



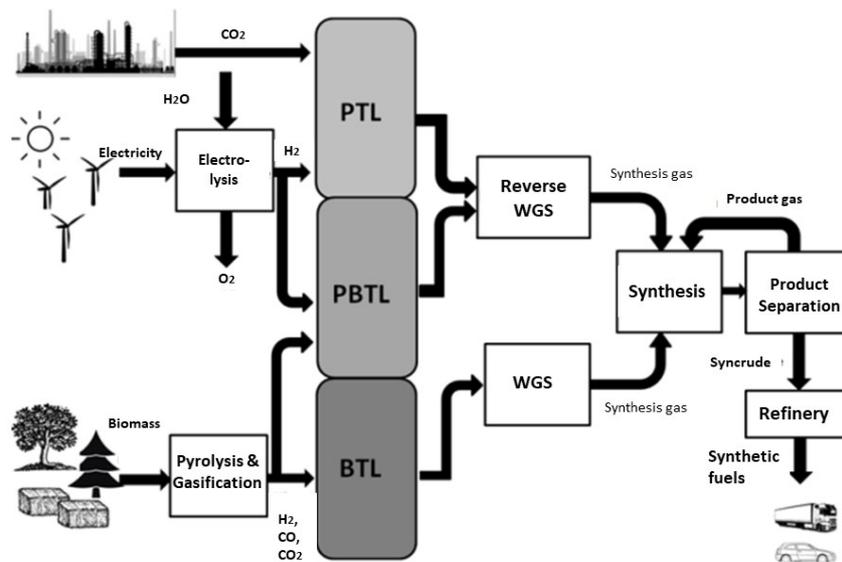
IEA Bioenergy
Technology Collaboration Programme

Gasification applications in existing infrastructures for production of sustainable value-added products

IEA Bioenergy Task 33 report

IEA BIOENERGY: TASK 33

DECEMBER 2021





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COVER PICTURE: SUMMARY OF DIFFERENT PATHWAYS FOR THE PRODUCTION OF SYNTHETIC FUELS (CASE STUDY)

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ABBREVIATIONS

CHP	Combined heat and power
EF	Entrained flow
FT	Fischer-Tropsch
HHV	Higher heating value
LHV	Lower heating value
MSW	Municipal solid waste
PV	photovoltaic
RDF	Refuse-derived fuel
SFR	Solid recovered fuel
SNG	Synthetic natural gas (or substitute natural gas)
WBA	World Bioenergy Association

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Introduction

The gasification technology can be applied in different, already existing industrial and agricultural infrastructures for production of further value-added products. The gasification potential is huge regarding the feedstock, operational parameters and products as well. In the following figure an overview on products from gasification can be seen. During the gasification, the producer gas is formed, which is after cleaning and conditioning called syngas. The syngas is a stepping or corner stone for further processing and production of biochemicals and biofuels as well as heat and power.

When biomass or organic waste is the fuel feedstock, gasification also offers the opportunity of co-producing one or more products, e.g. biochar. Biochar and sequester ready CO₂ are two examples of products that have a direct use also to replace fossil counterparts. However, they can also be applied in such a way that they generate negative emissions, it stores carbon for an extended period of time taking it out from the current carbon cycle.

From indirect gasifiers it is also possible to obtain olefins or aromatics, that normally are produced via steam cracking of naphtha. This cascaded approach in the valorization of biomass is also something the EU has recognized and is supporting the development of in the new Horizon Europe program.

As already mentioned, valuable by-product of biomass gasification can be biochar, depending on the gasification process. For some gasification processes such as dual fluidized bed gasification finally no biochar is left over. Common uses for biochars are found in agriculture where they serve as feed amendment, stable bedding, for slurry stabilization, in biogas plants or directly in soils, e.g. as a carrier matrix for nutrients. New applications of biochars include their use in building materials such as concrete or asphalt, in plastics or in high-tech, where they can replace fossil resources. In order to achieve climate neutrality by 2050, the creation of carbon sinks in the magnitude of 850 Mt of CO₂eq p.a. will need to be made available. Biochar can provide a third of this amount by mid-century if the respective regulations are set. Optimizing resource flows and closing local and regional material cycles are necessary for this goal. Biochar can help agriculture adapt to climate change and serve as the basis for a circular economy, producing goods that are endlessly recyclable.

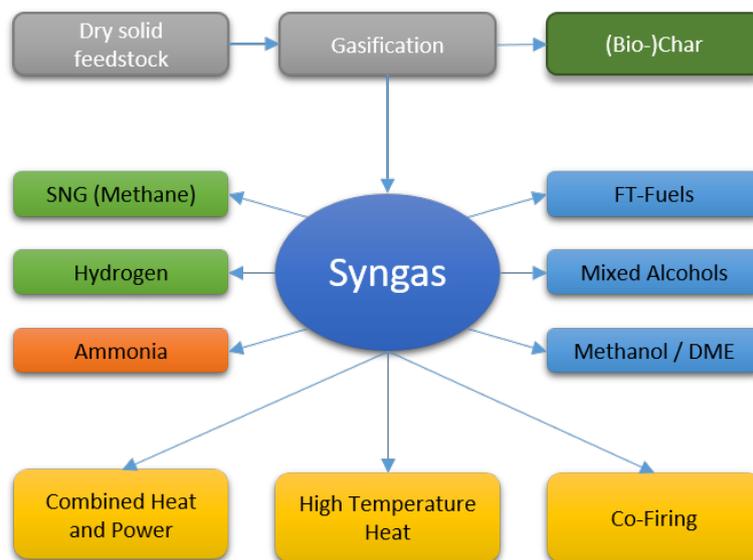


FIGURE 1: PRODUCTS OF GASIFICATION PROCESS

Combined heat and power production (CHP)

This gasification application is already a well-established technology. There are over 1700 operating gasification based CHP plants in Europe. The feedstock is mostly woody biomass, but also other materials

such as agriculture waste, chicken manure or sewage sludge could be used. These types of gasification facilities are able to cover the energy demand (power and heat) of hospitals, schools and hotels, they are often used also for district heating or in saw mills, food production facilities or farms, where the feedstock is readily available. Most of them are small scale gasifiers with an output up to 500 kW_{el} / 800 kW_{th}. There are also a few examples of plants with a total capacity of 5-6 MW_{el} and even selected plants with significantly higher power production (eg. Lahti gasifier).

Co-firing of product gas and high temperature heat

Gasification of biomass or biogenic residues can play an important role in the production of high temperature heat or steam for industrial processes, where typically only fossil fuels (natural gas, or oil) are used for combustion.

Production of biofuels and biochemicals

Typically, the production of biofuels requires a larger scale than the previously described routes. The following selected biofuels and biochemicals could be produced from syngas through different synthesis process: synthetic natural gas (SNG), hydrogen, ammonia, liquid biofuels based on Fischer-Tropsch (FT) synthesis (diesel, kerosine, petrol), mixed alcohols, and methanol/DME.

The crucial issues, influencing the product gas composition and further value-added products are the quality of feedstock and operating conditions, which are described further in this paper.

1. FEEDSTOCK

1.1 Categories and quantification

Feedstock suitable for thermochemical gasification can be generally divided into 3 categories:

Woody biomass and waste

(e.g. soft wood, hard wood, waste wood, etc.)

Agricultural residues and waste

(e.g. straw, maize, husks, manure, etc.)

Residential and industrial waste streams

(e.g. MSW, RDF, SRF, black liquor, sewage sludge, etc.)

The World Bioenergy Association (WBA) is focusing on biomass and bioenergy. It is the global organization dedicated to support and represent the wide range of actors in the bioenergy sector. Since its foundation in 2008, WBA has been working to address a number of pressing issues including certification, sustainability criteria, bioenergy promotion, and the debates about impact of bioenergy on food, land- use and water supply.

The WBA has published a factsheet¹ in which they nicely classify the different sources of biomass that could potentially be used for energy applications. In case of gasification also for chemicals/materials.

¹ WBA fact sheet: Global biomass potential toward 2035;
https://worldbioenergy.org/uploads/Factsheet_Biomass%20potential.pdf

TABLE 1: CLASSIFICATION OF THE DIFFERENT SOURCES OF BIOMASS (SOURCE WBA¹)

Main sector	Sub sector	Examples
Agriculture	Dedicated crops	Crops for biofuels (corn, sugarcane, rapeseed, oilpalm, jatropha, sorghum, cassava etc.), energy grasses (miscanthus, switchgrass), short rotation forests, other dedicated crops for energy
	By-products and residues	Herbaceous by - products: Straw from cereals, rice, corn, bagasse, empty fruit bunch from oil palm, prunings from stover, empty corn cobs etc.
		Woody biomass, regeneration orchards, vineyards, olive and oil palm plantations
		Other forms: Processing residues such as kernels, sunflower shells, rice husks, animal manure
Forestry	Main product	Stems, wood fuel from forests or trees outside forests, woody biomass from landscape cleaning
	By-products and residues	Residues of forest harvest (branches, tops, stumps), residues of wood industry (bark, sawdust, other wood pieces, black liquor, tall oil, recycled wood)
Organic waste		Municipal solid waste (MSW), food waste from stores, restaurants and households, used kitchen oil, waste from the food industries (from dairy, sugar, beer, wine, fruit juice industry, from slaughter-houses), sewage sludge

The quantification of feedstock as well as its potential is an important parameter for its utilization and the planning of new conversion facilities.

According to WBA, the biggest share of biomass for energy came from forests, 49 EJ out of total supply of 56.2 EJ in 2012. Detailed information regarding the global potential of biomass could be seen in table 2.

More actual and detailed information can be found in the WBA publication "Global energy statistics 2019"².

WBA estimates that by 2035, about 5% of the agricultural area (240 million ha) can be used for growing dedicated energy crops for biofuels and solid biomass for energy.

A conservative estimate of the energy potential of biomass from agriculture, forestry and waste sectors totals 150 EJ in the next 15 years. About 43% coming from agriculture (residues, by-products and energy crops), 52% from forests (wood fuel, forest residues and by-products of the forest industry) and 5% from waste streams.

