 | 0.101 | 5.27 | 26.16 | 0.013 | 20.84 | 21.00 |
| Deviation in % | - | 13.50 | 1.60 | 4.10 | 5.49 | 4.36 | 2.88 | 2.93 | 1.93 | 51.85 | 4.51 | 5.26 |

The data from the lab-scale matches the data from the pilot-scale within a deviation of 2-13%. The large deviation in the chlorine content can be explained with a higher uncertainty of the measurement of the chlorine content for low concentrations. Therefore, the results obtained on lab-scale are well transferrable to larger batch sizes.

2.3 Steam explosion - SE (VAL, MHPSE)

Steam Explosion (SE) was studied for softwood bark in Bioefficiency project. The idea was to study the potential of steam explosion technology integrated to a Kraft pulp mill as bark may be obtained in significant amount from pre-treatment of pulp wood. For instance, in Metsä-Fibre Bioproduct mill, (Äänekoski, Finland) potentially 100 000 t of bark may be available annually.

2.3.1 SE technology

Background

Industrial production of heat and power will be largely based on sustainable and renewable sources in a near future. Significant wind and photovoltaic based power production is already in place and is becoming increasingly important in many regions. But the power production from sun and wind does not always balance the consumption. Hence it is also necessary to develop renewable energy production which is independent of weather and day-light. It is required a biomass-based CO₂-neutral fuel that can be stored and used for balancing the consumption peaks. The dried and densified bio-mass in the form of briquettes or pellets is an interesting fuel option. Steam exploded “black” pellets made from woody materials are of importance as they offer savings in transportation, storage and use in comparison to standard “white” wood pellets. Properties that favour the use of black pellets are their high durability, energy density and resistance to ambient moisture. Thermal treatment of woody biomasses followed by steam explosion is a well-known method for production of fibre-board, it was developed already some 100 years ago in the USA (Masonite Process, Defibrator process) but its adaptation for production of substrates for densification to fuel pellets or briquettes is rather new. The steam explosion process is suitable for processing a wide range of lignocellulosic materials suitable for densification including both woody biomasses and agricultural residues. Bark, obtained as a by-product from wood processing industries is an abundant wood based raw-material. A natural consequence of bark abundance is a low-cost level rendering it as a competitive raw-material for production of fuel pellets.

The steam explosion method

The main steps of the steam explosion process are schematically shown in Figure 20 below. Ligno-cellulosic biomass is charged to a pressurized reactor vessel. Medium pressure steam is added to the reactor for heating of biomass to saturation by direct condensation.

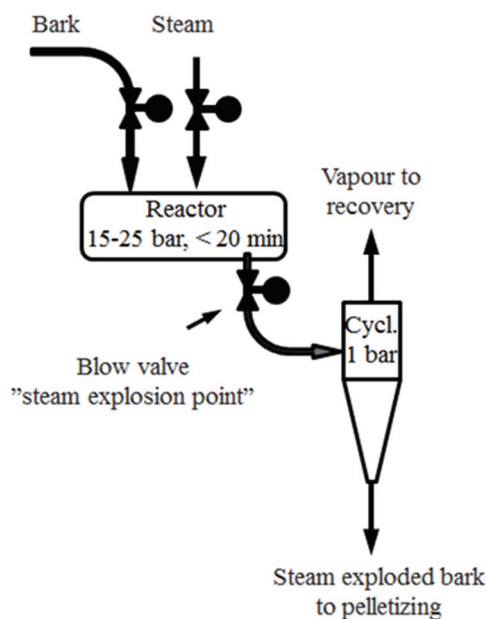


Figure 20. Steam explosion process principle layout.

The required pressure level of the reactor is around 20 bars and the retention time is up to 20 minutes. The reactor can be designed for continuous or batch operation. During heating, hemicellulose compounds hydrolyse to oligomers and monomers the molecular weight of lignin decreases due to the break of its β -aryl ether bonds. The hot and softened biomass is then released (blown) from the reactor through a blow valve or orifice and it cools rapidly when moisture evaporates as the pressure drops to atmospheric pressure. The expanding steam partly breaks the structure of the biomass which is origin of the wording “steam explosion”. The wording is however erroneous as most of the de-fibration is caused by shear forces and impact during the blow through the orifice or valve. Hot lignin and released sugars crosslink to a pseudo-lignin structure which later upon pressing and heating thermoset with fibres to a strong, water resistant pellet. The energy (power) consumption in the pellet presses is about half of what is required in pelleting of non-exploded wood material because the warm, still soft, steam exploded substrate is easy to densify.

