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Woody Biomass Gasification Technology and Market Update

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Disclaimers

While the information included in this guide may be used to begin a preliminary analysis, a professional engineer and other professionals with specialized experience in biomass energy systems should be consulted before committing resources to any particular project.

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Executive Summary

The use of woody biomass to generate heat, cooling, electric power, biofuels, and chemicals is a crucial development that supports society's transition to reduced reliance on traditional extractive energy resources, while increasing our use of renewable energy sources that reduce greenhouse gas emissions and other air pollutants. Also, biomass use will support demand for forestry waste woody biomass, critical for sustainable forest management especially in areas of the country where excess forestry materials cannot be left onsite. We expect that *woody biomass gasification* may play a significant role in meeting these growing societal needs, providing an efficient, low emissions method of capturing a large, underutilized resource of usable energy from wastes generated by forestry industries' wood harvest and processing.

Gasifiers are distinct from traditional biomass boilers, in that they produce a combustible gas product as a primary product, in addition to heat. This gas may be used directly in an engine to generate electricity, and/or indirectly, to produce various hydrocarbon products. Gasifiers are especially compelling compared to boilers for capturing wood energy at smaller scales, because they can easily support production of significant electricity as well as heat in small, modular unit sizes where conditions do not provide access to a large biomass resource in one location. Electric energy is generally more transmissible and valuable than heat, adding value to systems that can generate electricity at small scale.

Gasification of biomass and the use of the producer gas in boilers, furnaces and engines have a long and proven history, dating back to the 1800's. However, applying producer gas to efficient direct electricity generation and even more efficient combined heat and power (CHP), is a newer development that languished until recently, due primarily to difficulties in removing tars and other unwanted constituents from this gas fuel. Gasifier tar removal and automation technologies have continued to improve and have now been successfully demonstrated and proven reliable for small and micro-scale pre-packaged integrated CHP applications of woody biomass. Such gasifiers are now "commercial equipment" that can be purchased off the shelf from several manufacturers. Despite these advances, a number of barriers remain to wide adoption of such products. At this time, small-scale biomass gasifiers have seen only limited commercial applications internationally and have not yet been commercialized in the United States. These small, packaged gasifiers are a particular focus of this report.

This report provides an overview of new developments in and commercialization of small and medium scale gasifiers appropriate for distributed forest products industries and others with proximal access to relatively low-cost biomass materials. The report describes the current state of commercial technologies and market conditions for such gasifiers in the US particularly.

After providing an introduction and overview of gasification theory, current technology and challenges including, feedstock, and gas clean up, this report focuses primarily on the recent emergence of commercially successful pre-packaged, and integrated gasifier systems producing heat and electrical power (CHP) at micro (~50 $kW_{electrical}$), to small-scale (<500 kW_e). The report also provides updates on the operation of several successful

medium-scale gasifiers with CHP (>1 MW_e) that were previously profiled in an earlier 2010 gasifiers report by the WSU Energy Program[1].

Gasification is a thermochemical conversion process producing both heat and a relatively low energy-content combustible gas called *producer gas*. In contrast, traditional biomass combustion produces only heat, most commonly in a furnace, with an attached boiler generating steam or hot water for thermal applications, which may include electric power generation. With gasification, generation of the combustible gas is key to its importance. This gaseous fuel, once properly processed, may directly provide fuel for an internal combustion engine generating electricity, or it may be used as a boiler fuel. Gasification can also enable combined heat and power (CHP) at much smaller scale and higher electrical efficiency than in traditional steam-driven biomass CHP systems.

In addition to heat and power, there are a wide array of co-products possible with gasification that may improve the cost effectiveness of a gasification project and add environmental benefits. Significantly, biochar can readily be produced in the gasification process, as it can in traditional boilers. Char has several demonstrated markets and gives gasification the potential to be a carbon neutral or even possibly a carbon negative energy producer. Both combustion and gasification produce ash, which can also be marketed. Although not detailed in this report, some gasification processes can yield a higher energy *product gas* that may also be used as a feedstock to produce hydrogen and liquid hydrocarbons, such as ethanol, diesel, and other chemical precursors.

A small number of medium and large-scale gasifiers have been operating successfully in Europe and elsewhere for years, typically supported in part by government financial support and subsidies, such as electrical power feed-in tariffs. If and when subsidies ended or were withdrawn, many of these gasifier plants have shuttered, not being cost-effective. This report surveys such larger plants, focusing on two successful examples that have continued to operate for years. With increasing fossil fuel prices and carbon-offset markets maturing in Europe and beginning in the United States, gasifiers at all scales are likely to become cost-competitive, reinvigorating their developers. Evidence exists that this has already begun for small-scale, mass-manufactured gasifiers.