² WBA: Global bioenergy statistics 2019, http://www.worldbioenergy.org/uploads/191129%20WBA%20GBS%202019_HQ.pdf

TABLE 2: GLOBAL POTENTIAL OF BIOMASS IN 2012 AND 2035 (IN EJ)

Main sector	Sub sector	2012 - 2016	2035 - range	2035 - average
Agriculture	Dedicated crops - main product	3.5	26-34	30
	By-products and residues including manure	2.1	30-38	34
	Total agriculture	5.6	56-72	64
Forestry		48.9	72-84	78
Organic waste		1.7	6-10	8
Total		56.2	134-166	150

1.2 Feedstock qualification

The quality of feedstock influences, together with process conditions, the final products obtained from thermal gasification. Furthermore, the higher content of some elements in the feedstock, such as K, Cl and Na or S etc. could affect the operability of the gasifier and generate harmful emissions.

The most relevant parameters regarding the feedstock quality are, chemical composition (elemental analysis), ash and water content, which result in the higher- and lower heating values (HHV, LHV) of the feedstock.

Elemental analysis of several biomass types, such as woody biomass, including bark, energy crops can be seen in the following table. The list is intended to give examples of biomass feedstock available for use in gasification, it is not exhaustive any many others can be found in the literature, e.g. Phyllis2 database³.

The data in the table are based on results measured in several laboratories and calculated for dry basis. The feedstock moisture content is not included in the table because this parameter can vary a lot regarding on e.g. harvesting time or storage conditions and time. The moisture content influences also LHV of the feedstock, thus only HHVs are displayed in the table.

³ Phyllis2 - Database (<https://phyllis.nl/>)
<https://phyllis.nl/>

TABLE 3: ELEMENTAL ANALYSIS OF DIFFERENT BIOMASS TYPES⁴

Biomass	Fixed C	Volatiles	Ash	C	H	O	N	S	HHV	HHV
	wt-%								MEAS	CALC
d.b.									kJ/g	kJ/g
WOOD										
Beech	-	-	0.65	51.64	6.26	41.45	<0.01	<0.01	20.38	21.10
Black Locust	18.26	80.94	0.80	50.73	5.71	41.93	0.57	0.01	19.71	20.12
Douglas Fir	17.70	81.50	0.80	52.30	6.30	40.50	0.10	<0.01	21.05	21.48
Hickory	-	-	0.73	47.67	6.49	43.11	<0.01	<0.01	20.17	19.82
Maple	-	-	1.35	50.64	6.02	41.74	0.25	<0.01	19.96	20.42
Ponderosa Pine	17.17	82.54	0.29	49.25	5.99	44.36	0.06	0.03	20.02	19.66
Poplar	-	-	0.65	51.64	6.26	41.45	<0.01	<0.01	20.75	21.10
Red Alder	12.50	87.10	0.40	49.55	6.06	43.78	0.13	0.07	19.30	19.91
Redwood	16.10	83.50	0.40	53.50	5.90	40.30	0.10	<0.01	21.03	21.45
Western Hemlock	15.20	84.80	2.20	50.40	5.80	41.10	0.10	0.10	20.05	20.14
Yellow Pine	-	-	1.31	52.60	7.00	40.10	<0.01	<0.01	22.30	22.44
White Fir	16.58	83.17	0.25	49.00	5.98	44.75	0.05	0.01	19.95	19.52
White Oak	17.20	81.28	1.52	49.48	5.38	43.13	0.35	0.01	19.42	19.12
Madrone	12.00	87.80	0.20	48.94	6.03	44.75	0.05	0.02	19.51	19.56
Mango Wood	11.36	85.64	2.98	46.24	6.08	44.42	0.28		19.17	18.65
BARK										
Douglas bark	25.80	73.00	1.20	56.20	5.90	36.70	<0.01	<0.01	22.10	22.75
Loblolly bark	33.90	54.70	0.40	56.30	5.60	37.70	<0.01	<0.01	21.78	22.35
ENERGY CROPS										
Eucalyptus Camaldulensis	17.82	81.42	0.76	49.00	5.87	43.97	0.30	0.01	19.42	19.46
Casuarina	19.58	78.58	1.83	48.50	6.04	43.32	0.31	<0.01	18.77	19.53
Poplar	16.35	82.32	1.33	48.45	5.85	43.69	0.47	0.01	19.38	19.26
Sudan Grass	18.60	72.75	8.65	44.58	5.35	39.18	1.21	0.01	17.39	17.62
PROCESSED BIOMASS										
Plywood	15.77	82.14	2.09	48.13	5.87	42.46	1.45	<0.01	18.96	19.26
AGRICULTURAL Residues										
Peach Pits	19.85	79.12	1.03	53.00	5.90	39.14	0.32	0.05	20.82	21.39
Walnut Shells	21.16	78.28	0.56	49.98	5.71	43.35	0.21	0.01	20.18	19.68
Almond shells	17.96	81.10	0.94	49.70	6.30	42.79	0.26	0.01	2<0.01	20.10
Hazelnut shells	19.20	77.00	3.80	46.27	5.96	42.42	1.54	<0.01	18.30	18.33
Almond Prunings	21.54	76.83	1.63	51.30	5.29	40.90	0.66	0.01	20.01	19.87
Orange tree prunings	4.38	80.95	14.67	46.45	5.29	42.76	1.03	0.09	18.08	17.52
Black Walnut Prunings	18.56	80.69	0.78	49.80	5.82	43.25	0.22	0.01	19.83	19.75
Corncoobs	18.54	80.10	1.36	46.58	5.87	45.46	0.47	0.01	18.77	18.44
Wheat Straw	19.80	71.30	8.90	43.20	5.00	39.40	0.61	0.11	17.51	16.71
Cotton Stalk	22.43	70.89	6.68	43.64	5.81	43.87	<0.01	<0.01	18.26	17.40
Corn Stover	19.25	75.17	5.58	43.65	5.56	43.31	0.61	0.01	17.65	17.19
Sugarcane Bagasse	14.95	73.78	11.27	44.80	5.35	39.55	0.38	0.01	17.33	17.61
Rice Hulls	15.80	63.60	20.60	38.30	4.36	35.45	0.83	0.06	14.89	14.40
Pine needles	26.12	72.38	1.50	48.21	6.57	43.72			20.12	20.02

⁴ Sources: phyllis2, biobib database TUW, IEA Bioenergy

Cotton gin trash	15.10	67.30	17.60	39.59	5.26	36.38	2.09	<0.01	16.42	15.85
AQUATIC BIOMASS										
Water Hyacinth (Florida)	-	80.40	19.60	40.30	4.60	33.99	1.51	<0.01	14.86	15.54
Brown Kelp, Giant, Soquel Point	-	57.90	42.10	27.80	3.77	23.69	4.63	1.05	10.75	10.85

The chemical composition of biomass is depending on the type of biomass as well as location of the growth. Table 4 shows typical ranges for the main elements, major and minor, in different biomasses.

The further data regarding chemical composition of clean wood, waste wood, agricultural waste, sludge and manure can be found in attachment.

TABLE 4: ELEMENTAL BIOMASS COMPOSITION (dm [w-%])⁵

C	H	O	N	P	K	Na	S	Ca
40-47	~6	40-44	0.1-5	0.05-0.8	0.3-5	0.02-0.5	0.05-0.8	0.3-5
Si	Mg	B	Cl	Cu	Fe	Mn	Zn	
0.05-3	0.05-1	<0.015-0.01	0.02-1	<0.0102-<0.012	<0.015-0.1	<0.012-0.03	<0.011-0.01	

In addition to clean biomass, in the gasification process waste fractions could be employed as well. In the following figure, exemplary analysis of MSW and RDF can be found.

⁵ Kaltschmitt M., Hartmann H., (2001): Energie aus Biomasse, Springer, Berlin

TABLE 5: CHEMICAL COMPOSITION OF SELECTED WASTE MATERIALS⁶

	MSW, Germany, 2001-2002 ⁷	Average MSW/RDF fuel, Sweden, 2011 ⁸ (42 samples, 6 each from 7 WtE plants in different regions) Average (Min-Max)	RDF imported to Sweden from the UK, 2011-2012 ⁷ (34 samples from 6 WtE plants) Average (Min-Max)
Gross Calorific value (MJ/kg)	7-15	n.a.	n.a.
Net Calorific value (MJ/kg)	6-14.6 est.	11 (8.3-15)	13 (9.7-17)
Water %	15-40	38 (22-48)	32 (17-46)
Ash	20-35	21 (13-40)	(10 4.8-19)
Carbon (% d.s.)	18-40	n.a.	n.a.
Hydrogen (% d.b.)	1-5	n.a.	n.a.
Nitrogen (% d.b.)	0.2-1.5	n.a.	n.a.
Oxygen (% d.b.) by bal.	15-22	n.a.	n.a.
Sulphur (% d.b.)	0.1-0.5	0.37 (0.09-0.86)	0.13 (0.04-0.80)
Fluorine (% d.b.)	0.035-0.1	n.a.	n.a.
Chlorine (% d.b.)	0.1-1	0.78 (0.03-1.4)	0.38 (0.04-2.6)
Bromine (% d.b.)	n.a.	n.a.	n.a.
Iodine (% d.b.)	n.a.	n.a.	n.a.
Potassium (mg/kg d.b.)	n.a.	0.36 (0.17-0.59)	0.25 (0.22-0.29)
Lead (mg/kg d.b.)	100-2 000	n.a.	n.a.
Cadmium (mg/kg d.b.)	1-15	2.3 (0.2-16.0)	0.30 (0.07-0.98)
Copper (mg/kg d.b.)	200-700	n.a.	n.a.
Zinc (mg/kg d.b.)	400-1400	800 (250-1900)	98 (17-480)
Mercury (mg/kg d.b.)	1-5	0.50 (0.12-0.95)	0.14 (0.05-0.50)
Thallium (mg/kg d.b.)	< 0.1	n.a.	n.a.
Manganese (mg/kg d.b.)	250	n.a.	n.a.
Vanadium (mg/kg d.b.)	4-11	n.a.	n.a.
Nickel (mg/kg d.b.)	30-50	n.a.	n.a.
Cobalt (mg/kg d.b.)	3-10	n.a.	n.a.
Arsenic (mg/kg d.b.)	2-5	n.a.	n.a.
Chrome (mg/kg d.b.)	40-200	n.a.	n.a.
Selenium (mg/kg d.b.)	0.2-15	n.a.	n.a.
PCB (mg/kg d.b.)	0.2-0.4	n.a.	n.a.
PCDD/PCDF (ng I-TE/kg)	50-250	n.a.	n.a.

