Indirect gasification of waste to create a more valuable gas

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Abstract

Gasification is a thermochemical process which converts solid fuels into a gas with a useful heating value that can be further processed into a variety of products (heat, power, fuels and chemicals), thus creating smart market opportunities for the valorization of low-value solid feedstock. The feedstock composition and the gasification technology/conditions determine the quality of the resulting producer gas (composition, heating value, content and composition of tars and content of other contaminants). The properties of the producer gas together with the final application of the gas determine in turn the design of the gas cleaning section.

The Energy research Centre of the Netherlands (ECN) has been working in the last years on the development of technologies for the efficient conversion of biomass and waste into heat, power, fuels and chemicals. Some of the outcomes of this extensive work include the MILENA indirect gasification process, the OLGA tar removal system and the ESME system for production of SNG from biomass gasification. Royal Dahlman is currently marketing the MILENA and OLGA technologies worldwide.

As part of the work for development and commercialization of the MILENA and OLGA technologies at industrial scale, this paper reports and compiles results of gasification tests performed at pilot scale (800 kW_{th}, HHV)on an initial design MILENA gasifier, with different types of feedstock: biomass (wood) and waste (industrial waste, plastic-rich waste). The results from the most recent measurement campaign carried out at the pilot MILENA/OLGA using shredded Icopower® waste pellets as feedstock are described in detail. The results show that the use of biomass or waste as gasification feedstock lead to differences in the quality of the resulting producer gas, and thus to different considerations on the possibilities for final application and gas cleaning/upgrading of the resulting gas.

It can be concluded that gasification of plastic containing waste produces a high calorific value gas, which is particularly suitable for heat and power generation, synthesis and harvesting of valuable co-products from producer gas. Due to possible high temperature corrosion in boiler applications, fouling of gas coolers due to salts and agglomeration of bed material, the design and operating conditions of an industrial MILENA gasifier have been modified from the initial pilot design.

1- INTRODUCTION

Gasification is a thermochemical process in which a solid carbonaceous fuel (e.g. coal, biomass, or waste) is converted into a combustible gas called producer gas or syngas (depending on the gas composition) under sub-oxidizing conditions and medium-high temperatures (700-1200°C). The key feature of the gasification process is that the producer gas keeps 70-80% of the chemical energy initially contained in the initial solid fuel. The producer gas, in turn, is a versatile energy carrier which, after proper cleaning and upgrading, can be used in a number of applications: production of heat/power/mechanical energy, or feedstock for synthesis/recovery of fuels and chemicals. An overview of the possibilities for application of gasification producer gas is shown in Figure 1.

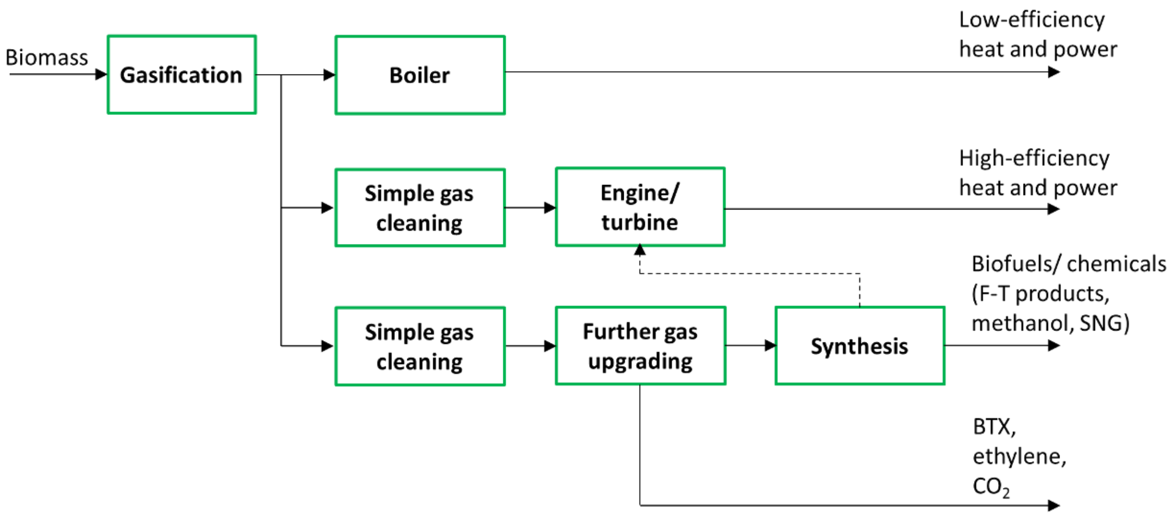

Figure 1: Overview of applications of gasification producer gas.

Gasification is thus a suitable option for the energy valorization of low-value solid feedstock such as agricultural residues or waste by converting them into a flexible gaseous energy carrier which can be cleaned and transported more easily than the initial solid feedstock, and which can be efficiently converted in a range of products.

Figure 2 shows schematically the process for the design of a gasification process. Firstly, the properties of the available feedstock (moisture content, density, particle size, heating value, proximate/ultimate analysis, and ash composition) will determine the range of suitable gasification processes. Once the gasification technology and the gasification conditions are selected, the use of the selected fuel will lead to the production of a combustible gas with different quality properties (gas composition, content and composition of tars, and content of other contaminants). The gas properties will in turn determine the range of possible final applications of the gas (e.g. N_2-diluted gas from direct air gasification is not suitable for synthesis applications). Once a suitable final application of the gas is selected (e.g. heat production in a boiler, power production in a gas engine, fuel synthesis), the required quality specifications of the gas (e.g. tar content, concentration of S-, N- and Cl compounds, H_2/CO ratio) will be determined, and thus, the design of the gas cleaning/upgrading section. Finally, in the design of the gasification process it is necessary to take into account also other economic and environmental considerations (capital costs, operating costs, emissions, etc.).