This report is intended primarily for use by the forest products and allied industries as well as other stakeholders in forestry and energy to help them understand how gasifiers work, the current state of their technical and market development, practical applications in the industry as well as barriers to their wider application in the United States. With recent developments in design standardization and factory production, small integrated and pre-packaged gasifiers are now beginning to be sold and applied worldwide. Gasifiers are also being applied by energy-focused solution providers unrelated to the wood products industries, providing renewable on-site heat and power in a variety of commercial and industrial facilities. Developers of this type will also find value in this report.

[1] Clean Heat and Power Using Biomass Gasification for Industrial and Agricultural Projects; Carolyn Roos PhD.; February 2010

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Introduction

With increased awareness of climate change and the urgent need to lower carbon emissions on a large scale, demand for low-carbon energy production has been increasing. Traditionally, electricity has been produced in centralized power plants through the combustion of coal or natural gas to drive a generator with a thermal engine of some type. Most industrial, commercial, and residential facilities in the United States derive their electricity from these power plants. Similarly, for commercial and industrial heating, most facilities in the United States either operate a furnace or a boiler by combusting natural gas or use electricity to heat water or air. The water or air then distributes heat throughout the building for climate control. In the case of industrial facilities, the heat may be used to power industrial applications. Constantly increasing concerns about carbon emissions associated with these traditional energy conversion processes have driven development of low-carbon energy supply alternatives. Some carbon-neutral electricity generation methods include solar, wind, hydro power, biomass (per federal policy)[2], and nuclear. Where thermal energy is required, current low-carbon options include biomass (such as wood, crops, or manure), biogas (such as landfill gas), geothermal, green hydrogen, solar thermal, renewable natural gas, and renewable diesel. This report focuses on a particular – and currently uncommon – process to exploit the largely untapped woody biomass resources available: producing combustible biogas through a process called *gasification*.

In short, gasification turns biomass into a combustible gas by heating, pyrolyzing and partially combusting it under specific conditions. This process is typically exothermic, so it is self-driving once initiated, and may produce significant thermal energy in addition to the combustible gas. The so-called *producer gas* produced can then be used to power an internal-combustion engine-generator, allowing production of both thermal energy through the gasification process and electricity through the engine powerplant. This gas may also fuel a traditional boiler, but a direct biomass-fueled boiler would typically be a better choice for producing heat alone. Alternately, gasifiers may be designed to produce a *product gas* containing different precursor constituents for production of a variety of organic chemicals. Varieties of gasification are described in some detail in a following section, but this report focuses primarily on gasifiers making producer gas for combined heat and power applications.

Demand for gasifier technology has grown in recent years as communities seek low-carbon energy options and generally reduced environmental impacts from combustion of forestry industry process woody wastes. Wood gasification is particularly appealing, since wood is considered a zero net carbon fuel in many jurisdictions (a matter some have debated)[3], though installations are typically limited to sites where wood feedstocks of acceptable quality and quantities are readily available. Large-scale gasification technology has had limited success in both the US and abroad when supported by subsidies, but small-scale gasifiers are a newer and separate development, offering different opportunities and challenges. European gasifier manufacturers in particular have

[2] Per Federal policy as of 2018: https://docs.house.gov/billsthisweek/20180319/BILLS-115SAHR1625-RCP115-66.pdf
[3] https://www.scientificamerican.com/article/congress-says-biomass-is-carbon-neutral-but-scientists-disagree/

relatively recently developed numerous successful small-scale commercial gasifiers fueled with higher-quality wood feedstocks, and these products have been operating successfully at customer sites. But even though these small-scale gasifiers have begun to demonstrate commercial viability abroad, they have not yet achieved any commercial market penetration success in the United States. In fact, this research has found only one small-scale gasifier manufacturer headquartered in the US with established commercial success.

Importantly biomass fuel feedstocks' value varies widely by type and location. In many areas – notably those with limited access to haul wastes – most all waste from forestry activities remains unused. In other settings, wood waste is regulated and costs money to dispose of. In some areas, wood chips, pellets, and shavings, as well as bark and even branches, leaves and other pruning offal, once considered simple waste to burn freely or cast aside, are now valued commodities to sell. Increasing demand for biomass in various forms and wood of all sizes that were once wasted is also coming from both more efficient utilization of the wood in primary timber products (e.g., cross-laminated timber and panels, composite products, etc.), as well as a plethora of by-product industries using wood fibers. Notably, these include several bioenergy conversion technologies, both in the U.S. and abroad. Summarized in Table 1, these trends appear likely to continue and expand.