⁶ L. Waldheim: Gasification of waste for energy carriers, A review, IEA Bioenergy Task 33 Special report 2018,

⁷ Integrated Pollution Prevention and Control. Reference Document on the Best Available Techniques for Waste Incineration. European Commission. August 2006

⁸ Bränslekvalitet. - Sammansättning och egenskaper för avfallsbränsle till energiåtervinning. Mattias Bisaillon, Inge Johansson, Frida Jones, Jenny Sahlin. Projektnummer WR-57, 2013. WASTE REFINERY. SP Sveriges Tekniska Forskningsinstitut. Borås, Sweden

TABLE 6: RDF AND SRF ANALYSES FROM PHYLLIS DATABASE⁵

Phyllis 2 Database ³	RDF, 16 samples in total				SRF, 17 samples in total			
	Mean	Min.	Max.	N	Mean	Min.	Max.	N
N denotes number of samples								
Net CV MJ/kg (daf)	21.54	16.13	27.80	16	25.33	18.96	32.46	17
Gross CV MJ/kg (daf)	22.72	17.40	26.57	15	27.10	20.28	34.75	17
Moisture cont. wt.%	13.12	2.82	38.70	10	28.46	1.90	59.00	13
Ash cont. wt.% (dry)	17.47	9.30	27.72	14	8.27	4.90	10.90	7
C wt.% (daf)	52.11	42.50	61.62	16	61.74	51.49	75.56	12
H wt.% (daf)	7.40	5.84	8.91	16	8.42	6.08	10.73	13
N wt.% (daf)	0.85	0.31	1.49	15	0.52	0.10	2.18	17
S wt.% (daf)	0.46	0.12	0.98	14	0.14	0.02	0.42	17
O wt.% (daf)	37.06	24.60	43.73	16	32.47	30.60	35.02	4
Cl mg/kg (daf)	7 265	55.0	14 341	14	0.5	0.5	0.5	1
Br mg/kg (daf)	50.1	50.1	50.1	1	n.a.			0
F mg/kg (daf)	88.2	88.0	88.5	2				
Al mg/kg (dry)	5 201	1 600	7 300	3	n.a.			0
K mg/kg (dry)	1 593	1 364	1 823	2				
Na mg/kg (dry)	2 772	2 590	2 955	2	n.a.			0
Ca mg/kg (dry)	23 915	21 936	25 895	2				
Si mg/kg (dry)	18 272	9 641	26 903	2	n.a.			0
Mg mg/kg (dry)	1 688	1 410	1 966	2				
Fe mg/kg (dry)	2 477	768	4 689	3	n.a.			0
P mg/kg (dry)	379	279	480	2				
Ti mg/kg (dry)	1 359	1 063	1 654	2	n.a.			0
As mg/kg (dry)	6.4	5.0	9.0	3				
Cd mg/kg (dry)	1.9	0.8	3.0	2	n.a.			0
Co mg/kg (dry)	5.6	4.2	7.0	2				
Cr mg/kg (dry)	168.4	8.0	429.0	3	n.a.			0
Cu mg/kg (dry)	386.0	35.0	610.0	3				
Mn mg/kg (dry)	83.2	57.0	126.0	3	n.a.			0
Ni mg/kg (dry)	100.3	2.0	266.0	3				
Pb mg/kg (dry)	134.4	50.0	260.0	3	n.a.			0
V mg/kg (dry)	4.7	3.1	7.0	3				
Zn mg/kg (dry)	232.1	85.0	393.0	3	n.a.			0
Ba mg/kg (dry)	341.7	142.4	541.0	2				
Mo mg/kg (dry)	9.2	1.4	17.0	2	n.a.			0
Se mg/kg (dry)	0.3	0.3	0.3	1				
Hg mg/kg (dry)	0.2	0.2	0.2	1	n.a.			0
Sn mg/kg (dry)	20.1	17.0	23.1	2				
Sr mg/kg (dry)	103.3	63.5	143.0	2	n.a.			0
B mg/kg (dry)	63.1	44.2	82.0	2				
Sb mg/kg (dry)	45.0	29.0	61.0	2	n.a.			0

1.3 Feedstock - limiting factors for gasification

1.3.1 Categories and quantification

Before entering into the conversion reactor, the feedstock must be adjusted to the feeding system and conversion conditions. This means size adjustment, removal of undesirable impurities, such as stones or metals, which derive from the biomass harvesting or from waste materials (e.g. demolition wood). For some processes, such as entrained flow gasification, thermal pre-treatment such as pyrolysis is necessary because the feedstocks have to enter the reaction chamber very finely due to low residence times.

1.3.2 Feedstock moisture

The moisture content of biomass or waste varies enormously depending on its type. It ranges from below 15% in cereals straw to more than 90% as in algae biomass.⁹ The moisture content is a critical parameter when using biomass or waste for thermochemical conversion processes since it has a marked effect on the conversion efficiency and heating value, which can be circumvented by pre-drying the material before feeding to the reactor. Moreover, high moisture content entails logistic issues since it increases the tendency to degrade, resulting in energy loss during storage¹⁰ and reduces the energy and cost balances.

The moisture content has a strong effect on the efficiency of the process. Drying the material upfront and using steam for the conversion helps to reach high conversion efficiencies. To reduce the moisture content of the feedstock, different processes could be applied.¹¹ However there are more parameters affecting the efficiency of the process, such as feedstock composition, reactor type and operation conditions.

1.3.3 Chemical composition

Chemical composition of the feedstock is one of the most important parameters for thermochemical conversion processes. In the chapter "Feedstock qualification and limiting factors for gasification" the chemical composition of some types of feedstock can be found. This chapter deals with the effect of the main constituents of the feedstock.

The behaviour of elements during thermochemical conversions, respective their distribution into gas, liquid and solid phase after the conversion process is a complex process which is influenced by many factors. Such factors are: conversion temperature, pressure, heating rate, equivalent ratio, oxidizing agent (air, oxygen, steam...), moisture of the fuel, particle size, fuel composition, residence time of the fuel particle in the conversion unit etc.

The most important step in the elements behaviour is the release of volatiles. The conditions of the devolatilization influence largely the distribution of each element in the gas, solid or liquid phase.

⁹ J. Sanchez et al, The Role of Bioenergy in the Emerging Bioeconomy Resources, Technologies, Sustainability and Policy Book • 2019

¹⁰ S. Dumfort, C. Kirchmair, K. Floerl, C. Larch, M. Rupprich, Storage as the Weak Link of the Biomass Supply Chain. In: Mpholo M., Steuerwald D., Kukeera T. (eds) Africa-EU Renewable Energy Research and Innovation Symposium 2018 (RERIS 2018). RERIS 2018. Springer Proceedings in Energy. Springer, Cham, 2018.

¹¹ Ho Ting Luk, Tsz Ying Gene Lam, Adetoyese Olajire Oyedun, Tesfaldet Gebreegziabher, Chi Wai Hui, Drying of biomass for power generation: A case study on power generation from empty fruit bunch, Energy, Volume 63, 2013, Pages 205-215, ISSN 0360-5442, <https://doi.org/10.1016/j.energy.2013.10.056>. (<https://www.sciencedirect.com/science/article/pii/S0360544213009080>)

Carbon and hydrogen

During the gasification process, the process conditions and the content of carbon and hydrogen influence the amount of CO and H₂ in the gas being produced, which are important components if synthesis is foreseen. However, biomass or waste consist not only of carbon and hydrogen, but other components, which affect the conversion process.

Nitrogen

The concentration of nitrogen varies widely with the biomass type. While nitrogen content of wood may be very low (much less than 1 wt-%), the nitrogen content in sewage sludge may be up to 8-9 w-%.

During gasification, feedstock nitrogen is mainly converted into NH₃, HCN and N₂. Some nitrogen ends up in waste streams, such as aromatic tar components (pyridine) and in solid char. Independent of the type of gasified feedstock, more NH₃ is formed than other nitrogen containing compounds in most gasifiers. The measured amount of NH₃ in the gas phase during the gasification seems to be dependent on the nitrogen content in biomass. Waste streams containing plywood, with polyurethane glues, will produce larger quantities of cyanide. So there is also a relation to the origin of the nitrogen to the type of gas phase molecules that are produced. Typically, nitrogen components need to be removed in order to use the gas in catalytic applications.

Sulphur

Sulphur is a particular troublesome component. First it can cause corrosion problems within the gasifier or downstream if not treated correctly. For catalytic applications it is a component recognized for catalysts deactivation. Sulphur content in untreated woody biomass is negligible (< 0.1 wt-%), however in waste wood or sewage sludge it increases drastically (up to 3 wt%), as well as manure (2-3 wt%¹²) and some other feedstocks. Sulphur from the feedstock is also distributed over various phases (gas, tars and char). Most of the sulphur will end up in the gas phase as H₂S and COS and can easily be removed, however the tar-like molecules (thiophene etc) are more difficult to remove and need special care in order to protect catalytic downstream processes.

Chlorine

Chlorine content in biomass typically varies between <0.015 wt-% (wood) and 1.5 wt-% (maize). The chlorine content in biomass can be influenced by closeness of the sea, fertilizers and leaching by the rain. The distribution of chlorine between gas, liquid and solid phase during the biomass conversion processes is dependent on the pressure and the temperature.

