PG&E GAS R&D AND INNOVATION

Gasification Technical Analysis

5/1/2018

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a Better California

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1 What is Gasification

Gasification is a thermochemical process that converts organic- or fossil fuel-based carbonaceous materials into carbon monoxide and hydrogen, with a small amount of carbon dioxide and water. Partial oxidation occurs at high temperatures (>1300°F), with oxygen, air and/or steam (NETL, n.d.). The resulting product is called syngas. Gasification is a source of renewable energy, if the syngas was produced from biomass (NETL, n.d.).

Two types of heating methods:

- Autothermal – direct heating (e.g. partial combustion of biomass)
- Allothermal – indirect heating (e.g. external heat source)

May be pressurized or at atmospheric pressure.

Typical processes (NETL, n.d.) (NETL, n.d.):

- Dehydration – free water evaporates
- Pyrolysis – devolatilization and breaking of weaker chemical bonds to produce volatile gases (e.g. tar vapors, methane, hydrogen, high molecular weight char)
- Combustion – volatile products react with oxygen to form CO2 and CO, providing heat for gasification reactions
    1. $C + ½ O_2 \rightarrow CO$ (-111 MJ/kmol)
    2. $CO + ½ O_2 \rightarrow CO_2$ (-283 MJ/kmol)
    3. $H_2 + ½ O_2 \rightarrow H_2O$ (-242 MJ/kmol)
- Gasification – remaining char reacts with CO2 and steam to produce CO and H2
    4. $C + H_2O \leftrightarrow CO + H_2$ "the Water-Gas Reaction" (+131 MJ/kmol)
    5. $C + CO_2 \leftrightarrow 2CO$ "the Boudouard Reaction" (+172 MJ/kmol)
- Water-gas-shift and methanation – reversible reactions simultaneously occurring in the gasifier, playing a small role.
    6. $C + 2H_2 \leftrightarrow CH_4$ "the Methanation Reaction" (-75 MJ/kmol)
    7. $CO + H_2O \leftrightarrow CO_2 + H_2$ "Water-Gas-Shift Reaction"(-41 MJ/kmol)
    8. $CH_4 + H_2O \leftrightarrow CO_2 + 3H_2$ "Steam-Methane-Reforming Reaction" (+206 MJ/kmol
        - If high carbon conversion, reactions 4-6 reduces down to 7-8

Note: Additional water-gas shift and methanation reactions are necessary downstream of the gasification process, as part of the upgrading/conditioning process to produce pipeline quality biomethane

1.1 FIXED-BED (MOVING) GASIFIERS

1.1.1 Updraft

(Biofuels Academy, 2018)

- Feedstock: injected at the top
- Gasifying agent (e.g. air/O_2 and/or steam): injected at the bottom
- Flow: counter-current
- Feedstock goes through different temperature levels in the reactor
- Product gas flows from reactor with little interactions with rest of biomass/char regions

1.1.2 Downdraft

(Biofuels Academy, 2018)

- Feedstock: injected at the top
- Gasifying agent: drawn in by suction blower via an air jacket or down through the top
- Fire at the bottom
- Incoming gasifying agent allows partial combustion in the lower hearth area. The resulting heat produces pyrolysis above and reduction below.

1.2 ENTRAINED-FLOW GASIFIERS

(NETL, n.d.)

- Feedstock + gasifying agent: fed co-currently
- The gasifying agents entrain the feedstock particles as they flow into the gasifier in a dense cloud
- Operation at high temperature, pressure and turbulent flow, causing rapid feed conversion and high throughput
- Syngas is tar-free
- Ash melts into vitreous inert slag

1.3 FLUIDIZED-BED GASIFIERS

(NETL, n.d.)

- Feedstock: injected at side
- Gasifying agent: injected near the bottom
- Feedstock is suspended in the gasifying agent, within the bed that acts as a fluid
- Back-mixing (new feedstock particles mix with gasified particles)

Two types: bubbling & circulating. In circulating, the bed particles can be removed using a cyclone separator, then recirculated. In addition, a gas vortex is created in the gasifier and separator, creating a long path of high temperature for the solids. (Biofuels Academy, 2018)

1.3 PLASMA

(Biofuels Academy, 2018)

- Feedstock: injected at side
- Gasifying agent: injected at side
- Uses plasma energy to convert feedstock to syngas. Plasma is an electrically charged gas (fourth state of matter). Process is can achieve temperatures close to the temperature of the surface of the sun (through a plasma torch). Due to the high temperatures, a wide range of feedstock is accepted e.g. biomass, MSW. No tar/char products are present.

(Gershman, Brickner & Bratton, Inc., 2013)
Two configurations: plasma assisted & plasma coupled with traditional thermal gasification. Plasma assisted has the plasma torch inside the gasification chamber.

1.5 COMPARISON

Cold gas efficiency (CGE)

(Ahmed, Sinnathambi, Eldmerdash, & Subbarao, 2014) (CompEdu, 2018)

The CGE is a measure of the gasifier performance. It is the ratio between the flow of energy in the product gas to the energy within the feedstock. It doesn't consider the product gas temperature. The higher the CGE, the better the feedstock conversion.