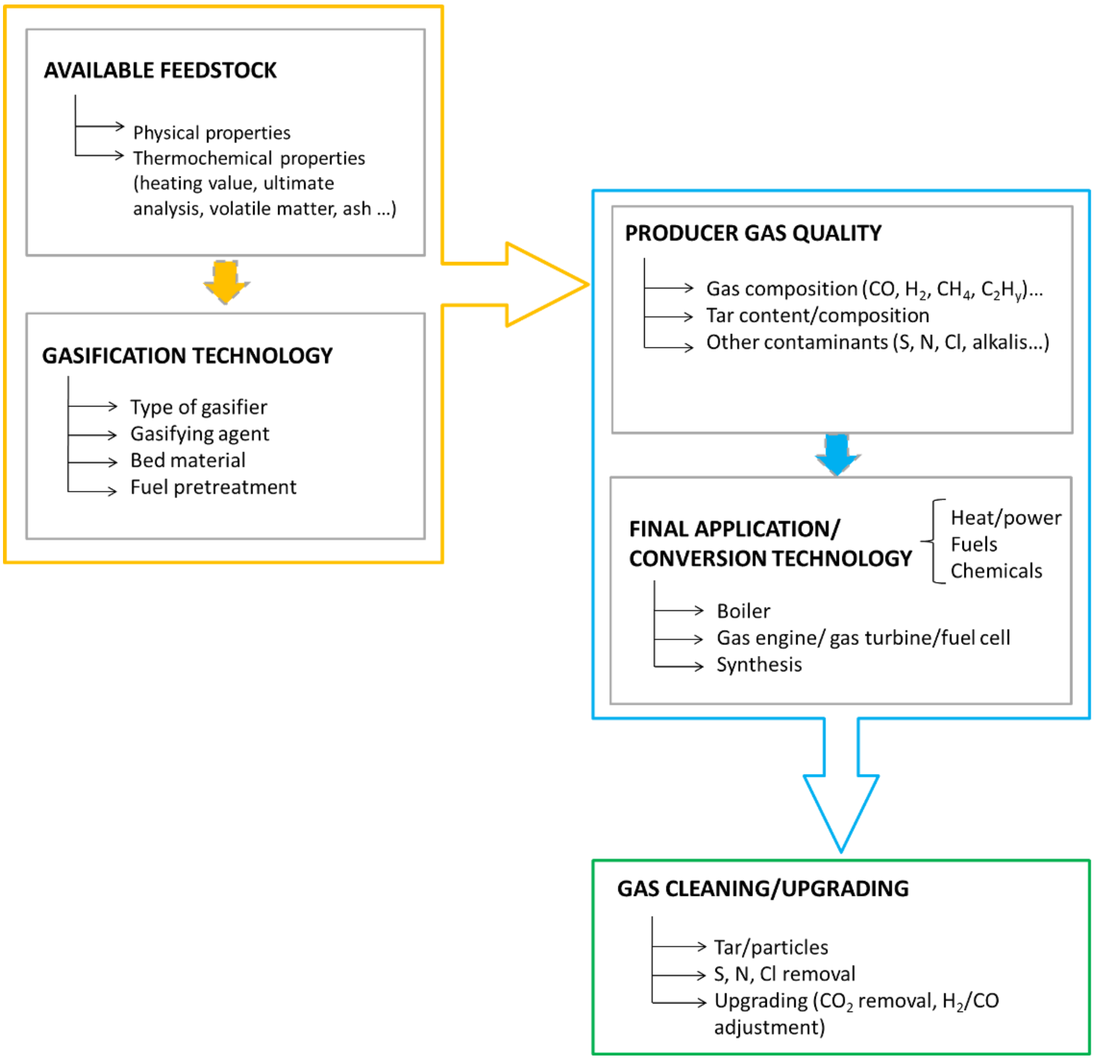

Figure 2: Schematic procedure of the design of a gasification process.

The first factor that has to be considered in the design of a gasification plant is the initial feedstock. The physical and chemical properties relevant for thermochemical conversion processes (summarized in Figure 3) will influence in the design of the fuel pretreatment system, the conversion process and the required gas cleaning train. Woody biomass has in general high moisture content, low bulk density, high volatile content, higher H/C and O/C ratios (thus, lower heating value) than coal, low N, S, and Cl content, and a low ash content with a high concentration of alkaline metals (Na, K). In comparison with woody biomass, herbaceous biomass (e.g. straw, miscanthus) has lower density, higher Cl and S content, and lower ash melting point. This makes herbaceous biomass more challenging in terms of conversion. The properties of lower-value fuels, such as waste-derived feedstock (e.g. RDF, SRF), pose even higher technical challenges on the process, including fouling, deposition and corrosion in the gas cooling sections of the plant, as well as bed agglomeration in fluidized-bed gasifiers/combustors. In spite of this fact, there is still a great opportunity for waste gasification with respect to the possibility of the harvesting of valuable co-products from producer gas. Waste gasification, due to the content of plastics of the solid waste fuel, boosts the yield of benzene, toluene, xylene (BTX) and unsaturated hydrocarbons, which are a potential source of income. Therefore, co-production cannot only help decrease the costs of gasification processes, but it also opens up the way to concepts such as circular economy.

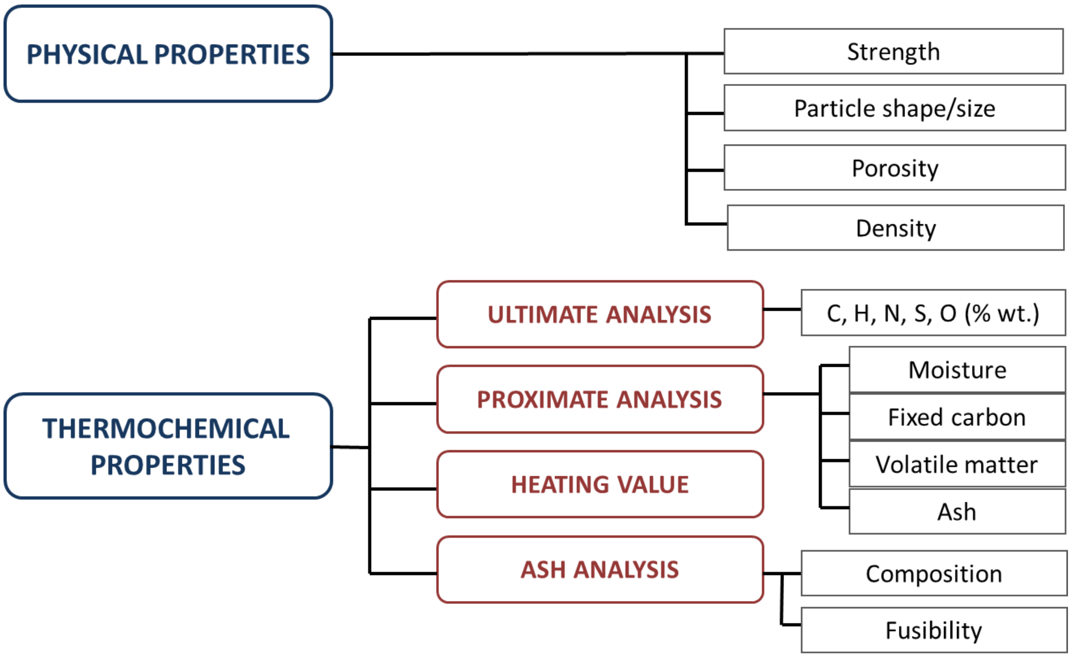

Figure 3: Overview of feedstock properties influencing the design of the gasification process.