The steam explosion process is long known from the fibre board industry. The first patents for the Masonite process were granted already at the end of the 1920-ies in the USA. The Defibrator method, a combination of steam explosion and mechanical de-fibration was developed somewhat later and it became the leading method for fibre board production. Valmet, a major project provider to pulping and power generating industries, continues the Defibrator heritage and has developed a multitude of processes and machineries which now can be applied at industrial pellet production.

Integrated production of steam exploded bark pellets

A steam explosion process is well suited for integration to an industrial process which emits low temperature waste heat, for example a Kraft pulp mill, Figure 21. Energy from hot water is utilized for drying of biomass and medium pressure steam for the steam explosion reactor is extracted from the turbine. Raw-material for the pellet plant is bark from the wood handling.

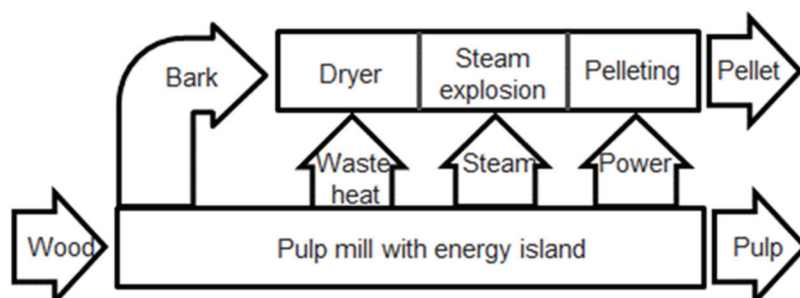


Figure 21. Steam exploded bark pellet line integrated to a Kraft pulp mill.

Pre-treatment (wood handling). The raw material is bark from debarking of wood in the form of “flakes”. They may contain a large portion of “fines” which is partly of organic origin but also dirt i.e. clay, gravel small stones etc. The fines are screened from the raw material; the purpose of such treatment is reduction of wear in downstream pelletizing machinery and improvement of final product quality by lowering its “ash” content. The particle size of the raw material is reduced and homogenized before drying by treating it, for example in a low speed crusher. The dryer is preferably a low temperature belt dryer as it is capable of utilising low-grade waste heat from the pulp mill. The technical arrangement for the *steam explosion reactor* is preferably a vertical, cylindrical pressurized vessel in which the dry biomass chips are heated to saturation with medium pressure steam. When the pressure is released, the mobilized lignin is condensing together with the sugars to a pseudo lignin which covers the cellulose. The steam exploded ligno-cellulosic material is mouldable and creates a strong water repellent product upon pelletizing. Biomass is separated from steam with a cyclone and the flash steam is led to preheating and drying of bark while the biomass is conveyed to the pelletizing plant. The mass yield of the process is around 91-93 %, the losses (volatile material from bark and wood) escapes with flash vapour at blowing of the steam explosion reactor. *Pelletizing.* The steam exploded material is preserved as hot as possible to reduce energy consumption in pelletizing which is the last process step.

Steam Explosion technology is today commercialized technology. Valmet will commission its first commercial plant for producing SE pellets in France during 2020 [11]. Steam Explosion technology is described in greater details in deliverable D2.2.