CGE = Cold gas efficiency %
LHVgas = lower heating value of the product gas (MJ/ m3n)
Vgas = normal volume flow of gas (m3n/s)
LHVfuel =lower heating value of the gasifier solid fuel (MJ/kg)
mfuel = solid fuel flow (kg/s)

CGE = [(LHVgas x Vgas)/(LHVfuel x mfuel)] x 100%

Note: HHV (higher heating values) may be used in place of the LHV (lower heating values)

Table 1 Comparison of each gasifier type (Gershman, Brickner & Bratton, Inc., 2013)

Gasifier Design	Tar in Syngas	Cold Gas Efficiency	Operating Energy Requirement	Ability to handle wide variety of waste with varying composition	Permissible Particle Size	Moisture Content (maximum)	Dust Content
Downdraft	Low	> 80%	Low	Moderate	< 4 in	~ 40%	Medium
Updraft	Very High	> 80%	Low	Low	< 2 in	~ 50%	Low
Fluidized Bed	High	> 90%	Moderate	Very Low	< 1/4 in	~ 10%	High
Plasma	Very Low	> 90%	High	Very High	NA	> 50%	Low
Entrained Flow	Very Low	> 80%	Low	Low	< 1/25 in	~ 10%	High
Plasma Enhanced Downdraft	Very Low	> 90%	Moderate	High	< 4 in	> 50%	Low

Table 2 Approximate composition of raw syngas from gasified biomass (Gershman, Brickner & Bratton, Inc., 2013)

	Air-blown Producer Gas (vol. %)	Oxygen-blown Synthesis Gas (vol. %)	Indirect-fired-steam gasification Synthesis Gas (vol. %)
CO	22	38	19
H_2	14	20	20
CH_4	5	15	8
C_2H_2 and higher	low	5	3
H_20	2	4	38
CO_2	11	18	11
N_2	46	trace	trace
	Plus tars, PM, and other		

Air-blown direct gasifiers produce a low energy gas (~ 150 Btu/ft^3).

Oxygen-blown direct gasifiers produce a medium energy gas (~350 Btu/ft^3). An air separator is needed to create a pure or enriched oxygen stream.

Air-blown indirect gasifiers produce a medium energy gas because the combustion reactor is separate from the gas producing reactor.

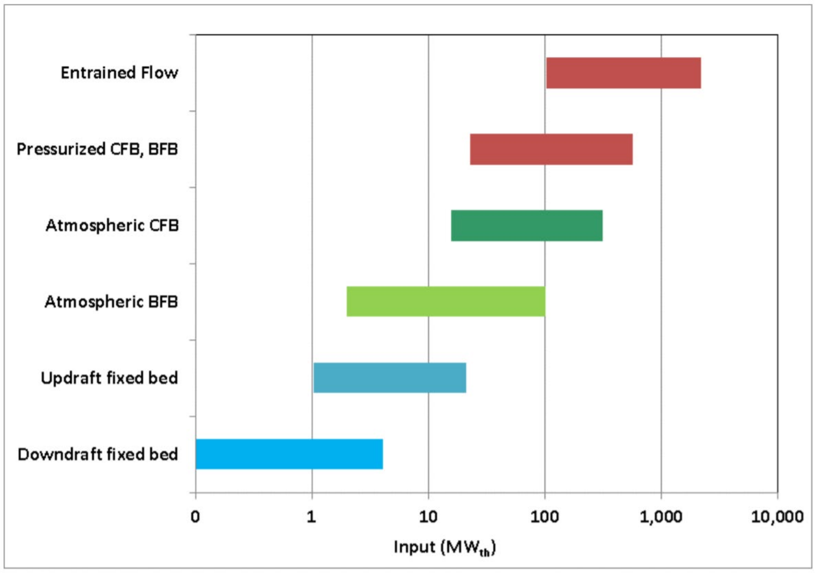


Figure 1 Gasifier Capacity Ranges (fuel energy input basis) (Gershman, Brickner & Bratton, Inc., 2013)

Table 3 Tar in raw gas by gasifier type (Gershman, Brickner & Bratton, Inc., 2013)

	Fixed Bed		Fluidized Bed		
	Updraft (counter current)	Downdraft (co-current)	Bubbling	Circulating	Entrained
Mean tar content (g Nm^{-3})	50	1	12	8	10
Range of tar (g Nm^{-3})	1-160	0.01-6	1 - 150	1 - 150	2 - 30

2 Gasification Technologies

2.1 GAS TECHNOLOGY INSTITUTE (GTI) - RENUGAS®

2.1.1 Summary of Technology

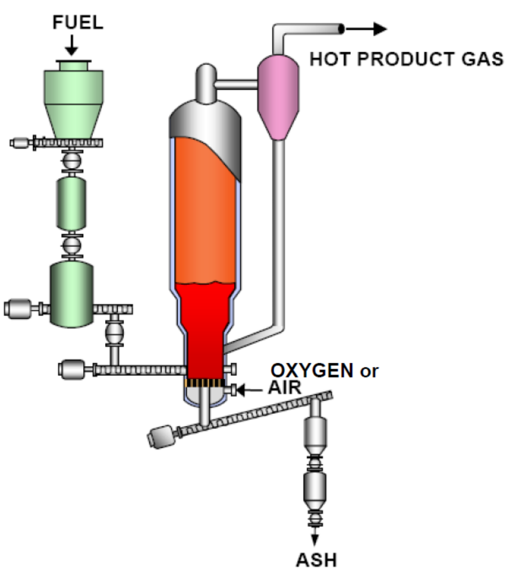


Figure 2 GTI's Gasification Process (Gas Technology Institute (GTI), 2009)