With respect to the gasification technology, a first classification distinguishes between direct gasification and indirect gasification. In direct gasification processes, the required heating for the endothermal gasification process is supplied in the same reactor by the combustion of a fraction of the fuel. In indirect gasification processes, the heat required is externally supplied through a heat-transfer medium or via the physical separation of the combustion and gasification zones. Whereas direct gasification processes result in a N_2-diluted producer gas and an incomplete carbon conversion of the fuel, indirect gasification overcomes this challenge by producing a high heating-value, N_2-free gas (which can be further used as feedstock for fuels and chemicals) without the need for an expensive air separation unit and with complete carbon conversion of the solid feedstock. Thus, indirect gasification (such as the MILENA gasifier used in this work) is an attractive option to boost the value of low-cost fuels.

Once the gasification technology is selected, the operating conditions influence both the quality of the producer gas (composition, tar content/composition, contaminants) and the process performance (cold gas efficiency, carbon conversion). Among the operating conditions, the operating temperature is one of the most influential, particularly during the gasification of low-value, troublesome waste feedstock. Temperature control can effectively contribute to the mitigation of ash-related problems, such as agglomeration, fouling and corrosion. In previous work of ECN[1] and Royal Dahlman where several waste feedstock (paper rejects, RDF, and meat and bone meal) were tested, it was found that gasification at temperatures of ~ 750°C leads to a trade-off between fuel conversion and release of contaminants to the gas phase, thus improving plant availability. Despite a lower carbon conversion towards product gas when decreasing gasification temperature, there is an increase of the retention of troublesome compounds in the bed material and the cyclone ash, and a decrease of the release into the gas phase. However, in an indirect gasifier the overall carbon conversion remains 100%, as remaining carbon will generate additional latent heat in the form of flue gas.

Another important factor influencing the performance of fluidized-bed gasifiers is the selection of the bed material. For example, Fe-containing materials (e.g. ilmenite, olivine) can display oxygen-transport capacity when subjected to redox cycles (such as in indirect gasification processes) [2]. The oxygen transported from the combustor to the gasifier leads to the oxidation of a fraction of the gas and tars, which leads to a decrease of the tar content (but also to an unwanted decrease of the gas heating value). Moreover, certain bed materials such as olivine can undergo activation processes, which eventually leads to an enhancement of the extent of the WGS reaction and tar conversion [3].

Complementary, the use of additives in gasification/combustion processes can contribute to mitigate ash-related problems. A previous ECN work showed that the addition of halloysite as sorbent in waste gasification reduces the formation of low-melting, corrosive eutectic compounds, thus leading to deposits less prone to fouling, slagging and corrosion thanks to the capture of K and Na in aluminosilicate structures [4].

With this background, this paper reports and compiles results of waste gasification performed at ECN at pilot scale (800 kW_{th}, HHV) with different types of feedstock: biomass (wood) and waste (industrial waste, plastic-rich waste). The data set includes the results from the most recent measurement campaign carried out at the pilot MILENA/OLGA using shredded Icopower® waste pellets as feedstock, which are described in detail. This extensive work has been carried out in the last years as part of the development of the MILENA, OLGA and ESME technologies [5][6][7]. These results will be put into perspective to analyze the effect of the biomass/waste feedstock on the quality of the resulting producer gas, and thus on the possibilities for the final application and gas cleaning/upgrading.

2- MATERIALS AND METHODS

In April 2016, a successful measurement campaign was carried out at the MILENA/OLGA pilot plant located at ECN. The 800 kWth pilot plant, which is described elsewhere [8], is composed of the MILENA gasifier, gas cooling system, OLGA tar removal and water scrubber. The clean producer gas is then directed to a burner. A schematic layout is displayed in Figure 4.

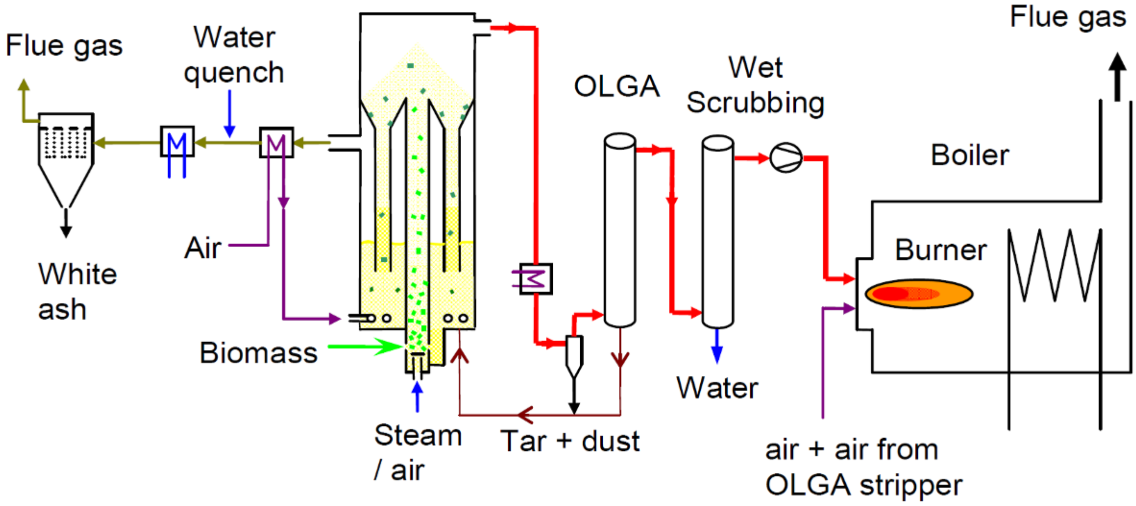

Figure 4: Schematic layout of pilot MILENA/OLGA plant [8]

The objective of the test was to gain further experience with waste gasification in the MILENA gasifier. For that, extensive measurements were carried out around MILENA and OLGA. Besides producer gas composition and flue gas composition, other contaminants such as tars, sulphur- and nitrogen compounds were analyzed in order to trace the fate and distribution of troublesome species during waste gasification.

The feedstock used for the gasification experiment was Icopower® energy pellets, a commercial product from industrial waste produced and supplied by ICOVA [9]. De feedstock for the production of Icopower® is waste from trade, services and authorities, and other waste products. Through a mechanical separation of the high-heating value fraction from the waste fraction, a secondary energy carrier with precise combustion properties is produced. The Icopower® energy pellets, supplied as a very homogeneous product, can be used to replace fossil fuels such as coal in industrial applications (e.g. cement production). The characterization of the waste-derived Icopower® feedstock used in the test is presented in Table 1. As can be seen, the fuel contains a large content of ash of ~ 14 wt.%.