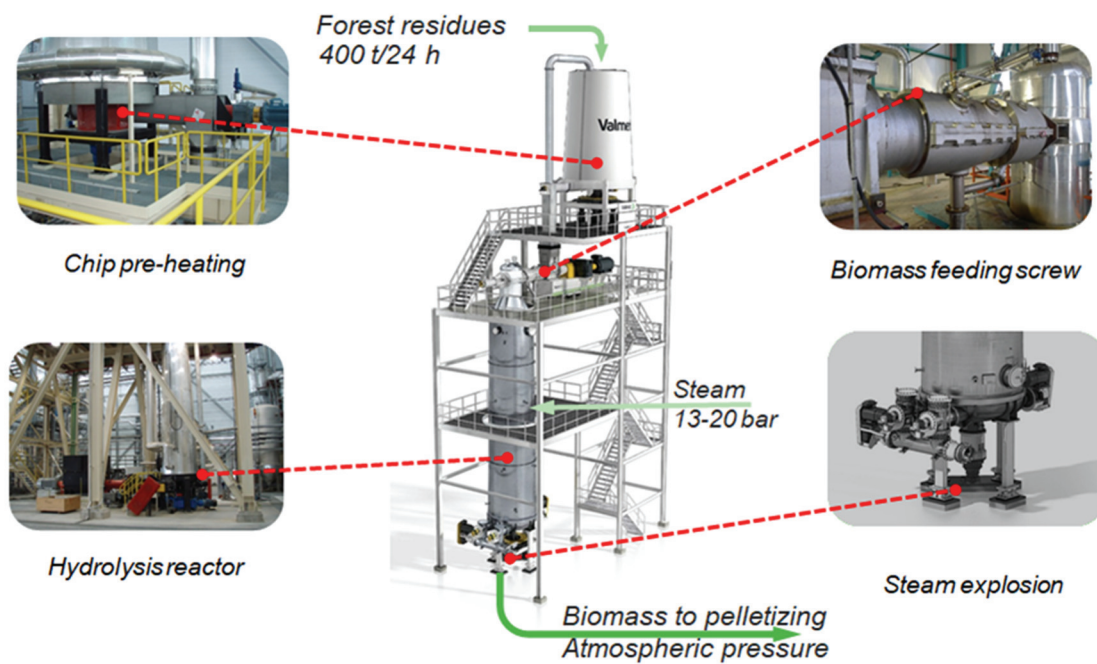


Figure Valmet BioTrac system [11].

2.3.2 Fuel properties of SE pellets

Steam explosion improves properties of woody biomass. Main benefits of the treatment are increased dry and wet durability, bulk density, energy density and grindability.

Steam explosion clearly improved durability of the pellets. Debris and dust produced in different points of value chain decrease the economic feasibility of pellets. Dust also rises risks of fires and explosion. Table 14 shows dry and wet durability of Softwood, SE Softwood, Bark and SE Bark pellet. Especially important is the increase in the wet durability test of all SE pellets and dry durability increase in the bark pellets. Steam Explosion gives to a strong, water resistant pellet. Ordinary Softwood pellets had no wet durability and disintegrated completely in water.

Steam explosion increases the energy density of pellets by 25 percentage as can be seen in Table 14, both for softwood and bark. Also, the bulk density increases approximately 20 % (Table 14). Both properties decrease cost in the value chain. Approximately, the savings in the transport is 10 % [12,13].

Table 14. Dry and wet durability, and bulk and energy for Softwood and Bark [12].

| Raw-material | Dry durability (%) | Wet durability (%) | Bulk density (kg/m ³) | Energy density (MWh/m ³) |
|----------------|--------------------|--------------------|-----------------------------------|--------------------------------------|
| Softwood | 98 | 0 | 617 | 3.0 |
| SE softwood | 98 | 94 | 739 | 3.7 |
| Bark pellet | 92.7 | 0 | 570 | 3.0 |
| SE bark pellet | 98.2 | 98.1 | 700 | 3.8 |

2.3.3 Grinding tests

Grinding tests at semi-industrial scale were performed by MHPSE at a vertical roller mill test facility (MPS®32). White wood pellets were used as a reference base. The grinding behaviour of untreated and steam exploded spruce bark pellets was examined with the performed grinding test. The effect of adding a very small percentage of grinding aids (fly ash / bottom ash) together with the pellets was evaluated. Milling fineness, as well as the wear rate of the equipment were measured and compared.

Considering the test parameters defined by MHPSE (see Table 15) the grinding tests were run at MHPSE subcontractors, Gebr. Pfeiffer SE. For this purpose a grinding plant with a vertical roller mill MPS®32, as depicted in Figure 22, was used. The test mill is equipped with a high-performance classifier type SLS 220.