Feedstock (e.g. woody biomass) goes through a pre-treatment drying step and then sent to the bubbling fluidized bed gasifier through a lockhopper system. Oxygen and steam is injected into the gasifier simultaneously. In the fluidized bed, the feedstock reacts with steam and oxygen at ~1600oF. The fluidized bed decakes, devolatizes, and gasifies fuel, and if needed, agglomerates and separates ash from the reacting char. The operating pressure is between 3-30 bar. The resulting raw syngas produced, consists mostly of hydrogen and carbon monoxide, with some carbon dioxide, water vapor, methane. Depending on the feedstock, you may also have hydrogen sulfide and other trace impurities. Main byproducts include tars, acid gases and ash. (GTI, 2007)

2.1.2 Benefits

(Bush, 2018) (LeFevers, 2018)

- Bed properties designed specific to woody biomass as the feedstock, to produce high quality syngas. This includes:
- sizing of the bed to allow for feedstock to perculate through the bed with sufficient residence time to optimize conversion to hydrogen and carbon monoxide
- chemistry of bed to make sure it’s reliable, efficient, and provides for a homogeneous thermal environment (e.g. control over gasification reactions)
- The specific blending of oxidants (oxygen and steam) at the bottom of the reactor is GTI’s proprietary design

2.1.3 Limitations

- Air separation unit required upstream to provide pure oxygen can be expensive. The alternative is to inject air into the gasifier and remove the nitrogen downstream. However, using air requires larger sized equipment to accommodate the large volume that inert nitrogen takes up (79% of air), and removing nitrogen downstream is challenging and expensive. (Bush, 2018) (LeFevers, 2018)
- Management of tar production
- Tar is one of the major impurities, that can foul and block equipment (Odongo, 2015)
- Downstream of the gasification process, GTI uses a catalytic reformer to treat tars. Multiple beds of catalytic material are used to crack tar species to hydrogen and carbon monoxide with minimal destruction of methane. This is the latest development in their technology. (Bush, 2018) (LeFevers, 2018)
- Feedstock includes coal and biomass varieties only (no MSW, medical waste, hazardous waste, etc.) (GTI, 2007)

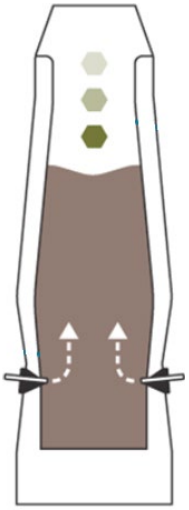
2.1.4 R&D Opportunities

- Retrofitting existing coal power plants with gasification technology to produce RNG from woody biomass → *existing GTI engineering study to be completed in August 2018*
- Depending on the result of the GTI engineering study, opportunity to collaborate with GTI to build a commercial facility in Northern California to take woody biomass and produce RNG to be injected into the grid
- Tar management
- Continued improvement within gasification process to minimize production of tars
- Inexpensive and commercial scale removal of tars downstream
- Inexpensive and commercial scale air separator to produce pure oxygen for the gasification process

2.2 SIERRA ENERGY – FASTOX® GASIFICATION

2.2.1 Summary of Technology

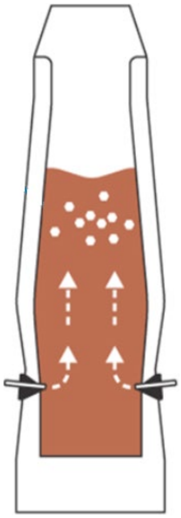
(Sierra Energy, 2018)



Feedstock is injected at the top of the gasifier through an air lock. Steam and oxygen are injected at the bottom of the gasifier.

High temperature syngas at the bottom of the gasifier rises-up through the feedstock and vaporizes water. The lower section of the gasifier operates at 4000°F.

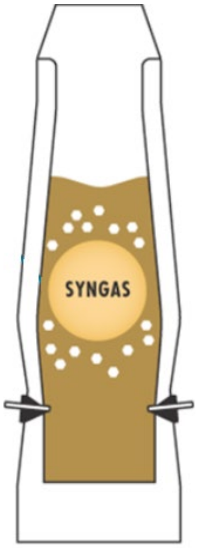
1



Feedstock descends into the volitization zone where the operating temperature is 1300°F. The chemical energy in the feedstock is released to produce light gases, hydrocarbons and condensable tars.

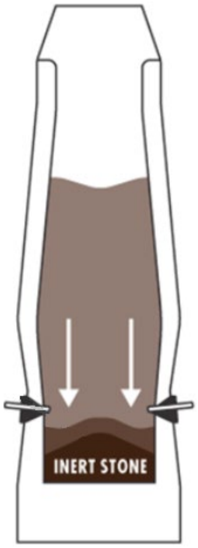
Solids that are produced are cleaned out of the syngas and recycled back to the gasifier during downstream gas cleaning.