Moreover, the molar S/Cl ratio, which is considered as a useful indicator of deposition and corrosion propensity, is 0.2 mol/mol, a value significantly lower than 2 mol/mol. This low S/Cl value implies a risk of high temperature corrosion [10], when co-firing the producer gas. The ash is rich in Ca, Si and Al, with significant concentrations of Fe, K and Na. All in all, these properties of the feedstock are likely to pose challenges in the gasification process, which will be further discussed in Section 3.

Moisture content 105°C (wt. %, as received)	2.3
Proximate analysis (dry basis)	
Ash content 550°C (wt.%)	13.8
Ash content 815°C (wt.%)	12.8
Volatile matter (wt.%)	76.9
Higher Heating Value, HHV (MJ/kg)	24
Ultimate analysis (dry basis)	
C (wt.%)	52.4
H (wt.%)	7.3
N (wt.%)	0.9
O (wt.%)	27.30
Br (mg/kg)	58
Cl (mg/kg)	11583
F (mg/kg)	92
Ash composition (mg/kg, dry basis)	
Al	9737
As	1.54
B	38.4
Ba	254
Ca	22616
Cd	1.64
Co	4.22
Cr	170
Cu	305
Fe	3500
K	2139
Li	3.34
Mg	1518
Mn	145
Mo	3.88
Na	3352
Ni	67.9
P	931
Pb	98.3
S	1844
Sb	81.6
Se	< 1.36
Si	19966
Sn	56.6
Sr	72
Ti	1545
V	3.59
W	2.19
Zn	286

Table 1: Characterization of Icopower® energy pellets used in the pilot MILENA/OLGA gasification test

Prior to the gasification tests in the pilot plant, the pellets were shredded to a screen size of approximately 15 mm to account for the limitations set by the small pilot plants feeding system and design. The bed material used in the test was quartz sand (particle size 0.3 – 0.5 mm). During the test, online monitoring of producer gas (H_2, CO, CO_2, CH_4) and flue gas (O_2, CO_2, CO, C_xH_y, NO, NO_2) was carried out. Complementary, online micro-GC analysis (CO, CO_2, CH_4, O_2/Ar, C_2H_2, C_2H_4, C_2H_6, C_6H_6, C_7H_8, H_2S, COS, N_2) of producer gas was carried out. Moreover, wet chemical analysis was performed for the determination of HCl, NH_3, HCN, and SO_2 (flue gas). SPA (Solid Phase Adsorption) analysis was carried out to determine the content and composition of tars at different locations of the gas line to track the performance of the OLGA tar removal system.

The settings of the MILENA gasifier are summarized in Table 2. The pilot plant experiment was started by warming up the gasifier using natural gas and wood pellets. Once a stable temperature was reached, the fuel was switched to Icopower® waste feedstock, at a rate of 96 kg/h. In order to compensate for the expected higher density producer gas, thus lower gas velocity and lower fuel flow (boiler limitation), external fluidization N_2 (15 Nm^3/h) was added to the riser. In order to compare results of different pilot scale experiments equally, nitrogen-free data is presented in Chapter 3. During the test, measurements and analyses were carried out over the process. Once the waste feedstock was near to depletion, the experiment was ended.

Experiment	100% shredded Icopower® pellets
Fuel flow (kg/h)	96
Steam flow (kg/h)	28
Fluidization N_2 (Nm^3/h)	15
Tgasification (°C)	750
Tcombustor bed (°C)	830
Combustion air (Nm^3/h)	140

Table 2: MILENA gasifier settings during pilot plant measurement campaign.

The settings of the OLGA tar removal system are summarized in Table 3. OLGA is a series of oil scrubbing towers where tars are gradually removed from the gas. The collector tower removes fine dust and heavy tars, whereas the absorber removes light tars (e.g. phenol, naphthalene). The oil used in the absorber loop is regenerated in a stripper which uses air as stripping medium. The pilot OLGA plant also includes an electrostatic precipitator (ESP) for the removal of fine dust and oil aerosols from the gas. Both heavy tars removed in the collector and tar-loaded stripping air can be further recirculated back to the combustor side of the MILENA gasifier, thus using the energy contained in the heavy tars in the gasification reactor. Moreover, another smart feature of OLGA is that it operates above the water dew point, so that the water is retained in the gas, and when further condensed, it does not contain tars. This makes the treatment of wastewater easier.

OLGA collector	
Inlet gas T (°C)	480
Oil temperature (°C)	80
Oil flow (kg/h)	340
Electrostatic precipitator (ESP)	
Temperature (°C)	80
Voltage/intensity	~ 45 kV / 9 mA
OLGA absorber	
Inlet oil temperature (°C)	80
Oil flow (kg/h)	500
OLGA stripper	
Oil inlet temperature (°C)	180
Oil flow (kg/h)	535
Stripping air temperature (°C)	180
Stripping air flow (Nm3/h)	80

Table 3: OLGA settings during pilot plant measurement campaign.

3- RESULTS AND DISCUSSION

Summary of pilot scale gasification test with Icopower®

In April, 2016, shredded Icopower® pellets were gasified in the pilot scale MILENA gasifier. The product gas was subsequently cleaned by the OLGA tar & dust removal system, followed by a water scrubber to remove water, HCl and NH_3. The cleaned product gas was burned in a boiler. In total, 53 hours of gasifying Icopower® at an average rate of 96 kg/h was achieved, resulting in a thermal input of the gasifier of on average 630 kW (HHV). There were two unforeseen shutdown events, the first was caused by a software problem, shutting down cooling fans and the second was caused by a faulty flame sensor of the boiler. Apart from these two events, the MILENA gasifier and OLGA tar and dust removal system operated flawless.

Observations

Figure 5 shows that the riser-gasifier temperature of MILENA stabilized at approximately 750°C, whereas the combustor temperature was about 80 degrees higher. The gasification temperature was intentionally kept at 750°C in order to mitigate ash related problems such as downstream condensation of evaporated salts, while maintaining sufficient fuel conversion.