Figure 22: Vertical roller mill MPS®32. (Source: Test facility Gebr. Pfeiffer)

Since the results of the grinding tests are currently under discussion in the consortium, they will be described in detail in the final report

Table 15: Test parameters for grinding tests

| | | Wood Pellets | | Bark Pellets pure | | SE Bark Pellets | |
|--------------------------------------|--------------------|--------------|--------|-----------------------|------|-----------------------|------|
| Delivered by | | Orsted | Orsted | VTT | VTT | VTT | VTT |
| Grinding aid | | coal fly ash | | coal bottom ash (dry) | | coal bottom ash (dry) | |
| Flow downstream classifier | m ³ / h | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| Specific grinding pressure | kN/m ² | 600 | 600 | 600 | 600 | 600 | 600 |
| Ambient classifier temperature | °C | 40 | 40 | 40 | 40 | 40 | 40 |
| Grinding table rotations | rpm | 80 | 80 | 80 | 80 | 80 | 80 |
| Classifier rotations | rpm | 0 | 0 | 0 | 0 | 0 | 0 |
| Residue: R_1000 µm Target setting | % | 30 | | ~6 | ~6 | ~8 | ~5 |

3. Concluding remarks (all partners)

Low-grade biomasses like grass, straw, miscanthus and bark were upgraded by washing and torrefaction with significant improved results. A quick and cheap analysis method, based on conductivity measurements of the eluates, was developed and applied with success and showed to be a feasible inexpensive technique to evaluate the washing efficiency. The upgraded biomasses showed good properties for energy use applications in terms of logistics and reasonable improved characteristics for combustion, regarding the calorific value and ash composition. The results obtained at lab-scale and pilot-scale were consistent with each other, proving that lab-scale tests are accurate enough to predict salts extraction efficiencies (K and Cl) and that it is possible to maintain extraction efficiencies at industrial scale, provided that the right and optimized conditions found at lab-scale are applied. About 90-95% of Cl, 50-80% K, 30-60% S and 30% P can be removed from the low-grade biomasses during upgrading. Washing step proved to be crucial to the removal of K and P, since during torrefaction those elements were not decreased. The wash step was important to remove Cl and S. Post-wash (washing after torrefaction) seems to be a viable route to upgrade dry-type biomasses, since it produced equivalent salts extraction efficiencies, compared to pre-wash, while allows decreasing the energy costs related to drying the washed dewatered cakes. Calculated fuel indexes for emissions, high temperature corrosion and ash melting tendency showed the improved potential of washing and torrefaction during the combustion of low-grade biomass materials. All the tested materials could be technically upgraded on large scale to commodity fuels, with some limitations on the quality, due to still significant alkali content in case of the roadside grass. However, since a gate fee of about 20 € can be charged, the price at which the upgraded roadside grass can be offered (4.7 €/GJ) is very attractive, leading to IRR in the range of 14%, which can be further increased to 18% if sludge disposal costs could be reduced from 60 to 40 €/t. Capital costs, consumables and sludge disposal are the most critical parameters for the economics profitability. Postwash was the most profitable option in the case of dried biomasses upgrading (straw and miscanthus). Wheat straw upgrading is not profitable unless a similar gate fee can be charged as well. This can be the case of residual straws from rice and sugar cane crops, upgrading the material locally and exporting it. A competitive price of 6.2 €/GJ can be applied for the upgraded straw giving an IRR of 7%.

Additionally several low grade, high moisture biomass feedstocks, such as EFB, digestate, horse manure, lawn cuttings, olive pomace and leave litter, were treated by HTC. HTC has high potential to convert a wide range of biomass into energy dense solid biofuels with superior chemical, physical and fuel properties compared with the raw biomass. Remarkable improvements in hydrochar include increased HHV, significantly lower chlorine and potassium content and improved hydrophobicity of the fuel. HTC can effectively work with wet biomass types, which are problematic for torrefaction. For comparison, the total cost of the HTC char produced from EFB, including shipping to Europe, according to Steman [14] amounts to appr. 8-10 €/GJ HHV. For HTC hydrochar pellets to be competitive with bituminous coal priced at about 2.6 €/GJ_{HHV}, public policy incentives, such as carbon certificates, are required.

Steam Explosion (SE) is a relatively new application in the production of advanced pellets. Valmet will deliver a SE plant in France for producing Black Pellets [11]. Black pellets are hydrophobic, high in energy density, easier to grind, and durable. Due to high energy density Black pellets offer approximately 10% monetary benefit in transport compared to white pellets. Significant enhancement is also the high durability, as Black pellets produce less dust in the handling. Based on the studies made in this project, production of SE Bark pellets look promising and feasible alternative for increasing the value of bark.