About 90% of chlorine, which is in the biomass mostly bond as KCl (especially grass) is water soluble. Chlorine releases from biomass in the form of HCl or bond with potassium as KCl or sodium as NaCl, although KCl forms easily during gasification in the presence of potassium, there is a specific conditions that makes the formation of KCl impossible.¹³ Chlorine is known to play an important role in agglomeration in fluidized bed due to ash interaction or corrosion when KCl is formed and deposited downstream. Dealing with chlorine is not too difficult, adding getter materials in the reactor can help mitigate the risks and when HCl is formed, this can be easily removed via water scrubbers.

Alkali metals

Alkali metals are bound in biomass organically and inorganically in form of salts such as chlorides, sulphates or hydroxides. In biomass, potassium is found especially in the fast growing parts of trees, in the straw,

¹² Wang, Yue et al. "The Characteristics of Carbon, Nitrogen and Sulfur Transformation During Cattle Manure Composting-Based on Different Aeration Strategies." *International journal of environmental research and public health* vol. 16,20 3930. 16 Oct. 2019, doi:10.3390/ijerph16203930

¹³ Kuramochi, H., Wu, W., Kawamoto, K., (2005): Prediction of the behaviours of H₂S and HCl during gasification of selected residual biomass fuels by equilibrium calculation; *Fuel*, 84 (4), 377-387

grass and in corn hulls. Much of this alkali is present in water-soluble or ion-exchangeable forms.

Alkali compound emissions during thermochemical conversion of biomass cause problems such as agglomeration, slagging (formation of sintered deposits on the heat transfer surfaces or refractories subjected to radiative heat transfer), fouling (deposition of ash on the convective heat transfer section of the steam generator at temperatures below the melting point of the ash) and metal corrosion in the conversion process systems. Understanding the behaviour of alkali metals emissions from biomass fuels is very important for solving these problems.

In the table below, alkali metals concentration in different feedstock materials can be seen. It is obvious, that alkali metals concentration in straw is much higher than in clean wood or even waste materials, this therefore explains why straw and also other agricultural waste are considered as a problematic feedstock, e.g. for fluidized bed gasification. Further it can be seen in the table, that potassium content is significantly higher than that of sodium. That is the reason, why potassium content is mostly in focus regarding fouling and slagging problems.

Potassium releases to the gas phase in two stages. The first stage is at temperature range of 200°C to 500°C. The potassium release at lower temperatures can be well coupled to biomass devolatilization and insensitive to the chlorine content in the biomass. In this first stage the organic bond potassium releases following the devolatilization of the biomass constituents, cellulose, hemicellulose and lignin. In the second stage at temperatures above 500°C, the potassium releases at full speed, depending on chlorine presence in the fuel. In this stage, potassium releases mostly in form of KCl and KOH.

TABLE 7: ALKALI METALS CONCENTRATION IN SELECTED FEEDSTOCK¹⁴

		Coal	Lignite	Peat	Wood saw dust	Straw	RDF	Sew. sludge
Na	mg/kg, dry	100-1500	100-300	400	40	100-5000	3000-5000	2000
K	mg/kg, dry	50-3000	100-1000	700	300-500	5000-10000	2000-3000	6000

The effect of alkali metals on the gasification process is described in several publications¹⁵, where the effects of alkali and alkaline earth metals (AAEM) on the component and distribution of products, gasification reactivity, catalytic mechanism and char-ash/slag transition during biomass gasification are reviewed.

Typically the limit for alkali metals compounds in the product gas entering the combustion chamber is of the order of 0.1 ppmw¹⁶ or even less.

There are two possibilities of removal of alkali metals from gas phase: to lower the gas temperature or use of alkali sorbents (e.g. emathlite, kaolinite, bauxitic kaolinite, attapulgitite or Ca-montmorillonite).

Anyway, it should be also mentioned here, that alkali metals can have also positive influence on gasification

¹⁴ Zevenhoven, Kilpinen, (2001): Chapter 8, Trace elements and alkali metals, <http://www.abo.fi/~rzevenho/tracalk.PDF>

¹⁵ Junqin Yu, Qinghua Guo, Yan Gong, Lu Ding, Jiajian Wang, Guangsu Yu, A review of the effects of alkali and alkaline earth metal species on biomass gasification, Fuel Processing Technology, Volume 214, 2021, 106723, ISSN 0378-3820

¹⁶ Kurkela, E., Ståhlberg, P., Laatikainen, J., (1995): Part 2. Experiences from peat and coal gasification and hot gas filtration, 249, VTT Publications

process, e.g. in entrained-flow gasifiers with liquid slag removal they make it possible to lower the gasification temperature and thus increase efficiency. Furthermore, the impregnation of biomass with alkali metals results in increased gasification reaction rates and consequently reduced tar and soot formations.¹⁷

Trace elements

Trace elements are those ones; which average concentration is less than 100 ppm or less than 100 µg/g.

For thermal gasification following trace elements are of relevance:

As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Sn, Tl and V. Emissions of these elements are regulated for waste incinerators and cement plants.

The following table offers an overview on trace elements concentrations in different feedstock, such as fossil fuels, wood and waste materials.

As can be seen in Table 5, wood is a relatively “clean” fuel regarding trace elements, but treated wood, which is e.g. covered with protecting coat of chromated copper arsenate (CCA wood) contains ~ 15 ppmw of Cr, ~ 5 ppmw of Cu and ~ 10ppmw of As. Sewage sludge is a rather “dirty” fuel, with trace elements concentrations higher than coal or RDF.

Many factors influence whether and in what form a trace element will be found in the gaseous or the solid phase. The most important factors are:

- how the trace element is bond in fuel
- temperature and pressure during the conversion process (coupled with boiling point)
- oxidizing or reducing conditions
- the presence of halogens, most important is the presence of chlorine
- the presence of compounds that can act as sorbents, e.g. calcium

¹⁷ Kirtania, K., Axelsson, J., Matsakas, L., Christakopoulos, P., Umeki, K., Furusjö, E., 2016. Kinetic study of catalytic gasification of wood char impregnated with different alkali salts. Energy 1-11. <http://dx.doi.org/10.1016/j.energy.2016.10.134>.

TABLE 8: TRACE ELEMENTS CONCENTRATIONS IN SELECTED FEEDSTOCK¹⁸

	mg/kg, dry	Coal	Peat	MSW	RDF	Wood	Waste wood	Waste paper	Sew. sludge
Hg	mg/kg, dry	0.02-3	~ 0,07	< 15	1-10	0.01-0.2	n.d.	~ 0.08	0.5-10
As	mg/kg, dry	0.5-10	1-3	0.5-500	~ 3	~ 0.2	n.d.	n.d.	0.1-100
B	mg/kg, dry	5-100	n.d.	< 0.5	n.d.	n.d.	n.d.	~ 0.5	n.d.
Be	mg/kg, dry	0.1-10	~ 0.1	1-40	~ 1	n.d.	n.d.	~ 0.8	n.d.
Cd	mg/kg, dry	0.05-10	n.d.	< 100	1-10	n.d.	~ 0,5	~ 0.7	1-10
Co	mg/kg, dry	0.5-20	1-2	< 20	n.d.	~ 0.1	n.d.		~ 5
Cr	mg/kg, dry	0.5-60	0.5-2	< 1500	50-250	~ 1	1-4	~ 6	~ 100
Cu	mg/kg, dry	5-60	~ 10	< 2500	< 1000	0.5-3	~ 15	~ 18	200-700
Mn	mg/kg, dry	5-300	30-100	< 1000	~ 250	10-1000	n.d.	~ 27	~ 200
Ni	mg/kg, dry	0.5-100	5-10	< 5000	10-100	~ 0.5	< 20	~ 7	~ 50
Pb	mg/kg, dry	1-300	1-5	< 2500	100-500	1-20	< 50	~ 8	100-300
Sb	mg/kg, dry	<1	n.d.	< 80	< 5	n.d.	n.d.	~ 5	100-500
Se	mg/kg, dry	0-3	~ 1	< 10	3-6	~ 0.2	n.d.	~ 0.08	n.d.
Sn	mg/kg, dry	<10	n.d.	3-10	~ 500	n.d.	n.d.	~ 8	n.d.
Tl	mg/kg, dry	~1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
V	mg/kg, dry	1-100	5-50	n.d.	n.d.	~ 2	n.d.	n.d.	n.d.
Zn	mg/kg, dry	1-1000	~ 20	~ 2 w-%	300-800	5-150	< 30	~ 150	~ 1000

¹⁸ Zevenhoven, Kilpinen, (2001): Chapter 8, Trace elements and alkali metals, <http://www.abo.fi/~rzevenho/tracalk.PDF>

1.3.4 Tars

During the gasification process, tars are formed and are part of the producer gas. Tars are defined as aromatic hydrocarbons, larger than benzene and toluene, it means all organic compounds present in the gasification producer gas excluding gaseous hydrocarbons (C1 through C6)", according to CEN/TS 15439, 2006. They contain also hetero-atoms such as sulphur (thiophene), nitrogen (pyridine), oxygen (phenol) or chlorine (dioxines). They typically cause problems in the cooling trajectory of the product gas, due to deposition on cold surfaces.

For the tar classification various ways are accessible, for instance the division in primary, secondary and tertiary tar¹⁹. Primary tar emerges from the pyrolysis process. The three main components of wood (i.e. cellulose, hemicellulose and lignin) can be identified as source for the primary tar. Cellulose and hemicellulose, which contain a lot of oxygen, form mainly oxygen rich primary tar products like alcohols, ketons, aldehydes or carbon acids. On the contrary bi- and trifunctional monoaromatics, mostly substituted phenols, occur from lignin. Verifiable substances are e.g. phenol, dimethylphenol and cresol. The formation temperature for those primary tars lies between 200° - 500° C.