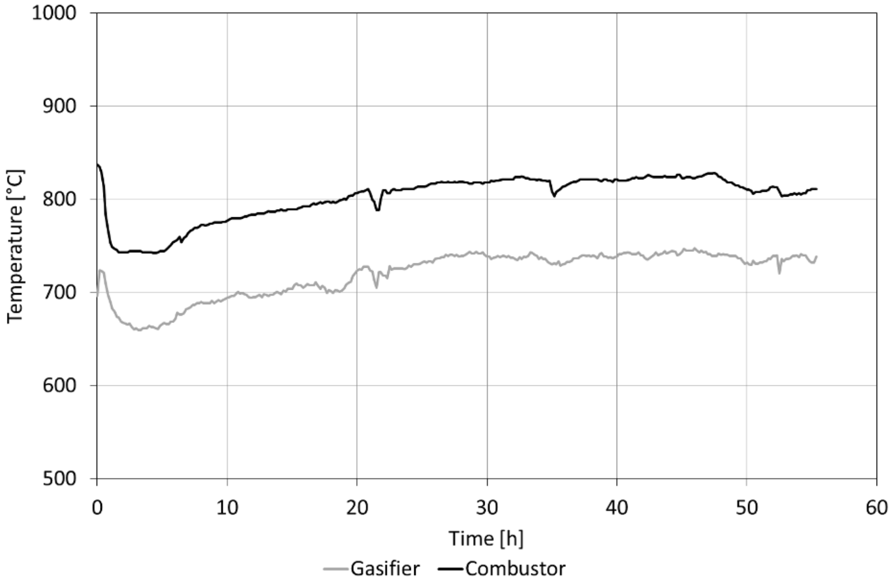

Figure 5: MILENA temperature

In the Figure 6 to Figure 8, three minor hiccups in the trending can be observed, caused by 1), a gas sampling system fault (loose connection), 2), an emergency shut down due to a software problem and 3) a shutdown due to a faulty flame sensor.

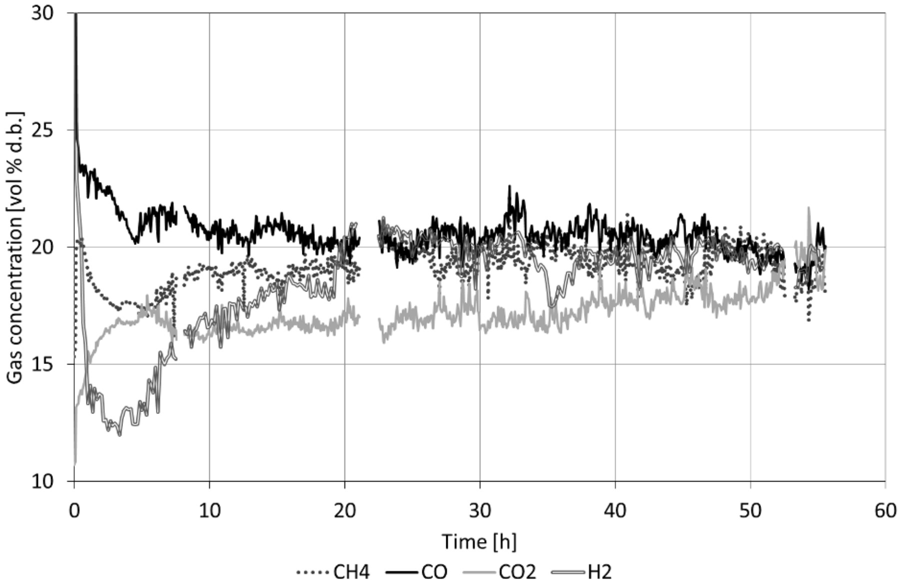

Figure 6: Producer gas composition

Gasifying inhomogeneous feedstock like waste often results in less stabile producer gas composition. Figure 6 to Figure 8 confirm that even with shredded Icopower® pellets, the gas composition was fluctuating around a relatively stable average value, with short-term spikes and a longer term variation. Both variations primarily originate from different sized and/or different density feedstock particles, as well as the rotary valves batch transport of material, the single feeding bunker screw frequency and the gradual emptying and periodic filling of the small feeding bunker of the pilot gasifier can contribute to the fluctuations and can be counteracted on industrial scale by the correct design.

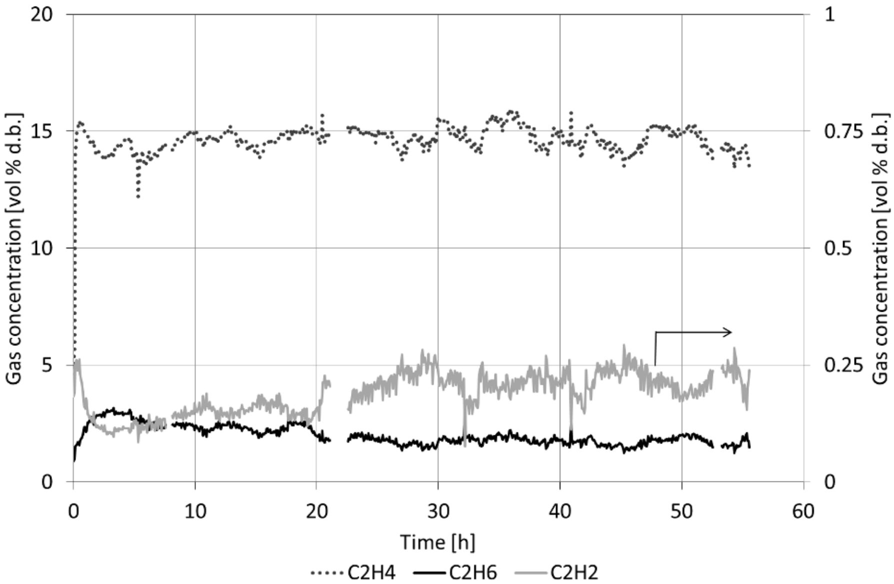

Figure 7: C2 in producer gas

It is striking to see the high amount of hydrocarbons in the producer gas, when gasifying shredded Icopower® pellets at a gasification temperature of 750°C. At the same time, syngas components like CO and H_2 are lower, compared to wood gasification results. The next section of this chapter will go into more detail, comparing these results with data obtained from pilot experiments of wood and plastic waste gasification.