References

- [1] N. Brosse, A. Dufour, X. Meng, Q. Sun, A. Ragauskas, Miscanthus: A fast-growing crop for biofuels and chemicals production, *Biofuels*, Bioprod. Bioref., (2012).
- [2] M. Boosten, J. Oldenburger, *Biomassapotentieel NBLH-sector in 2020 en 2050*, Probos, mei 2014.
- [3] J.H. Spijker, R.R.C. Bakker, P.A.I. Ehlert, H.W. Elbersen, J.J. de Jong, K. Zwart, *Toepassingsmogelijkheden voor natuur- en bermmaaisel*, Alterra-rapport 2418, ISSN 1566-7197, 2013.
- [4] S. Boschma, K. W. Kwant, Rice straw and Wheat straw. Potential feedstocks for the Biobased Economy June 2013, NL Agency report.
- [5] P. Abelha, A. Janssen, C. Mourão Vilela, P. Nanou and M. Carbo. Low-Grade Biomass Upgrading by Washing and Torrefaction: Lab and Pilot-Scale Results. 26th European Biomass Conference and Exhibition, (2018) 1209-1220, 14-17 May, Copenhagen, Denmark (3DV.6.3).
- [6] T.R. Miles, T.R. Jr. Miles, L.L. Baxter, R.W. Bryers, B.M. Jenkins, L.L. Oden, Alkali deposits found in biomass power plants – a preliminary investigation of their extent and nature. Golden CO: National Renewable Energy Laboratory (NREL) report. Sub-contract TZ 2–11226-1; 1995.
- [7] P. Sommersacher. T. Brunner and I. Obernberger, Fuel Indexes: A Novel Method for the Evaluation of Relevant Combustion Properties of New Biomass Fuels, *Energy Fuels* 26 (1) (2012), 380–390
- [8] P. Yrjas, B.-J. Skrifvars, M. Hupa, J. Roppo, M. Nylund, P. Vainikka, Chlorine in deposits during co-firing of biomass, peat, and coal in a full-scale CFBC boiler, *Proceedings of 18th International Conference on Fluidized Bed Combustion*, Toronto, Canada, (2005).
- [9] M. Pronobis, Evaluation of the influence of biomass co-combustion on boiler furnace slagging by means of fusibility correlations, *Biomass and Bioenergy* 28 (2005) 375-383.
- [10] P. Abelha, Preliminary techno-economic assessment of biomass upgrading by washing and torrefaction. 27th European Biomass Conference and Exhibition, 27-30 May 2019, Lisbon, Portugal (3DO.6.3).
- [11] Valmet, Valmet to deliver the world's first BioTrac™ Steam Explosion System for black pellet production in France, <https://www.valmet.com/media/news/press-releases/2018/valmet-to-deliver-the-worlds-first-biotractm-steam-explosion-system-for-black-pellet-production-in-france/>, September 11 2018.
- [12] Björklund P., Material changes during steam explosion of bark, *European Pellet Conference*, 1 – 2 March 2017, Wels, Austria.

- [13] Björklund P., Joronen T., Bolhår-Nordenkamp M., Steam-exploded pellets for heat and power generation, VGB PowerTech, April (2016).
- [14] Stemann, J., Erlach, B. & Ziegler, F. Waste Biomass Valor (2013) 4: 441. <https://doi.org/10.1007/s12649-012-9190-y>

APPENDIX A – TNO upgraded biomass pellets (washed and torrefied)

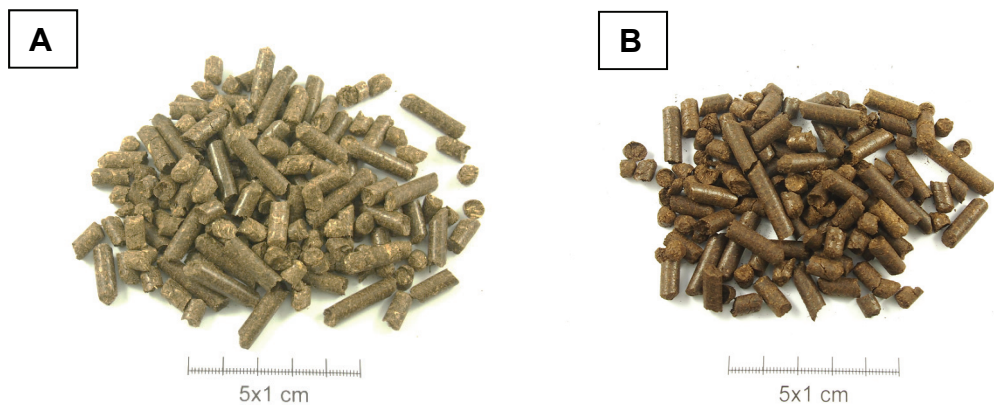


Figure 23 Biomass feedstocks for pilot scale testing: (A) original road side grass pellets, (B) torrefied road side grass pellets.