Due to increasing temperature and presence of an oxidant (oxygen, air or steam) a part of the cellulose contributed primary tars react to small gaseous molecules. The residual primary tars form secondary tar, which are composed of alkylated mono- and diaromatics including heteroaromatics like pyridine, furan, dioxin and thiophene. Over 800° C tertiary tar can be found. Tertiary tars are also called recombination or high temperature tars. Typical tertiary tars are benzene, naphthalene, phenanthrene, pyrene, and benzopyrene (polynuclear aromatic hydrocarbons PAH).

1.3.5 Heating value

The heating value of a biomass feedstock represents the energy amount per unit mass or volume released on complete combustion. The heating value is referenced in two different ways, the higher (or gross) heating value (HHV) and lower (or net) heating value (LHV). The HHV includes the latent heat contained in the water vapour that in practice cannot be used effectively, while the LHV excludes the heat of evaporation of the water formed from the hydrogen contained in the biomass feedstock and its moisture content. Thus, the LHV is the appropriate value to assess the energy available for subsequent use.

LHV of the feedstock is an important parameter regarding the product gas LHV, it means from feedstock with low LHV, e.g. fermented sewage sludge (LHV about 10 MJ/kg), no product gas with high LHV could be achieved through gasification process.

HHV and LHV of fuels can be calculated based on their content of carbon, hydrogen, nitrogen, sulphur, oxygen and water (in mass-%)²⁰.

$$\text{HHV} = (34.0 \cdot m(\text{C}) + 124.3 \cdot m(\text{H}) + 6.3 \cdot m(\text{N}) + 19.1 \cdot m(\text{S}) - 9.8 \cdot m(\text{O})) \quad [\text{MJ/kg}]$$

$$\text{LHV} = (34.0 \cdot m(\text{C}) + 101.6 \cdot m(\text{H}) + 6.3 \cdot m(\text{N}) + 19.1 \cdot m(\text{S}) - 9.8 \cdot m(\text{O}) - 2.5 \cdot m(\text{H}_2\text{O})) \quad [\text{MJ/kg}]$$

It is obvious, that carbon, hydrogen, nitrogen and sulphur content increase the heating values and oxygen and moisture content decrease it. HHV and LHV of product gas can be calculated based on hydrogen, CO, H₂ and C_xH_y (as molar fractions).

¹⁹ I. Aigner, U. Wolfesberger, H. Hofbauer: Tar Content and Composition in Producer Gas of Fluidized Bed Gasification and Low Temperature Pyrolysis of Straw and Wood - Influence of Temperature, https://www.best-research.eu/files/publications/pdf/PubDat_177839.pdf

²⁰ <https://www.chemie-schule.de/KnowHow/Heizwert>

$$\text{HHV} = (282.98 \cdot n(\text{CO}) + 285.83 \cdot n(\text{H}_2) + 890.63 \cdot n(\text{CH}_4) + 1411.18 \cdot n(\text{C}_2\text{H}_4) + 1560.69 \cdot m(\text{C}_2\text{H}_6) + 2058.02 \cdot n(\text{C}_3\text{H}_6) + 2219.17 \cdot n(\text{C}_3\text{H}_8) + 2877.40 \cdot n(\text{C}_4\text{H}_{10}))$$

[kJ/mol]

$$\text{LHV} = (282.98 \cdot n(\text{CO}) + 241.81 \cdot n(\text{H}_2) + 802.60 \cdot n(\text{CH}_4) + 1323.15 \cdot n(\text{C}_2\text{H}_4) + 1428.64 \cdot m(\text{C}_2\text{H}_6) + 1925.97 \cdot n(\text{C}_3\text{H}_6) + 2043.11 \cdot n(\text{C}_3\text{H}_8) + 2657.32 \cdot n(\text{C}_4\text{H}_{10}))$$

[kJ/mol]

HHV and LHV of gaseous components from product gas were determined by different institutions and companies, details can be seen in the next table.

TABLE 9: CALORIFIC VALUES IN MJ/Nm³ ²¹

Component	H2	CO	CH4	C2H6	C2H4	C2H2	Company
HHV	12.745	12.633	39.819	70.293	63.414		TU Wien
	12.769	12.622	39.781	69.693	63	58.059	NREL
	12.753	12.626	39.721	69.595	62.952		ECN
	12.766	12.641	39.847	70.402	63.998	58.975	DMT
	12.761	12.634	39.747	69.636	62.989	58.039	Carbona
	12.76	12.617	39.663	69.511	63.042	57.934	Univ. Sherbrook
	12.758	12.631	39.739				Vattenfall
	12.761	12.634	39.75	69.642	62.994	58.022	Nykomb
LHV	10.783	12.633	35.883	64.345	59.457		TU Wien
	10.788	12.622	35.814	63.748	59.036	56.078	NREL
	10.789	12.626	35.796	63.704	59.024		ECN
	10.8	12.6	35.8	63.71		56.03	Verenum
	10.757	12.641	35.787	64.333	59.938	56.924	DMT
	10.748	12.634	35.725	63.605	59.011	56.028	Carbona
	10.793		35.81				Vattenfall
	10.8	12.634	35.823	63.756	59.07	56.06	Nykomb
	10.797	12.635	35.821	63.749	59.068		TPS
	10.789	12.630	35.812	63.744	59.033	56.088	Bioelettrica
Component	C3H8	C3H6	i-C4H8	i-C4H10	n-C4H10	C6H6	Company
HHV	101.242	93.576	125.088	133.119	134.061		TU Wien
	99.091	91.879				142.893	NREL
						147.299	ECN
	101.794	94.343	121.843	131.972	133.981	146.329	DMT
	99.108	91.894		128.502		147.385	Carbona
	98.244					147.143	Univ. Sherbrook
	99.116	91.902	120.696	128.207	128.513	147.398	Nykomb
	LHV	93.215	87.575	116.934	122.91	123.81	
91.163		85.934				141.41	NREL
						141.408	ECN
93.548		88.191	113.806	121.592	123.517	140.301	DMT
91.066		85.862		118.449		141.352	Carbona
91.268		86.016	112.848	118.703	118.703	141.512	Nykomb
91.164		85.925	113.371	117.668	118.569	159.502	Bioelettrica
Component		NH3	H2S				
HHV	13.072	25.105					ECN
		25.07					Kvaerner
	17.245	25.7					DMT
	17.094	25.123					Carbona
		25.096					Nykomb
LHV	10.128	23.142					ECN
		23.12					Kvaerner
	14.189	23.69					DMT
	14.079	23.134					Carbona
	14.132	23.152					TPS
	14.136	23.113					Bioelettrica

²¹ L. Waldheim, T. Nilsson: Heating value of gases from biomass gasification, Report for IEA Bioenergy Agreement, 2001

1.3.6 Moisture content and LHV

LHV is depending not only on the feedstock composition, but also on its moisture content. The effect of moisture content of wood and its LHV was studied by EUBIA. In the figure below the decreasing LHV with increasing moisture content is displayed.

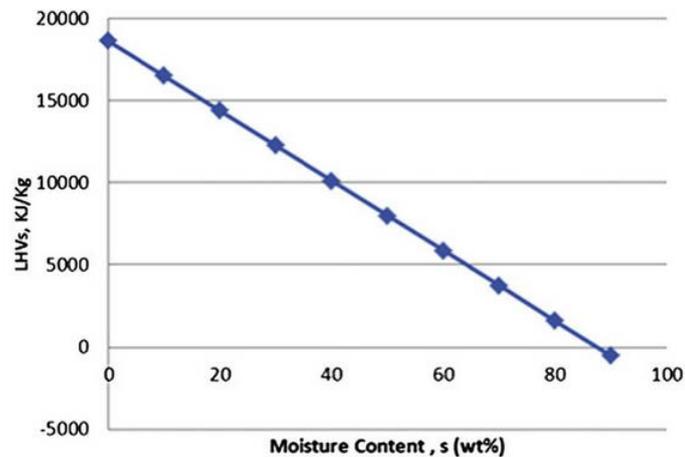


FIGURE 2: LHV_s VERSUS MOISTURE CONTENT OF WOOD²²

When organic waste or biomass are directly used for energy, e.g. combustion or gasification, the LHV is one of the most distinctive properties. If the LHV is higher than 5-6 MJ/kg fresh matter, waste or biomass are combustible without additional fuel.²³

LHVs of different waste materials are displayed in the following figure.

²² EUBIA. European Biomass Industry Association. <http://www.eubia.org/115.0.html>.
https://www.researchgate.net/publication/257177200_Optimum_biomass_drying_for_combustion_-_A_modeling_approach/figures?lo=1

²³ L. Laible et al.: Organic waste for heat and power production - status quo and potential in German energy supply, Conference: World Renewable Energy Congress VII, Proceedings, Ed. Sayigh, 5pp. At: Cologne, Germany, 2002
https://www.researchgate.net/publication/272679020_Organic_waste_for_heat_and_power_production_-_status_quo_and_potential_in_German_energy_supply/figures?lo=1