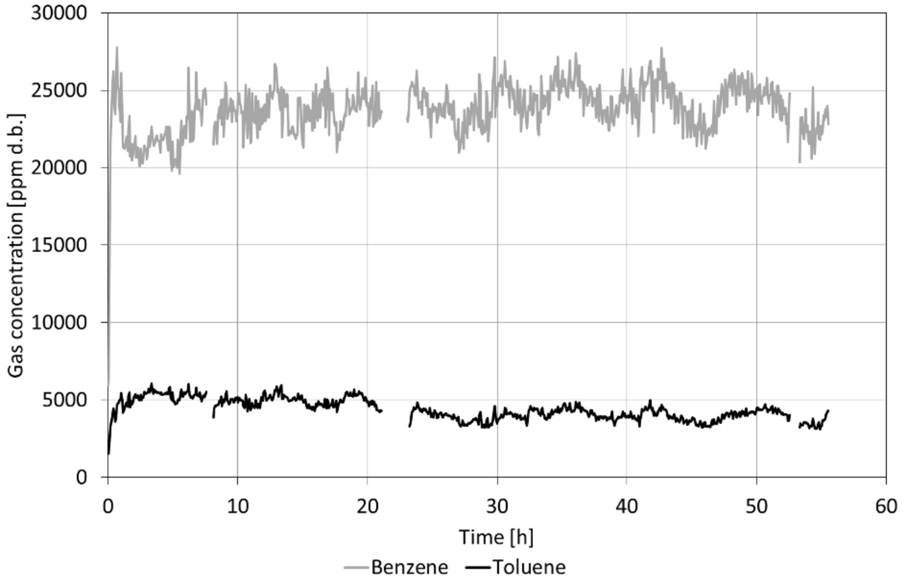

Figure 8: Benzene and toluene in producer gas

Feedstock derived from waste often contain significantly more ash, chlorine and sulphur than clean wood. Together with the relatively high plastic content in the feedstock, the OLGA tar and dust removal system will most likely have to process a higher concentration of tar and dust in the producer gas, compared to clean wood. This was confirmed by higher ash flows of the cyclone upstream of OLGA as well as by the amount of tar and dust in the producer gas. Figure 9 shows the pressure drop of the producer gas in the OLGA collector and absorber column as well as the pressure drop of the stripper gas. As can be seen, despite a higher tar and dust load, no signs of fouling were found and the OLGA system operated smoothly.

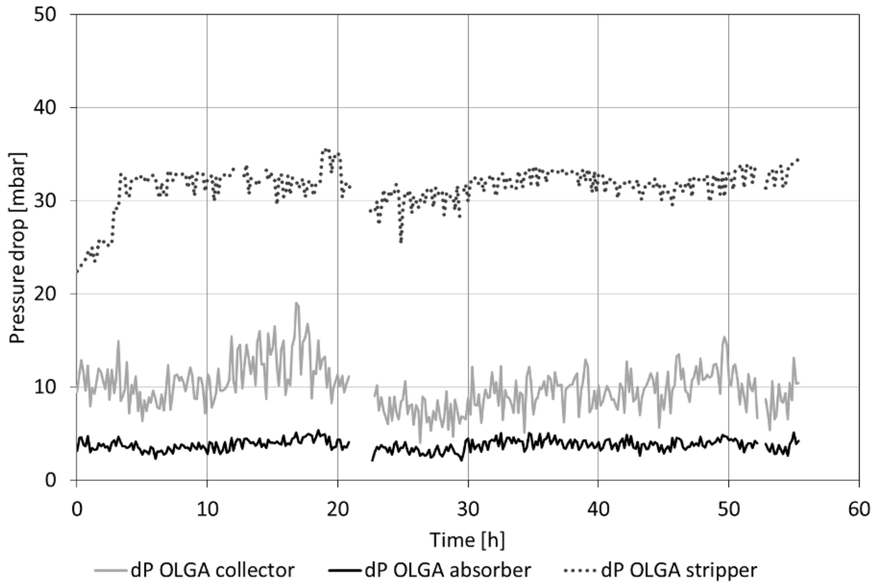

Figure 9: Pressure drop of the OLGA tar and dust removal system

The combination of the high chlorine content and ash composition poses technical challenges in the conversion of the feedstock (agglomeration, fouling and deposition, as well as high temperature corrosion).

Figure 10: Agglomerate found in Bubbling Fluidized Bed (BFB)

The post-test inspection of the gasifier showed that near the air nozzles, at the reactor wall, an agglomerate was found. Figure 10 shows the sand and salt agglomerate, caused by sticky salts binding to the sand, in a zone where the bed temperature is decreasing. Apart from this agglomerate, a significant amount of small pieces of metal were found in the bottom ash, see Figure 11. This shows that despite the pretreatment of the industrial waste, consisting of separation of unwanted parts like glass and stones, extraction of metals, pelletizing and shredding, metal pieces end up in the gasifier.


Figure 11: Small pieces of metal, sieved out of bottom ash

Using feedstock based on waste streams will require specific design features and/or operational and maintenance strategies, like periodic sieving and recycling of bed material, as well as periodic cleaning of nozzles, air distributors and other parts where material could settle and accumulate, with the risk of disrupting the (hydrodynamic) process. Therefore an industrial MILENA is designed with a self-cleaning bed system with sieving equipment.

The full understanding of these properties by conducting realistic pilot scale experiments enabled Royal Dahlman to include different system design considerations compared to the pilot scale design (gasification reactor, gasification operating conditions, gas cleaning train) in order to cope with the potential challenges associated to the waste fuels.

Comparison of producer gas composition for pine wood, Icopower® and plastic waste.

Table 4 compares the characterization of the different feedstock used in the pilot tests in 2012, 2015 and 2016. In 2012 a 500 hour test was performed using pine wood at a gasification temperature of 810°C. In 2015 a short term pilot test was done using plastic waste with a low biogenic material content and a high plastic content. The gasification temperature was 700°C. Recently, in April 2016, shredded Icopower® energy pellets were gasified at 750°C. In all cases steam was used as a fluidization agent in the riser reactor. As can be seen, wood contains a significantly high oxygen content, which is reflected in the low heating value compared with the waste fuels. As the plastic content increases, both the carbon and hydrogen content increase, whereas the oxygen content decreases. The overall effect is an increase in the heating value from 20 MJ/kg (wood, dry basis) to ~33 MJ/kg (plastic waste, dry basis). Moreover, it can be observed the dramatically high content of ash of the waste feedstock (11-14 wt.%) compared to wood (< 1 wt.%). It is noteworthy the relatively high Cl content of the waste fuels (1.2-1.6 wt.%), which is dramatically higher than that of wood. The S/Cl ratio of the plastic waste and the Icopower pellets (0.06 mol/mol and 0.18 mol/mol, respectively) is far below the threshold of 2 mol/mol, which indicates the high risk of these fuels to corrosion [10]. It is also interesting to observe the relatively high sulfur content of the Icopower feedstock (~ 10 times higher than that of pine wood), which is reflected afterwards in the high H_2S concentration in producer gas.