2



Partial oxidation occurs in the lower section of the gasifier, and the remaining carbon-containing materials in the feedstock react with steam and oxygen. These oxidation reactions give off heat and increase the operating temperature from 2500°F to 4000°F, contributing to conversion of the remaining carbon to syngas. The energy produced during this stage allows the FastOx system to be self-sustaining.

3



At 4000°F, inorganic compounds and metals melt and form a molten state at the bottom of the gasifier. These are later removed as non-leaching inert stone and recovered metals.

The high temperatures of the FastOx system allow complete conversion of feedstock without producing toxic by-products.

4

2.2.2 Benefits

- Feedstock includes Municipal Solid Waste (MSW), biomass, medical, industrial, C&D, and hazardous (Sierra Energy, 2018)
- Byproduct of inert stone can be used as aggregate material for other processes e.g. in construction.
- Due to high operating temperatures, tar management occurs within the gasifier

2.2.3 Limitations

- Air separation unit required upstream to provide pure oxygen can be expensive (Sierra Energy, 2018)
- High temperature of 4000^{o}F requires a large amount of electrical energy

2.2.4 R&D Opportunities

- Commercial scale thermochemical conversion process is needed to convert landfill waste (non-recyclable) into clean renewable natural gas (RNG) that could be injected into the grid or used to fuel vehicles as compressed RNG
- Within the process, the treatment of sulphur products, such as siloxanes need to be addressed

2.3 ADVANCED PLASMA POWER (APP) - GASPLASMA®

2.3.1 Summary of Technology

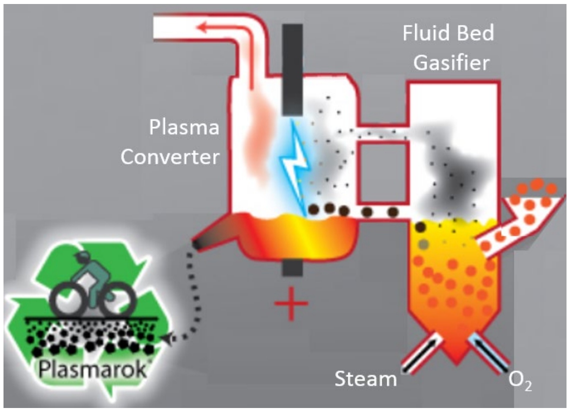


Figure 3 Portion of Gasplasma® process (Advanced Plasma Power, 2018)

Feedstock consists of residual waste (non-recyclable) from a landfill. The feedstock is shredded and dried to produce Refuse Derived Fuel (RDF) which is then fed into the GasPlasma process.

The GasPlasma process consists of two coupled reactors. The first reactor is where fluidized bed gasification takes place with steam and oxygen. The resulting crude syngas produced, containing tars and chars, is then transferred to the second reactor where plasma conversion takes place using plasma arcs to achieve extremely high temperatures of up to 14,430°F (8000°C). The ultraviolet light of the plasma cracks tar substances and breaks down char materials. The cracking creates syngas, and the inorganic elements in the ash are vitrified into Plasmarok® (inert).

2.3.2 Benefits

- Feedstock includes residue waste (non-recyclable) from landfills (Advanced Plasma Power, 2018)
- Byproduct of Plasmarok® can be used as aggregate material for other processes e.g. in construction (Advanced Plasma Power, 2018)
- Due to high operating temperatures, tar management occurs within the plasma conversion reactor (Advanced Plasma Power, 2018)

2.3.3 Limitations

- Air separation unit required upstream to provide pure oxygen can be expensive (Advanced Plasma Power, 2018)
- Plasma torches may have short life span and power limitations (Fabry, Rehmet, Rohani, & Fulcheri, 2013)

2.3.4 R&D Opportunities

Note: We are not interested in pursuing this technology, but I've listed R&D opportunities below for reference

- Improvement of plasma torch design to increase life span and remove power limitations associated with DC or DC + RF technology (Fabry, Rehmet, Rohani, & Fulcheri, 2013)

- Commercial scale thermochemical conversion process is needed to convert landfill waste (non-recyclable) into clean renewable natural gas (RNG) that could be injected into the grid or used to fuel vehicles as compressed RNG
- Within the process, the treatment of sulphur products, such as siloxanes need to be addressed

2.4 GOBIGAS – GOTHENBURG BIOMASS GASIFICATION PROJECT

GoBiGas project involves scaling-up of technology to a pre-commercial size (ALMUNIA, 2010). The technology is allothermal gasification by Repotec (Austrian company) (California Biomass Collaborative, 2017).

2.4.1 Summary of Technology

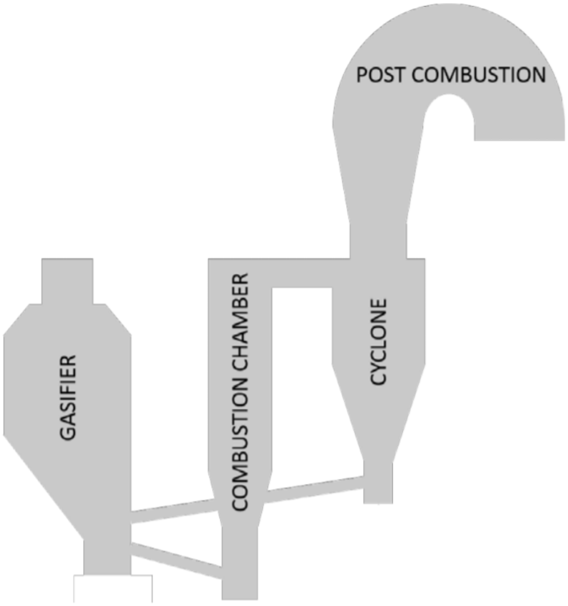


Figure 4 Overall process flow diagram (Karlbrink, 2015)