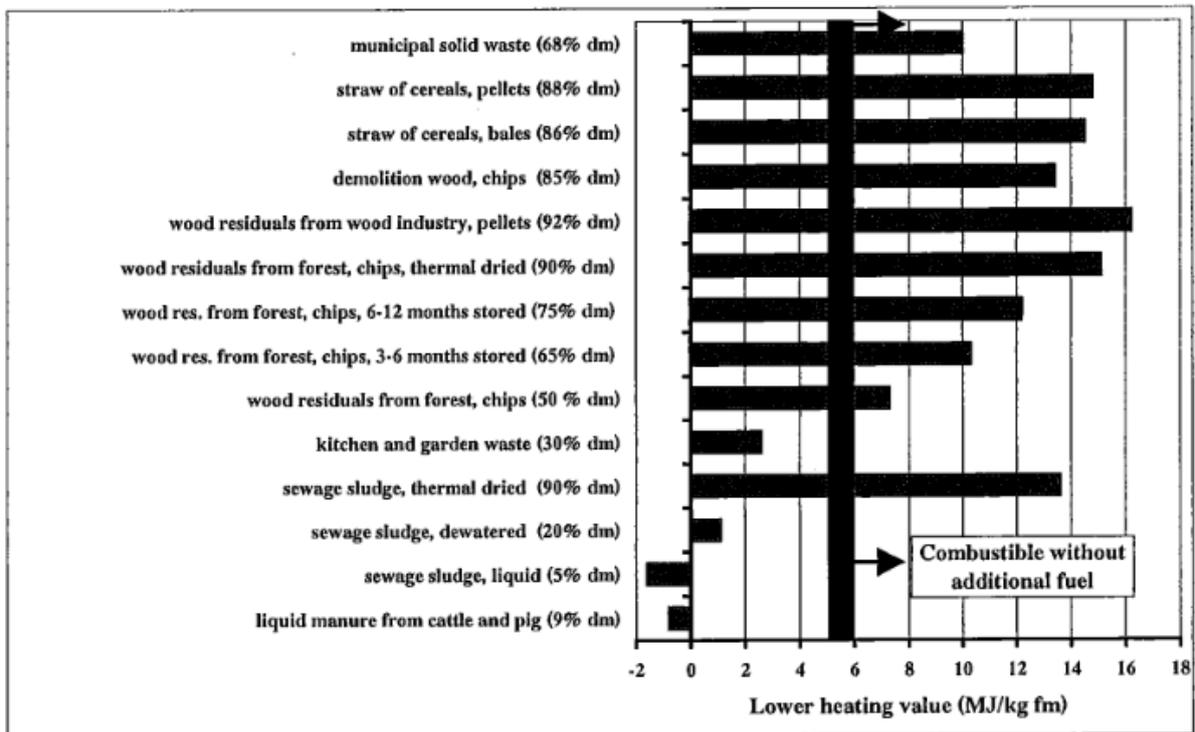


FIGURE 3 LOWER HEATING VALUE OF ORGANIC WASTES DEPENDING ON DRY MATTER CONTENT (DM)²⁴

1.3.7 Ash content

Also ash content and composition of the feedstock should be taken into account by choice of the conversion reactor type. Generally, it could be stated out that the ash content of woody biomass without bark is very low (lower than 1 wt-%), on the other hand, bark and agricultural residues contain between 2-7 wt-% of ash, waste materials such as sewage sludge even more than 10 wt-%.

Major ash forming elements (Al, Ca, Fe, K, Mg, Na, P, Si) are of relevance for the ash melting behaviour and deposit formation.

Volatile ash forming elements such as Cl, S, Na, K, As, Cd, Hg, Pb, Zn play a major role regarding gaseous and especially aerosol emissions as well as concerning deposit formation, corrosion and ash utilisation/disposal²⁵.

In the following table, the ash content of wood and agricultural biomass is displayed.

²⁴ L. Leible, A. Arlt, S. Kälber, E. Nieke, D. Wintzer, B. Fürniss: Organic waste for heat and power production - Status quo and potential in German energy supply, Conference paper, World Energy Congress VII, 2002

²⁵ F. Biedermann, I. Obernberger: Ash-related Problems during Biomass Combustion and Possibilities for a Sustainable Ash Utilisation

TABLE 10: ASH CONTENT OF DIFFERENT TYPES OF BIOMASS

Biomass type	Ash content [wt%, d.b.]
Wood without bark	0.3
Bark	4.0 - 5.0
Logging residues	1.5 - 2.0
Short rotation coppice Willow	2.0
Straw from wheat, rye, barley	5.0
Straw from oilseed rape	5.0
Grains from wheat, rye, barley	2.0
Miscanthus	4.0
Virgin reed canary grass	6.4
Grass in general	7.0

1.3.8 Ash melting behaviour

It is known that K and Na, in the presence of Cl, S, and Si, undergo chemical and physical transformations, forming low-melting-temperature alkali silicates in the bottom ash and also alkali sulphates and chlorides in the fly ash, resulting in a deposit formation on the heat transfer surfaces of the conversion reactor. Even relatively small amounts of K and Na can cause sintering or slag formation in the conversion reactor, which reduces plant availability and its lifetime. Chlorides and low melting alkali- and alumina silicates may also significantly decrease the ash melting point.

Based on the knowledge of the $\text{SiO}_2\text{-CaO-K}_2\text{O}$ system the fusibility tendencies can be predicted. Phase equilibria and liquid phase behaviour of the $\text{K}_2\text{O-CaO-SiO}_2$ system for entrained flow biomass gasification was studied by Santoso et al.²⁶ Combining the phase equilibrium data with calculated viscosity of $\text{K}_2\text{O-CaO-SiO}_2$ slags, it can be used for proposing slag compositions preferable to be used in entrained flow biomass gasifiers with minimal operational challenges related to the ash and slag flow, thus maximizing the efficiency and availability of the gasifier.

On the other hand, elements increasing the ash melting temperature are Ca and Mg, thus these elements are often used as additives²⁷ or as a part of bed materials to increase the melting temperature.

²⁶ I. Santoso, P. Taskinen, A. Jokilaakso, M. PaekD. Lindberg, Phase equilibria and liquid phase behavior of the $\text{K}_2\text{O-CaO-SiO}_2$ system for entrained flow biomass gasification, Fuel, DOI:10.1016/j.fuel.2019.116894

²⁷ J. Hrbek, C. Oberndorfer, P. Zanzinger, C. Pfeifer: Influence of Ca(OH)_2 on ash melting behaviour of woody biomass, Carbon Resources Conversion 4 (2021), 84-88

2. TYPES OF GASIFICATION FACILITIES BASED ON THEIR CONSTRUCTION

According to the design of the fuel bed, the gasifiers can be divided into fixed bed, fluidized bed and entrained flow. The main differences in the design of the gasification reactor you can see in the figure below. This is just exemplary, since many variations can be found in literature.

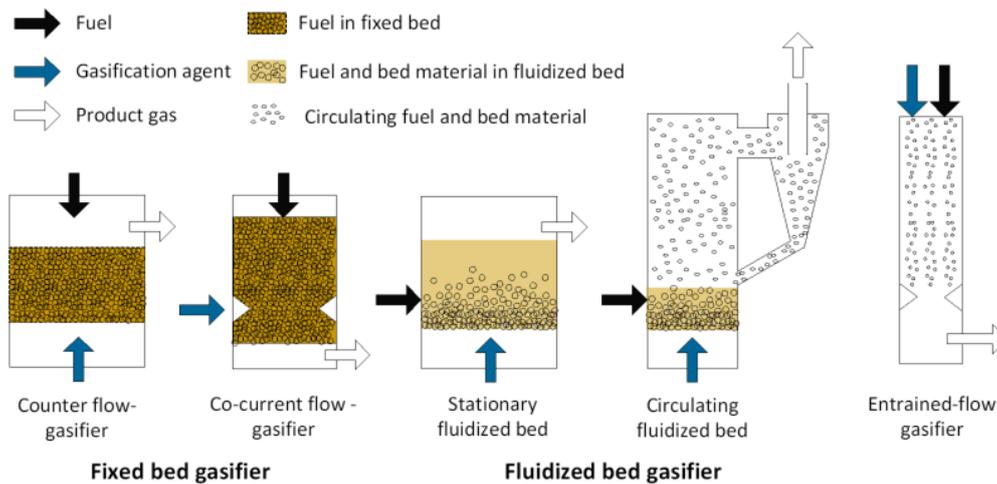


FIGURE 4: TYPES OF GASIFICATION REACTORS

2.1 Fixed bed gasifiers

Fixed-bed gasifiers are the oldest and most commonly employed reactors for the gasification of biomass feedstock on account of their simple design, ease of operation, high thermal efficiency along with minimum pre-treatment of raw materials. In commercial markets, these gasifiers are considered as the first choice for small-scale gasification plants of less than 10 MWth for local power and heat generation.

Fixed bed gasifiers can be divided into:

- Updraft (counter flow)
- Downdraft (co-current flow)
- Floating fixed bed
- Cross-flow

Fixed bed gasifiers require mechanically stable fuel of smaller particle size (1-5 cm), such as pellets or wood chips to ensure free and easy passage of gas through the bed. Depending on the direction of flow of the feedstock and the gas, these gasifiers are classified as updraft and downdraft gasifiers. A special case is a floating fixed bed gasifier or a cross-flow gasifier.

In **updraft fixed bed gasifiers**, the fuel is fed from the top while air is blown into the bottom of the reactor. It is more robust than other fixed bed gasifiers because it is less sensitive to variations in size and quality of biomass. This arrangement can withstand biomass of higher moisture content (up to 40-50 wt-%) as well as higher ash content (up to 15 wt-%). This is because the hot gas exiting the gasifier initiates the combustion process by drying and pyrolyzing the fuel as it moves down the gasifier until finally undergoing gasification and combustion at the bottom. The ash is removed from the bottom of the conversion chamber. The product gas is generally used for heat and power generation and not applicable for synthetic fuels and chemicals,

due to the higher amount of tars (50-100 g/Nm³)²⁸ contained in it.

In **downdraft fixed bed gasifiers**, the fuel is fed in from the top while oxidizing agent is introduced at the sides above the grate and combustible gas blown through the grate. The setup is very simple and of low cost. The gas produced is relatively clean compared with that produced in updraft fixed bed gasifiers and contains significantly lower amounts of tars. The gasifier can handle uniformly sized biomass fuels having moisture content of 20 wt-% and ash content about 5 wt-% respectively.

Also **staged gasification** process should be mentioned here. Talking about staged gasification, two or three step process is mentioned: drying, pyrolysis and gasification. Each process takes place in different reactor.

Almost two step process is applied, it means pyrolysis and gasification. In the following figure, the difference of staged fixed-bed and staged floating-fixed-bed gasifiers are visible.