	Pine wood	Icopower® energy pellets	Plastic waste
Moisture content 105°C (wt. %, as received)	11.0	2.3	0.2
C (wt. %)	50.0	52.4	65.0
H (wt.%)	6.4	7.3	9.8
N (wt.%)	< 0.1	0.9	0.8
S (wt.%)	0.02	0.18	0.08
O (wt.%)	45	27.3	14.4
Cl (wt.%)	0.008	1.16	1.58
Volatile matter (wt.%)	83.0	76.9	85.2
Ash 550°C (wt.%)	0.55	13.8	10.8
Ash 815°C (wt.%)	0.46	12.8	9.8
HHV (MJ/kg)	20.1	24	32.6

Table 4: Overview of characterization of woody biomass (pine) and waste feedstock (Icopower® and plastic waste).

Table 5 compares the producer gas composition (on nitrogen-free basis), obtained in the pilot scale experiments. As can be seen, with increasing plastic content in the fuel, more hydrocarbons like methane, ethane, ethylene, C_3 to C_5, and BTX are formed, while the fraction of syngas components CO and H_2 accordingly decreases. The effect of the producer gas composition on the calorific value of the gas can be seen clearly by an increase of 18.5 MJ/Nm^3 to 48 MJ/Nm^3. This makes the producer gas in particular suitable for synthesis- and co-production-, besides heat and power applications. Apart from heat and power, synthesis of the gas to e.g. Substitute Natural Gas (SNG) is an attractive options since a large fraction of methane is formed already directly in the gasification process. However, hydrogenating and reforming the C_2H_4, C_3H_6, C_4H_8 unsaturated hydrocarbons and BTX to methane comes at the expense of a hydrogenation and pre-reformer reactor and efficiency. It would make more sense to extract these hydrocarbons from the gas prior to hydrogenation and methanation. The increasing amounts of higher hydrocarbons, compared to the wood case show the potential of these compounds as a source of income. Therefore, co-production cannot only help decrease the costs of gasification processes, but it also opens up the way to concepts such as circular economy. Concepts for BTX recovery, ethylene recovery are currently under development at ECN and partners.

Producer gas	Pine wood	Icopower®	Plastic waste	
CH_4	15.5	19.6	26.4	[vol.%]
CO	43.4	20.6	7	[vol.%]
CO_2	12.0	17.1	7.3	[vol.%]
H_2	23.6	19.7	11.7	[vol.%]
O_2	0	0	0	[vol.%]
Ar	0.05	0.20	0.15	[vol.%]
N_2	0	0	0	[vol.%]
C_2H_2	0.19	0.22	0.15	[vol.%]
C_2H_4	4.96	14.90	24.65	[vol.%]
C_2H_6	0.53	1.80	3.71	[vol.%]
Sum C_3	n.m.	2.6	9.5	[vol.%]
Sum C_4	n.m.	1.0	4.0	[vol.%]
Sum C_5	n.m.	0.03	0.17	[vol.%]
H_2S	150	1653	575	[ppmV]
COS	11	49	12	[ppmV]
Thiophene	n.m.	59	16	[ppmV]
Benzene	0.94	2.42	4.04	[vol.%]
Toluene	0.10	0.40	0.67	[vol.%]
NH_3	46	3825	1802	[ppmV]
HCN	n.m.	3012	2544	[ppmV]
HCl	9	305	n.m.	[ppmV]
LHV	>18.5	29.4	48	[MJ/Nm^3]

Table 5: Summary of gas composition, nitrogen free

Tars have been plotted according to the tar classification system [11], based on solubility:

Class 1: Unknowns, not measured by GC.
Class 2: Heterocyclic components (phenol, cresol).
Class 3: Aromatic components 1 ring: xylene, benzene and toluene. These components cannot be detected via SPA. Micro-GC analysis is thus used for these components.
Class 4: Aromatic components (2, 3 rings)
Class 5: Aromatic components (>3 rings).

Gasifying high ash, plastic rich feedstock may result in fouling downstream of the gasifier due to large, heavy tars and condensation of salts. In order to avoid fouling, and mitigate ash related issues, a gasification temperature of maximum 750°C was used, based on results in previous work [1]. Furthermore, when gasifying the plastic-rich waste, it was decided to lower the temperature even more to 700°C, in order to avoid ash and tar related problems.

Exp nr	Location	Class 2 [g/Nm³]	Class 3 [g/Nm³]	Class 4 [g/Nm³]	Class 5 [g/Nm³]	Unknowns [g/Nm³]	Total tar [g/Nm³]
Pine wood	After MILENA	1.5	2.8	35.7	8.1	18.4	66.2
Pine wood	After absorber	0.0	0.1	0.8	0.0	1.1	2.1
Pine wood	After quench	0.0	0.0	0.3	0.0	1.2	1.9
Icopower®	After MILENA	5.2	9.9	33.5	2.6	30.2	81.4
Icopower®	After absorber	0.0	4.9	0.3	0.0	2.1	6.2
Icopower®	After quench	0.0	4.3	0.4	0.0	2.4	7.1
Plastic waste	After MILENA	2.7	25.4	37.9	3.1	40.5	109.4
Plastic waste	After absorber	0.1	6.5	0.7	0.0	5.4	12.8
Plastic waste	After quench	0.0	2.3	0.6	0.0	4.0	7.0

Table 6: Summary of tar measurements, nitrogen free

The tar content and composition in the producer gas is summarized in Table 6. As can be seen, the total amount of tar of the plastic containing feedstocks is higher. However, the concentration of the high dew point, class 5 tars, is lower than for the pilot experiment using wood. Typically, class 5 tars condense at relatively high temperature at low concentrations thus can cause tar related fouling issues. When gasifying waste at a temperature of less than 750°C, the tar distribution shift towards the class 2, 3 and 4 tars. These tars are less problematic and can be removed easily by OLGA. Overall, the tar removal efficiency of the OLGA system is in accordance with the design specifications of this pilot-scale OLGA system. It is noted that this OLGA system was initially designed for tar removal downstream a direct air blown gasifier operated on clean biomass, not an indirect gasifier operated on waste.