(Thunman, et al., 2018)
The gasification section consists of a dual fluidized bed (DFB) biomass gasifier, which is composed of the endothermic bubbling fluidized bed (BFB) gasifier and the exothermic circulating fluidized bed (CFB) combustor. The bed material (olivine sand) is heated up in the combustion chamber and separated from the combustion gases in the cyclone. Then, the heated bed material is fed to the gasifier where the heat is released, and recycled back to the combustion chamber fluidized with steam at the bottom of the gasifier.

The wood pellets are transported on a belt conveyor to two biomass silos. The silos alternate operations such that one silo is always in operation and feeding pellets into the biomass dosing bin, while the other silo is being filled with pellets. The pellets are fed through the biomass feeding screw, into the steam fluidized gasifier where the pellets are pyrolyzed and gasified.

The resulting syngas consists of CO, H_2, CO_2, CH_4 and water vapor, and leave at the top of the gasifier.

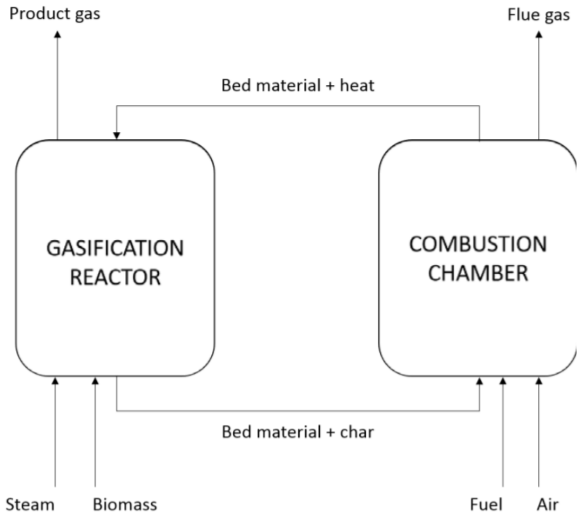


Figure 5 Process flow diagram of the gasifier portion (Karlbrink, 2015)

Indirect gasification obtains the heat for gasification from an external source. In indirect gasification the product gas has a very low nitrogen content, since the gasification reactor is fluidized with steam and not air. A dual fluidized bed (DFB) gasifier is an example of an indirect gasifier.

2.4.2 Benefits

- Use of air instead of pure oxygen is more cost effective, no air separation unit is required (Karlbrink, 2015)
- Oxygen in the gasifier is minimized by using a DFB system. This in turn minimizes oxidation of the produced gas to CO_2, and subsequently less separation of CO_2 from the syngas is required downstream. (Thunman, et al., 2018)
- Bed material and ash chemistry optimized to achieve high gas quality (Thunman, et al., 2018)
- The alkali and earth alkali metals (mainly potassium) that occur naturally in the biomass ash, used in combination with specific bed materials, and balanced by sulfur and calcium, allow the potassium to catalyze the conversion process to produce high quality syngas
- Unconverted char from the gasifier is used as the main fuel for the combustor, and recirculated by-products from the downstream process are used as supplementary fuel (Thunman, et al., 2018)

2.4.3 Limitations

- During process start-up, fouling from alkali salts or large PAH deposits on the surfaces of the heat exchangers occurs, until the activity of the bed material has been reached (Thunman, et al., 2018)
- Management of tar production
- Tar is one of the major impurities, that can foul and block equipment (Odongo, 2015)
- The abilities of certain bed materials to capture and release the active ash species, with potassium being the most important, were found to be key in limiting the yield of tar from the gasifier (Thunman, et al., 2018)

- Feedstock includes biomass varieties only (no MSW, medical waste, hazardous waste, etc.) (Thunman, et al., 2018)

2.4.4 R&D Opportunities

Note: The 20 MW plant was terminated due to financial reasons, the R&D opportunities listed below are for reference only (Walsh, 2018)

- Retrofitting existing plants (e.g. district heating infrastructure; pulp, paper, and saw mills; oil refineries and petrochemical industries, etc.) with gasification technology to produce RNG from woody biomass
- Better understanding of the function of potassium and tar chemistry, to optimize gasification process (Larsson, 2017)

2.5 GAYA PROJECT

GAYA project involves developing an innovative method for decentralized biomethane production based on gasification of lignocellulosic biomass characterized by small, reliable, profitable and highly energy-efficient plants. In addition, research on the evaluation of the biomass supply chain with reference to different types of biomass to develop more flexibility for improved market penetration. (ALMUNIA, 2010)

The project ran from 2010 – 2017. It covered gasification of woody biomass. The Fast Internally Circulating Fluidized Bed (FICFB) process was chosen for gasification. Repotec (Austrian company) was the technology supplier. (Rasmussen & Iskov, 2013)