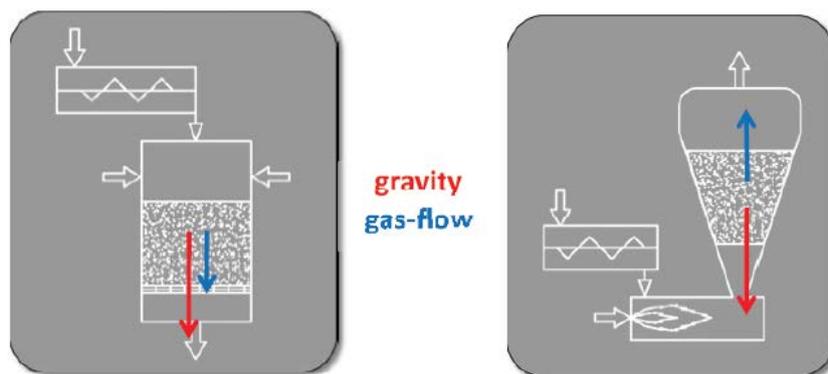


FIGURE 5: STAGED FIXED BED AND STAGED FLOATING FIXED BED GASIFIERS²⁹

²⁸ S. Chopra, A. Kr Jain: A Review of Fixed Bed Gasification Systems for Biomass, Agricultural Engineering International: the CIGR Ejournal. Invited Overview No. 5. Vol. IX. April, 2007
https://www.researchgate.net/publication/228668672_A_review_of_fixed_bed_gasification_systems_for_biomass

²⁹ M. Huber, M. Huemer, A. Hofmann, S. Dumfort: Floating-fixed-bed-gasification: from vision to reality
https://www.researchgate.net/publication/308739028_Floating-fixed-bed-gasification_From_Vision_to_Reality

2.2 Fluidized bed gasifiers

Fluidized bed gasifier (FBG) consists of one or two vessels in which the gasifying agent is introduced from the bottom at a velocity fast enough (0.5-1.0 m/s) to agitate the bed material which sits at the lower part of the gasifier or even higher (> 2 m/s) if the bed material is moved between those two vessels (gasification and combustion zones).

In the case of FBGs, fluidization provides a uniform temperature distribution which helps to increase carbon conversion efficiency and production of gas with high heating value. However, issues that need to be kept in mind when designing a FBG is the carbon conversion and tar formation. FBGs are easy to scale up and operate with feedstock of different types and sizes³⁰.

Fluidized bed gasifiers have following sub-categories:

- Stationary or bubbling bed gasifiers
- Dual fluidized bed gasifiers
- Circulating fluidized bed

2.2.1 Bubbling fluidized bed gasifiers

This type of gasifiers could be applied to small, medium or even large scale gasification processes. Feedstock is fed from the side into or immediately over the hot bed, where devolatilization takes place. Char particles and volatiles (tar precursors) are gasified and cracked by contact with the hot fluidized bed. The gasifying agent can be supplied in two different zones. The first zone is within the fluidized bed in order to mix and distribute the feedstock over the bed allowing a good temperature control. The second zone is located above the bed and it aims to convert entrained unconverted volatiles and char particles into fuel gas.

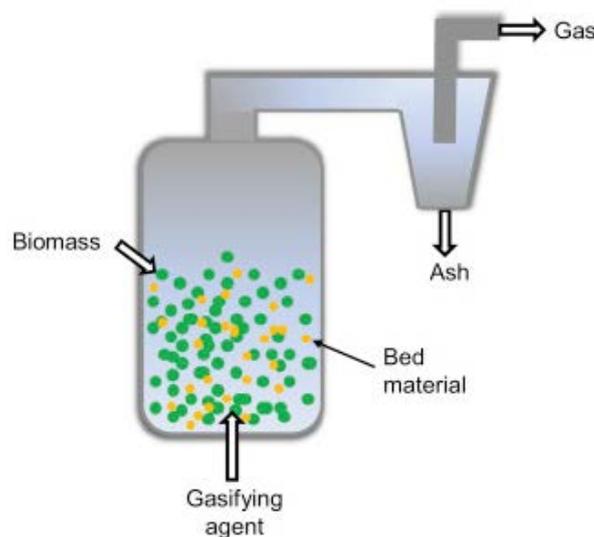


FIGURE 6: BUBBLING FLUIDIZED BED REACTOR³¹

The advantage of the BFB is good heat transfer due to mixing the feedstock with a hot bed material as well

³⁰ Warnecke R. Gasification of biomass : comparison of fixed bed and fluidized bed gasifier. Biomass and Bioenergy. 2000;18:489-97.

³¹ J.M. Bermudez, B. Fidalgo: Production of bio-syngas and bio-hydrogen via gasification, in Handbook of Biofuels Production (Second Edition), 2016

as scalability, on the other hand the disadvantage is the ash melting behaviour of some biomass ashes, such as grasses, straw etc., causing slugging and fouling and thus immobilization of the bed material. The resulting agglomerates avoid proper mixing and fluidization inside the reactor. This could be mitigated by using a proper bed material, lower bed temperatures or with the use of additives.

2.2.2 Dual fluidized bed gasifiers / circulating fluidized bed gasifiers

A DFB gasifier consists of two fluidized beds, which are connected to each other: a bubbling fluidized bed (BFB), where the gasification takes place and a circulating fluidized bed (CFB) or fast fluidized bed (FFB), where the residual char from gasification process is combusted. These reactors can also be operated inversely by gasifying in the FFB and combusting in the BFB. The two fluidized beds are controlled separately, but interconnected using e.g. loop seal valve to ensure the circulation of bed materials (heat carrier) between the beds. A nice review on biomass gasification using dual fluidized bed gasification systems was written by N. Hanchate, 2021, here also various configurations and designs of DFB gasifiers can be found.

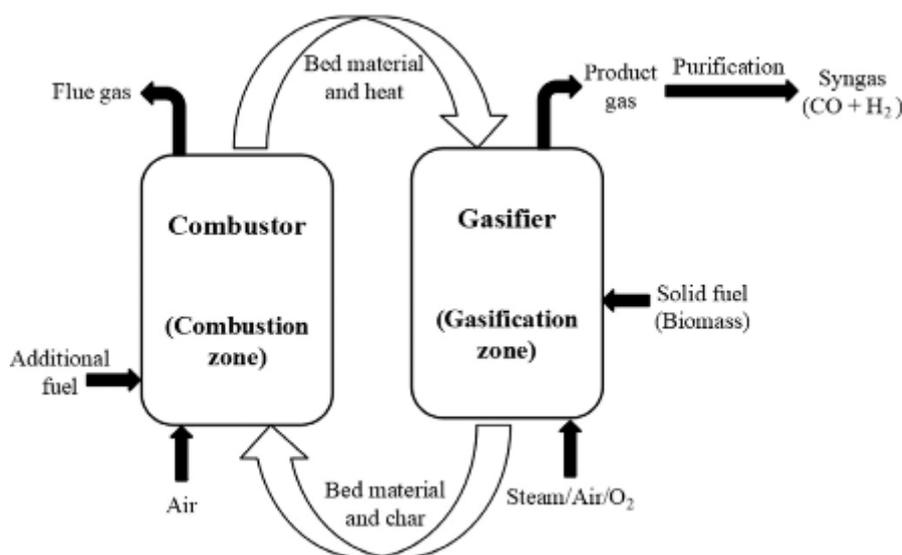


FIGURE 7: SYSTEMS WITH TWO FLUIDIZED BEDS³²

An additional/excess fuel inlet could be provided to the combustion zone to maintain temperature in the reactor in this case also feedstock with low LHV could be gasified relatively easily.

2.3 Entrained flow gasifiers

Entrained flow gasifiers operate with feed and oxidant in co-current flow. The particle residence time inside the gasifier is very short (few seconds). The feed is ground to particle size of 200 μm or less to promote mass transfer and allow transport in the gas. Given the short residence time, high temperatures (1200°C-1500°C) and high pressure (20-80 bar) are required to ensure a good conversion. Therefore, all entrained flow gasifiers operate in the slagging range (i.e. above the melting temperature of the ash). The high-

³² N. Hanchate, S. Ramani, C.S. Mathpati, Vishwanath H. Dalvi, Biomass gasification using dual fluidized bed gasification systems: A review, Journal of Cleaner Production, Volume 280, Part 1, 2021, 123148, ISSN 0959-6526, <https://doi.org/10.1016/j.jclepro.2020.123148>.

temperature operation creates a high oxygen demand for this type of process. The ash is produced in the form of an inert slag or frit. The EF gasifiers were developed in 1950ies for coal gasification, but today also biomass and waste materials are employed in this process.

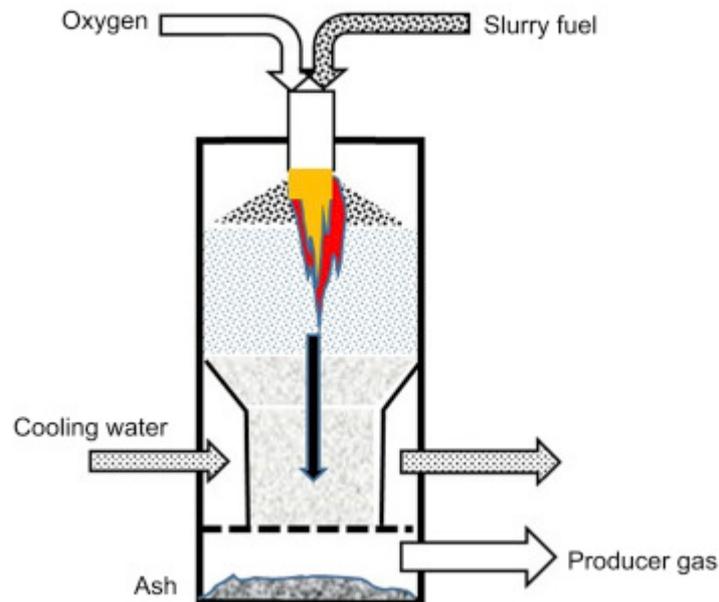


FIGURE 8: ENTRAINED FLOW GASIFIER³³

3. OPPORTUNITIES FOR THERMAL GASIFICATION

Thermal gasification of wood flourished quite well before and during the second world war. The technology disappeared soon after the second world war, when liquid fuel became easily available again. Anyway, the history of coal gasification is much longer.