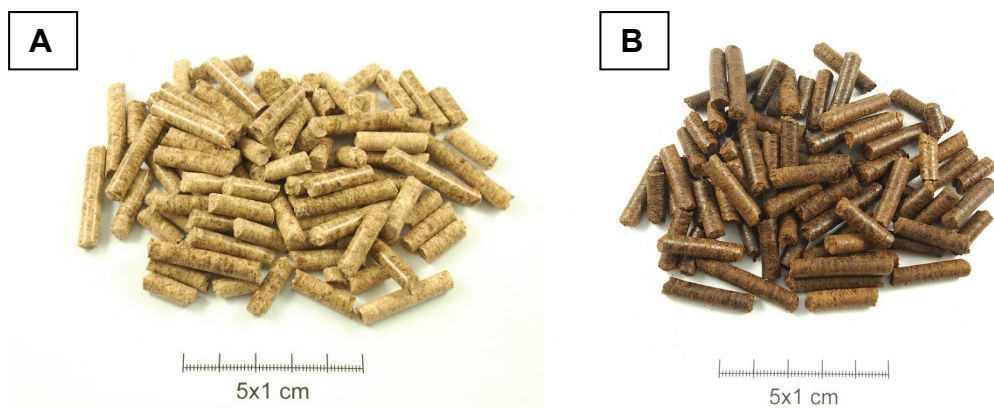


Figure 24 Biomass feedstocks for pilot scale testing: (A) original miscanthus pellets, (B) torrefied miscanthus pellets.

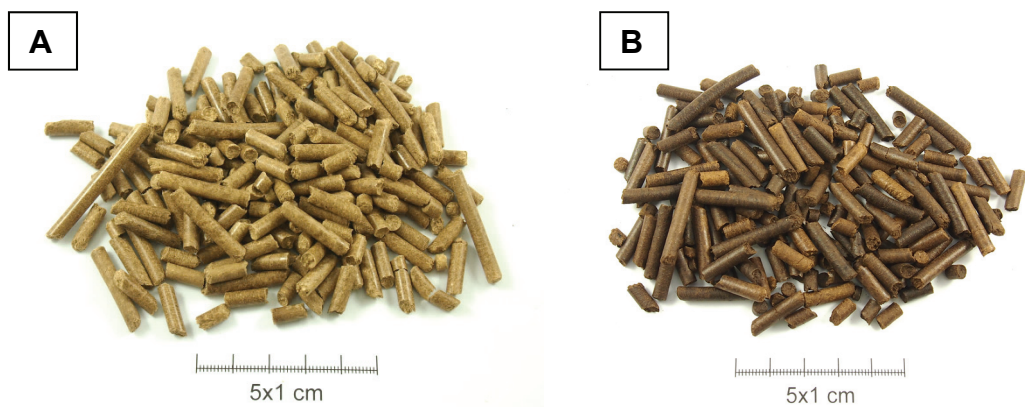


Figure 25 Biomass feedstocks for pilot scale testing: (A) original wheat straw pellets, (B) torrefied wheat straw pellets.

Table 16 The main characteristics of the original and the torrefied pellets of road side grass, miscanthus and wheat straw.

| | PDI (%) | Moisture content (%) | Bulk density (db) (kg/m³) |
|----------------------|----------------|-----------------------------|---|
| Original grass | 90.8 | 8.7 | 600 |
| Torrefied grass | 86.4 | 1.0 | 520 |
| Original miscanthus | 99.4 | 11.1 | 581 |
| Torrefied miscanthus | 98.5 | 1.0 | 551 |
| Original straw | 95.0 | 2.5 | 610 |
| Torrefied straw | 91.7 | 1.2 | 542 |

db: dry basis