It was the first demonstration platform for biomass conversion to biomethane in Europe. It is a collaboration of 11 companies with Engie as the leader and support by the French government through ADEME R&D program on 'Innovative Renewable bio-fuels (Perrin, Mambre, Guerrini, & Perreux, 2012). 11 companies included: engie; repotec; UCFF; The Ensiacet Chemical Engineering Laboratory in Toulouse (LGC); Process Reaction and Engineering Laboratory (LRGP); Lille Solid Catalysis and Chemistry Unit (UCCS); Rapsodee; French Atomic Energy and Alternative Energy Commission (CEA); International Cooperative Agronomic Research Center for Development (CIRAD); Grenoble Technical Center for the Paper; Cardboard and Cellulose Industry (CTP); French Technological Institute for Forestry, Cellulose, Construction Timber and Furnishing (FCBA); French Environment and Energy Management Agency (ADEME); Tenerrdis (gaya, 2014).

2.5.1 Summary of Technology

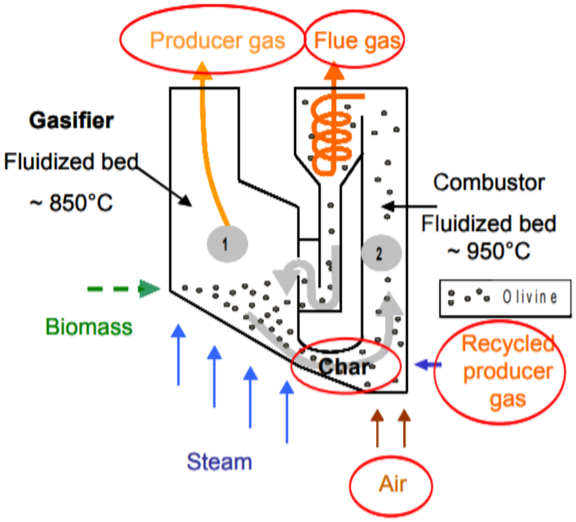


Figure 6 Gasifier process (Noubli, Valin, & Spindler, 2013)

The biomass is fed into the bubbling fluidized bed gasification reactor. Steam is used both as a fluidization and gasification agent. The bed material, usually sand or olivine, flows from the gasification reactor to the combustion reactor carrying ungasified chars. The ungasified chars and additional fuel for temperature control are burned in the combustion zone. Heated bed material leaving the combustion zone goes to a cyclone for separation. The product gas and flue gas pass through a seal loop recycling to the gasifier to prevent mixing. The high temperature bed material from the combustion chamber provides heat to the gasifier reactor. Recycled syngas is burned in the combustion zone as an additional fuel. (Perrin, Mambre, Guerrini, & Perreux, 2012)

2.5.2 Benefits

- Use of air instead of pure oxygen is more cost effective, no air separation unit is required (Karlbrink, 2015)
- Unconverted char from the gasifier is used as the main fuel for the combustor (Noubli, Valin, & Spindler, 2013)

2.5.3 Limitations

- Management of tar production
- Tar is one of the major impurities, that can foul and block equipment (Odongo, 2015)
- Feedstock includes biomass varieties only (no MSW, medical waste, hazardous waste, etc.) (Rasmussen & Iskov, 2013)

2.5.4 R&D Opportunities

- Commercial scale (20-60 MW) demonstration facility → *part of existing GAYA project timeline*
- Tar management
- Continued improvement within gasification process to minimize production of tars
- Inexpensive and commercial scale removal of tars downstream

2.6 WEST BIOFUELS – CIRCLEDRAFT®

West Biofuels is a recent awardee of a $2 million Energy Commission grant to develop a modular system to facilitate forest fuel reduction treatments (California Biomass Collaborative, University of California, Davis, 2015). The “Circle Draft” gasifier (created by INSER in 2011) is a unique modified downdraft reactor that recirculates the product gas through the charcoal bed before exiting the reactor. The arrangement supposedly produces lower-tar gas. Design piloted Italy (tar production data not available). The Circle Draft gasifier is less complex than the FICFB and supposedly should have a lower capital cost.

2.6.1 Summary of Technology

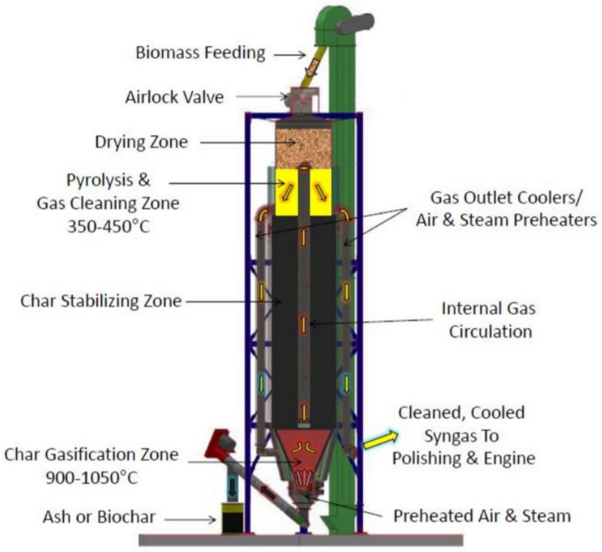


Figure 7 Gasification process (California Biomass Collaborative, University of California, Davis, 2015)

The CircleDraft gasifier is a combination of a downdraft and updraft type gasifier, that produces low tar content raw gas. The system is gravity fed with four temperature zones: drying, pyrolysis & gas cleaning, char stabilizing, and char gasification. (West Biofuels, 2016)

Air and steam are injected at the bottom. The syngas moves to the pyrolysis zone where it is filtered through pyrolysis char for initial cleaning. The char goes through the char stabilizing zone and to the gasification zone where heavy contaminants are reintroduced to the high temperature zone for further break down. Produced biochar is derived from the gasification zone without any contaminants from the gas filtration stage.