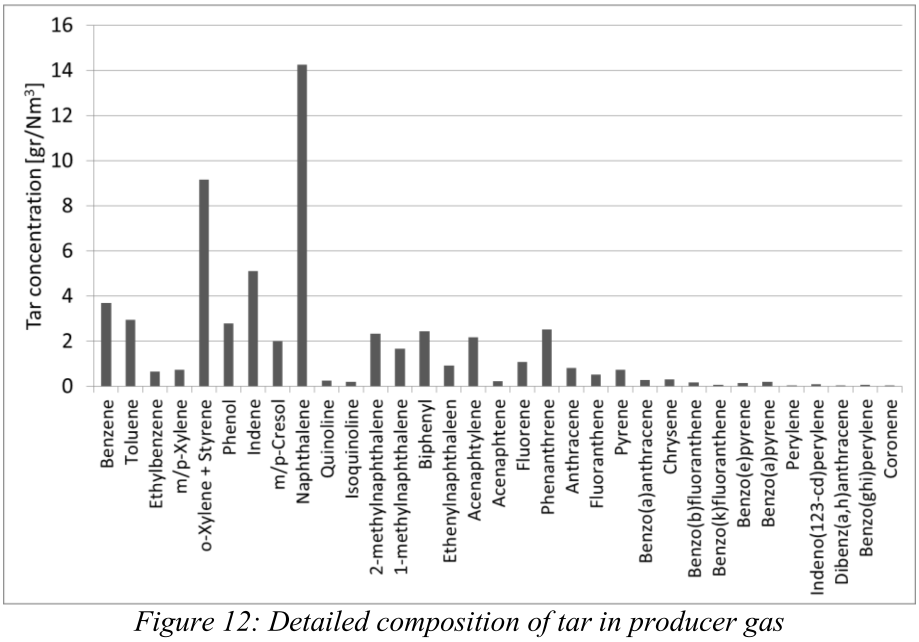

Figure 12: Detailed composition of tar in producer gas

Figure 12 shows the detailed composition of the tars in the producer gas of the experiment using shredded Icopower® pellets as feedstock. As can be seen, it is clear that the distribution of tars is towards the aromatic 1-, 2- and 3-ring compounds like styrene, indene, naphthalene and phenanthrene.

A comparison of price scenarios is shown in Figure 13 and Figure 14. The assumptions for the scenarios are given in price data based on market information, see Table 7. It is clear that the input cost of waste is lower compared to wood and at the same time, the producer gas of gasified waste represents a higher value due to the higher amount of C_2+ hydrocarbons, especially the unsaturated hydrocarbons. Furthermore, the ratio of the accumulative value of syngas and CH_4 to C_2+ hydrocarbons shifts more to the C_2+ hydrocarbons side for the waste feedstocks.

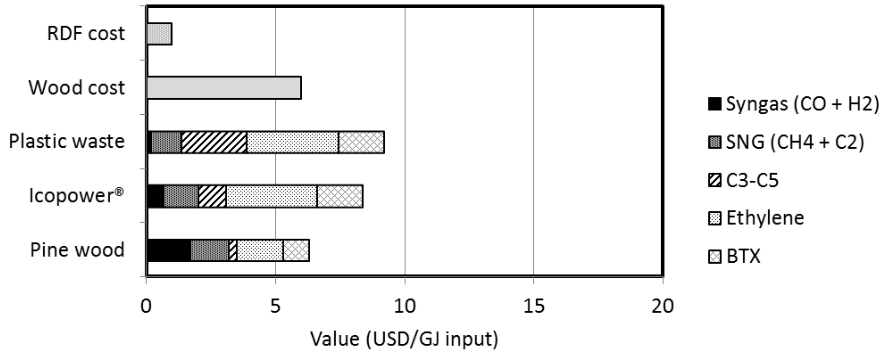

Figure 13: Price scenarios for producer gas components for the low price scenario

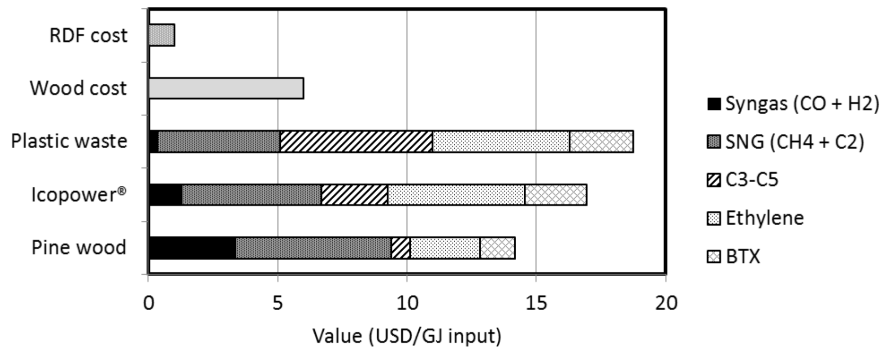

Figure 14: Price scenarios for producer gas components for the high price scenario

	Low-price scenario	High-price scenario		Low-price scenario	High-price scenario	
Syngas (CO + H2) ($/GJ)	5	10		5	10	($/GJ)
SNG (CH4 + C2H6) ($/GJ)	6	24		6	24	($/GJ)
C3-C5 ($/GJ)	12	28		12	28	($/GJ)
Ethylene ($/ton)	800	1200		15	22	($/GJ)
BTX ($/ton)	650	900		16	21	($/GJ)

Table 7: Price data for the scenarios [12][13][14]

4- CONCLUSIONS

Gasification, and in particular indirect gasification, is a suitable option for the energy valorization of waste feedstock by converting it into a versatile gaseous energy carrier which can be efficiently converted in a range of products (heat, power, fuels, and chemicals). Despite the technical challenges of waste feedstock during thermochemical conversion (e.g. fouling, agglomeration, corrosion), waste gasification is a great opportunity for the co-production of high-value chemicals (e.g. BTX, ethylene…), thus making possible the concept of circular economy and helping to reduce the production cost. The understanding of the effect of the feedstock composition on the quality of the resulting producer gas allows an enhanced assessment of the possible applications for the gas as well as improved design and optimization of gas cleaning systems. In this sense, the extensive lab- and pilot work carried out in the last years by ECN opens up the way for new commercialization opportunities for the MILENA and OLGA technologies in the valorization of waste feedstock.

As part of this development work, this work has described the successful measurement test carried out in April 2016 at the MILENA/OLGA pilot plant located at ECN. During the experiment, extensive analysis (gas composition, tar content/composition, S-/N-/Cl-compounds) was carried out to track the performance of the gasifier and the gas cleaning section. The results have shown that gasification of plastic containing waste results in a high calorific value producer gas that is suitable for heat and power generation, synthesis and harvesting of valuable co-products from producer gas. Challenges lie in possible high temperature corrosion in boiler applications, fouling of gas coolers due to salts and agglomeration in the BFB. Lowering the gasification temperature to 700-750°C (depending on the ash and plastic content of the feedstock) results in stable operation and a trade-off between fuel conversion and release of contaminants to the gas phase. This is one strategy, amongst others, like use of additives for mitigation of ash related problems, that can be applied.

The full understanding of these properties by conducting realistic pilot-scale experiments has led to insights that resulted in different system design considerations (gasification reactor, gasification operating conditions, gas cleaning train) in order to cope with the potential challenges associated to the waste fuels, as well as profiting from the rich resource of valuable compounds.

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