The interests in the gasification technology has undergone many ups and downs in recent decades. Today, especially because of environmental concern, there is renewed interest in this technology.

Thermal gasification shows a huge potential regarding feedstock flexibility. A broad range of different biomass types and waste materials can be used for production of power/heat/fuels/chemicals, which could be employed in further industrial and agricultural processes. In this way, the gasification offers a great advantage talking about circular economy, where the waste is becoming feedstock again and can be converted to further value-added products.

Furthermore, the gasification process can be included to another industrial processes to avoid fossil fuels utilization, then the product gas from gasification can be used e.g. for high temperature heat.

Gasification process can be employed as a district heating technology; or it can be coupled with PV or wind power parks for boosting the production of biofuels or as a balancing-the-grid technology.

Biomass gasification enables production of renewable power/heat/fuels/chemicals. This technology is carbon neutral and clean products, e.g. biofuels could be produced in this way.

³³ Shusheng Pang, in [Fuel Flexible Energy Generation](#), 2016

Furthermore, from biomass a biochar as a by-product of gasification could be produced. In this case we talk about carbon negative technology. The biochar utilization potential is huge and nowadays not all possibilities are well known. It can be applied as a carbon long-term storage medium (e.g. as an additive to asphalt = green road, building materials, etc.). It can be used in agriculture as a fertilizer for soil improvement, a part of feeding mixtures for animals; in industry as a filtering medium etc.

Overall, thermal gasification technology is distinguished by its wide range of areas in which it can find application. In this report of the IEA Bioenergy Task 33, some of them have been examined taking into account the present context of renewed attention to energy, environmental and circularity issues. In particular, the four case studies herein presented were selected to show the broad range of applications of gasification in (bio)refinery concepts. In the following, a brief description and main findings of the case studies are summarized.

4. CASE STUDIES BRIEFLY

An important part of this publication are 4 case studies, describing 4 different cases where the gasification process could be successfully employed. It is clear that there could be many further case studies written to show the potential of thermochemical gasification process.

CASE STUDY 1

Entrained flow biomass gasification in the pulp and paper industry

In this case study, two main gasification integration options are considered:

- 1) replacing the bark boiler of a pulp mill with an entrained-flow biomass gasifier
- 2) full or partial utilization of the black-liquor stream for entrained-flow gasification

Main findings:

- The overall energy system efficiency is generally higher and the economic performance better if the production is integrated in a pulp mill in comparison to separate stand-alone operations of the mill and the gasification plant
- The pulp mill characteristics such as capacity and type is decisive for what integration concept that is the most favourable from a techno-economic viewpoint
- Gasification with downstream synthesis to biofuels is less appropriate for pulp mills already limited in the lime kiln, due to the increased causticizing load. In case of black liquor, downstream synthesis processes generally result in good economic and energy performance that could result in important economic benefits to the pulp and paper industry

CASE STUDY 2

Integration between gasification and anaerobic digestion to methanol

Two subcases were considered in this case of gasification application:

1. Production of biomethanol by enriching in hydrogen the producer gas from biomass gasification via steam reform of AD biomethane
2. Integration between gasification and anaerobic digestion by considering the anaerobic digestate as a feedstock to the gasification stage.

Main findings:

- In the case 1, the biomass flowrate strongly affects the syngas composition for methanol synthesis, as well as the total and specific power consumption. Despite the increase of syngas to be compressed, the increase of the biomass flowrate causes a slight decrease of electricity demand for compression. This effect is related to the total methanol productivity.
- In the case 2, the productivity of methanol is slightly lower than case 1. This may be associate to a different syngas composition. Anyway, this concept is promising for the future. In fact, it provides a possible alternative use of the solid residue from AD, whose availability is expected to exceed the capacity of use as agricultural soil improver when produced from fermentable agricultural residue or avoid accumulation as waste when the material produced does not reach the specifications for commercial uses.

CASE STUDY 3

Integration of renewables into existing refineries

The aim is to show the possibilities for integration of gasification systems into conventional oil refineries for

the production of synthetic bio-fuels. In this case the complete synthesis pathway of the 2nd generation bio-fuels is studied on-site in the refinery by using one of Germany's largest refineries, Mineraloelraffinerie Oberrhein (MIRO), as an example.

Two possible implementations were considered:

- 1) implementation of the Fischer-Tropsch process
- 2) implementation of the Methanol/DME-to-Gasoline processes

Main findings:

- The Fischer-Tropsch process with the implementation of a hydrocracker unit was shown to produce higher yields of diesel components compared to the catalytic cracking and also a higher overall energy efficiency
- Methanol/DME-to-Gasoline processes deliver lower synthetic fuel energy efficiencies compared to the Fischer-Tropsch process
- Amongst the Methanol-to-Gasoline and DME-to-Gasoline processes, the DtG process could deliver a higher yield of synthetic gasoline, so also a higher synthetic fuel energy efficiency compared to the MtG process, but the product and overall energy efficiency of the MtG process were shown to be higher.
- The integration of the Fischer-Tropsch process resulted to be slightly more economic than the Methanol/DME-to-Gasoline processes

CASE STUDY 4

Gasification of RDF and integration into an existing naphtha cracker

The aim is to employ gasification technology to provide circular and biobased feedstock to an existing naphtha cracker of a petrochemical plant. In this case, the indirect gasification technology MILENA, OLGA tar removal and SEWGS were considered to be integrated into naphtha cracker.

Main findings:

- to maintain 100% recycling efficiency for the plastics, a certain amount of biogenic residue is in fact crucial, this will in itself also reduce the need of mechanical recycling, since residual paper/wood in the RDF is not an issue but a very attractive outcome.
- Policy measures will have a major impact on how these processes can or need to develop. If the focus is to generate as much circular materials from waste, the gasification route needs to be supported with CO₂ mechanisms favouring the sequestration of biogenic carbon.

Conclusions

The actual climate change debate shows clearly that renewable energy resources need to be further optimised and installed to reach the goals of the UN climate targets. Limited natural resources make it necessary to provide optimised process chains to gain the maximum output of feedstock materials. Moreover, closed material, energy and nutrient circles are necessary to use biomass in a renewable way. The aim of the present report is to suggest process routes to be implemented either into existing industries or even to suggest new process chains with a focus on biorefinery systems. Some of the above mentioned examples can be seen already as biorefinery (even though these industries were not designed following a biorefinery concept; eg the pulp and paper industry has widely optimized flow sheets and process combination to provide multiple bio-based products). Four case studies were selected and developed to provide a wide range of examples how gasification processes can be implemented into existing industries to utilize waste streams instead of disposal of those streams. Different gasification concepts are applied whereas in large scale applications obviously mainly fluidized bed as well as entrained flow reactors are suitable. However, for decentralised systems even fixed bed application can be applied; eg combined heat and power production with additional utilization of biochar for different applications (soil amendment, activated charcoal, feed additive, ...). The first 2 case studies deal with either improvement of the gasification processes being applied or utilization of residues respectively waste streams from a pulp mill or a biogas plant. The second 2 case studies deal with the substitution of fossil fuels in existing refineries based on synthesis processes using producer gas from gasification plants using biomass or RDF as feedstock.

One main intention of this report was to show that gasification processes are relatively flexible with regard to feedstock utilization and can therefore be implemented at different positions of complex process chains such as applied in biorefinery concepts. The possible feedstock and their limitations are comprehensively presented in section 1 of this report. Obviously feedstock materials as well as residues from forestry offer high quality with typically low ash contents and other impurities such as S, Cl, heavy metals, ... Residues from agriculture are generally high in alkali metals and create therefore problems with the ash melting. Waste materials such as MSW, RDF, ... are typically high in impurities such as heavy metals, Cl, S, ... and moreover have more or less unpredictable compositions. Depending on the origin and composition all these materials release more or less tars and therefore induce typically significant gas cleaning efforts.

Different gasification reactor types are described in chapter 2 with different applicability to biorefineries and different gas qualities as well as scalability. Generally, fixed bed gasifiers are suitable for clean feedstock materials with defined particle size distribution. These systems are well suited for combined heat and power production. As exception staged gasification processes typically allow very high gas qualities (low tar amounts) and are therefore well suitable for synthesis gas applications if the synthesis process can be demonstrated in small to medium scale.

For industrial applications generally fluidized bed reactors are well suited since they offer a high reliability, high fuel flexibility and relatively low costs. However, gas cleaning can be an issue and typically those systems are operated in autothermal mode leading to high nitrogen fractions (up to 60vol%) in the gas with relatively low heating value ($\sim 5\text{MJ}/\text{m}^3$). The special system of the dual fluidised bed gasifiers needs higher complexity but offers significantly higher gas quality ($\sim 12\text{-}15\text{MJ}/\text{m}^3$). For large scale entrained flow reactors offer as main advantage a very high syngas quality (no hydrocarbons left) and a low volume/power ratio.

Summarising the case studies, gasification can be used to utilize residues from pulp mills (eg. black liquor) or from biogas plants (eg. biogas slurry) to increase the syngas quality. The first case study is based on entrained flow gasification and the second case study on a bubbling fluidized bed reactor. As additional option for the biogas case the biogas could be processed by steam reforming to increase the hydrogen fraction in the syngas from the gasification process. For case studies 3 and 4 two different approaches were chosen and would offer interesting options. Case study 3 would use gasification to provide a syngas which will be further processed to either diesel, methanol or DME. These products can be finally integrated into a classical refinery to substitute fossil fuels. Case study 4 aims to recover plastics from waste streams to be integrated into an existing naphtha cracker of a classical refinery.

Details on the case studies can be found in the appendix of this report and will be further used to calculate biorefinery concepts. Summarising the benefits of the implementation of gasification in existing process

routes could be clearly shown. These cases can be seen as frame conditions but are not limited to these specific cases. Depending on the frame conditions other process combinations are possible and have to be looked into it in detail. Summarizing, gasification processes offer a wide application in the field of bioeconomy/biorefinery to utilize residues and waste streams which would have to be disposed of. This will increase the overall efficiency of conversion process chains and lead to optimised material utilisations.



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