Traditional downdraft and updraft type gasifiers can’t guarantee good syngas quality. They also require dry and select feedstock, with the resulting gas cleaning process being complex. Traditional fluidized bed type gasifiers require special feedstock preparation to get it to the right size and dryness level, and have more complex operations than downdraft/updraft types. The CircleDraft supposedly overcomes these limitations, with an air blown and non-pressurized system. (Faussone, Biomass Gasification with Circle Draft, 2011)

2.6.2 Benefits

- Use of air instead of pure oxygen is more cost effective, no air separation unit is required (Karlbrink, 2015)
- Low tar production within the gasifier < 20 mg/Nm^3 (California Biomass Collaborative, University of California, Davis, 2015)
- Every type of biomass can be gasified (e.g. wood, straw, rice husk, manure, etc.) (Faussone, Biomass Gasification with Circle Draft Process, 2011)
- Higher LHV (11 MMBTU/Nm^3) compared with downdraft standard (4 MMBTU/Nm^3) (Faussone, Biomass Gasification with Circle Draft Process, 2011)
- Community-scale modular gasifier (West Biofuels, 2016)

2.6.3 Limitations

- Feedstock includes biomass varieties only (no MSW, medical waste, hazardous waste, etc.) (Rasmussen & Iskov, 2013)
- Large amounts of inert N_2 (46-50%) in the raw syngas, causing dilution and a downstream separation stage (West Biofuels, 2016)

2.6.4 R&D Opportunities

- Tar production study from 2 MW scale test facility to validate lower tar content in comparison with downdraft / updraft / fluidized bed gasifiers
- Commercial scale (e.g. 20 MW) demonstration facility
- Economic feasibility with operation of conversion at low pressure in combination with a compressor stage downstream to raise pressure to match grid pressure
- Inexpensive and commercial scale removal of N2 downstream to meet biomethane pipeline quality specifications

2.7 VIRESCO – STEAM HYDROGASIFICATION PROCESS (SHR)

Licensed technology from UCR – College of Engineering – Center for Environmental Research & Technology

2.7.1 Summary of Technology

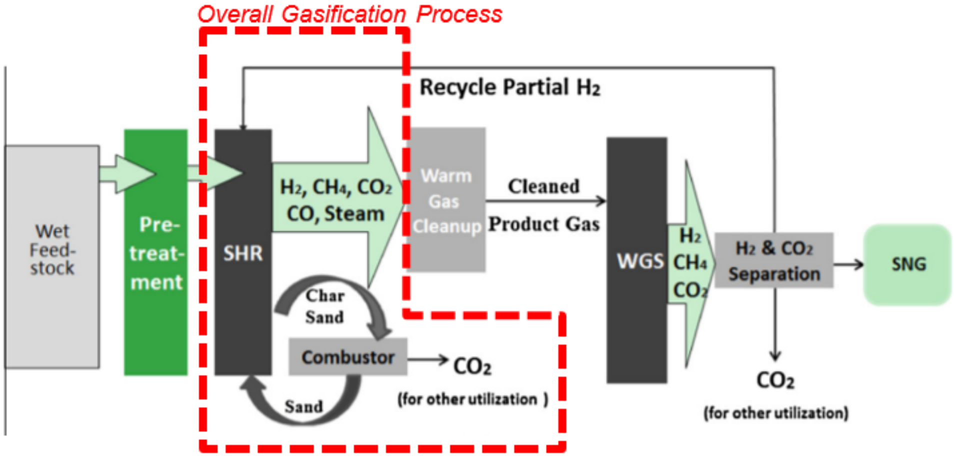


Figure 8 Gasification process flow chart (Liu, Norbeck, Raju, Kim, & Park, 2016)

Hydrogasification: Gasification occurs in a hydrogen environment, instead of air or pure oxygen. Hydrogen is supplied through a water gas reaction of the char or steam methane reforming of the product gas. Requires high pressure (100 atm) or a catalyst. (Raju, 2011)

$$C_xH_yO_z + 2H_2 \rightarrow CH_4 + \text{Others}$$

Steam Hydrogasification: The same as hydrogasification, except with the presence of water to the reaction (Raju, 2011)

$$C_xH_yO_z + H_2O + 2H_2 \rightarrow CH_4 + H_2O + \text{Others}$$

Others: CO, CO_2, C_2

Addition of steam promotes additional hydrogen formation. This hydrogen can be separated and reused but the advantages may be offset by the cost of gas separation. (Faussone, Biomass Gasification with Circle Draft Process, 2011)

The wet feedstock is first pretreated to produce a pumpable slurry. The slurry is then fed into the gasifier in the presence of steam and hydrogen to get methane-rich syngas at 750 C. A circulating fluidized bed system (a gasifier and a combustor) with sand circulation between is the proposed ideal reactor type. The unreacted char from the gasifier is burned in the combustor to provide heat for the gasifier. The warm gas cleanup step removes impurities like H2S from the product gas to protect downstream operations. The majority of CO in the product gas is converted to H2 and CO2 via a two-stage WGS using high temperature and low temperature shift catalysts in series. This step produces enough H2, which is separated from the main stream for cyclic use. CO2 is then separated from the methane to produce fuel grade SNG. The process byproducts such as ash and CO2 can beneficially be reused. (Liu, Norbeck, Raju, Kim, & Park, 2016)

2.7.2 Benefits

(Raju, 2011)

- Internal H_2 feedback (from product gas recycled back)
- Can handle wet feedstock without drying
- Utilizes a high pressure slurry pump to reduce costs
- Suitable for low-rank coal with high moisture content, e.g. lignite
- Less water per ton of feed compared to other gasification processes (most of the water is recycled)
- No oxygen plant required
- Process is suitable for smaller scale, distributed facilities (ideal for biomass/waste, coal/biomass feedstock)
- Higher thermal efficiency
- Suitable for low-rank coal with high ash content

2.7.3 Limitations

- Pre-treatment of feedstock to produce a pumpable slurry at high pressure (Raju, 2011)
- Management of tar production
- Tar is one of the major impurities, that can foul and block equipment (Odongo, 2015)

2.7.4 R&D Opportunities

- Pilot scale test of sorption enhanced steam hydrogasification (SE-SHR) with woody biomass as the feedstock (Liu, Norbeck, Raju, Kim, & Park, 2016)
- Inexpensive and commercial scale production of H_2

3 Comparison of Gasification Technologies

3.1 METRICS

Technology Provider	Gasifier Type	Feedstock Accepted	Moisture Content	Other Inputs	Temp.	Press.	Byproducts	Energy Efficiency	Scale Achieved
GTI [1]	Bubbling fluidized bed (direct)	Woody biomass, peat, coal, coke, char	20%	O_2, steam	1600ºF	3-30 bar	Tar, ash, char, acid gases	69%	165 tons biomass/day

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[1] (Gas Technology Institute (GTI), 2007), (Gas Technology Institute (GTI), 2009), (GTI, 2007)

Technology Provider	**Gasifier Type**	**Feedstock Accepted**	**Moisture Content**	**Other Inputs**	**Temp.**	**Press.**	**Byproducts**	**Energy Efficiency**	**Scale Achieved**
Sierra Energy[2]	Fixed bed and updraft (direct)	Landfill waste, petroleum coke, ag-waste/shells	50%	O_2, steam	1300-4000ºF	> -10 mbar	Metal, inert stone, particulate matter, gaseous contaminants	Data not available	20 tons MSW & biomass per day
APP[3]	Plasma conversion coupled with fluidized bed gasification (direct)	Landfill waste	10-14%	O_2, steam	2800-14,432 ºF	-1 to -7 mbar	Inert stone (plasmarok®), particulate matter, acid gases, volatile metal vapors	74%	20 MW 100,000 tons RDF/yr (~ 274 tons RDF/day)
GoBiGas[4]	Circulating fluidized bed (indirect)	Woody biomass	20%	Air, steam	1600ºF	1 bar	Tar, ash, char	58-63%	20 MW 150 tons biomass/day 5.9 MMBTU/hr
GAYA [5]	Circulating fluidized bed (indirect)	Woody biomass	22-30%	Air, steam	1600ºF	1 bar	Tar, ash, char	Data not available	500 kW
West Biofuels[6]	CircleDraft (direct) - combo downdraft / updraft gasifier	Woody biomass (chips, shells, residue pellets & cubes)	25%	Air, steam	660-1920ºF	< 20 in. H_2O (0.05 bar)	Tar, ash, char, slag	75%	2 MW 12 tons biomass/day 6.75 MMBTU/hr
Viresco[7]	Circulating fluidized bed (indirect)	Wood, crop waste, ag res, energy crops, MSW, plastic, polymers (rubber, tires)	60-70% (upper limit for lignite)	H_2, steam	1390ºF	~100 bar	Tar, ash, char	Data not available	Bench level Note: 5 tons coal/day pilot terminated – insufficient funding

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[2] (Sierra Energy, 2018), (Sierra Energy, 2018), (Sierra Energy, 2018)

[3] (Advanced Plasma Power, 2018), (Advanced Plasma Power, 2018), (Advanced Plasma Power, 2018), (Advanced Plasma Power), (Advanced Plasma Power, 2018)

[4] (Karlbrink, 2015), (Larsson, 2017), (Skov, Mathiesen, & Connolly, 2013), (Thunman, et al., 2018)

[5] (Noubli, Valin, & Spindler, 2013), (Perrin, Mambre, Guerrini, & Perreux, 2012), (Biollaz, Held, & Seiser, 2016)

[6] (Rasmussen E. , 2011), (Faussone, Biomass Gasification with Circle Draft, 2011)

[7] (Faussone, Biomass Gasification with Circle Draft Process, 2011), (Liu, Norbeck, Raju, Kim, & Park, 2016), (Raju, 2011)

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