Additionally, volatile prices for conventional energy sources, active renewable energy credits markets and emergent markets for greenhouse gas emissions reductions are changing the economics and are also driving society toward more efficient use of our biomass resources. As an example, rising electricity prices and increasing demand for renewable energy have made biomass-fired power plants and combined heat and power (CHP) systems more attractive.

When it comes to the availability and use of biomass for heating and/or electricity production, each region is unique in terms of its needs. Not all regions that have plentiful biomass resources make use of it, and there are countries with high demand for bioenergy and low supply that import biomass from other countries. The IEA Bioenergy group quantifies the relationship between availability and demand including global trends across countries in their 2021 report, "IEA Bioenergy Countries' Report-Update 2021: Implementation of Bioenergy in the IEA Bioenergy Member Countries." [1] The authors consider the amount of bioenergy from biomass used in each country and compare this with the domestic forest area in each country, respectively. One observed trend is that countries that use a lot of biomass to meet their energy demands tend to have a large amount of domestic forest area per capita [1]. Population density plays a role as well, with low population density generally corresponding to larger amounts of available biomass resources. Countries with high solid biomass use tend to have important wood processing industries in addition to high domestic forest area per capita [1].

Annual forest growth volume additions relative to use must also be considered. For example, even countries with high biomass usage may not need to import biomass if their annual use is lower than their forest's annual additions. Countries like Germany, Austria, and Italy have both higher levels of solid biomass use relative to their forest square footage, but their forests have higher additions due to better climatic conditions compared to other countries [1].

Biomass gasification can help to support these changes by achieving higher efficiencies in generating heat and electricity and lower emissions compared to traditional combustion heating technologies. Further, gasification increases the possible uses of biomass since the producer gas has value not just as a fuel in itself, but also as a potential feedstock to produce other fuels, such as ethanol and hydrogen, and as a chemical precursor in an economy that is increasingly valorizing recycled materials. Several gasifiers profiled in this report produce biochar as a byproduct, illustrating this: When added to soil as an amendment – its most common application – carbon is sequestered in soils for a long period, with positive impacts on greenhouse gas accumulations. Some gasifiers producing biochar are claiming that their useful energy producing operations can actually be carbon-negative under the proper circumstances. These are advertised as having the potential to provide a significant and growing revenue stream to their operators.

While there has been significant interest in biomass gasification for many years, its technical and market developments have been repeatedly delayed by technical difficulties due to the high biomass feedstock quality requirements, as well as the typical scale of operations. Recently, technological advances particular to biomass gasification including better systems control– and in particular, standardization and testing of components and systems in packaged gasification products - have been successfully demonstrated and commercial-scale production of these packaged systems by several manufacturers are proceeding.

Table 1. Summary of Current Woody Biomass Energy Conversion Technologies

Technology	Technology Status	Possible Products	Facility Type
Thermochemical Conversion			
Biomass Combustion	Mature	Power, heat, **cooling,** biochar, soil amendments, and other co-products	Wide range of facility types, including residential, commercial, institutional, forest products, industrial, agricultural and food industries
Biomass Gasification	Early Commercialization	Power, heat, combustible gas, chemical feedstocks, hydrogen, biochar, soil amendments	Primarily forest products wastes but also waste from agricultural/food processing industries, as well as commercial / institutional settings in foreign countries
Biomass Pyrolysis	Early Commercialization	Power, heat, liquid fuel ("bio-oil"), combustible gas, chemical feedstocks, soil amendments, biochar	Forest products industries
Biochemical Conversion			
Lignocellulosic Conversion	Research & Development; demonstration projects in development	Cellulosic ethanol, chemical feedstocks, hydrogen, and other co-products	Biofuels and biorefineries, especially in the forest products industry

Comparing Gasification to Other Thermal Conversion Processes

Combustion, gasification, and pyrolysis are three thermal conversion processes by which energy is obtained from biomass. Distinctions between these three processes are summarized in Tables 1 and 2. In short, combustion occurs with sufficient oxygen to completely oxidize the fuel, i.e., convert all carbon to carbon dioxide, all hydrogen to water, and all the sulfur to sulfur dioxide. Gasification occurs with insufficient oxygen or with steam such that complete oxidation does not occur. Pyrolysis occurs in the absence of an oxidizing agent (air, oxygen, or steam). As an intermediate process between combustion and pyrolysis, gasification is sometimes referred to as "partial oxidization" and sometimes as "partial pyrolysis."

Gasification, combustion, and pyrolysis each have advantages and disadvantages. In any particular project, it is important to evaluate the goal of the project, the biomass resources available, and particular needs of the facility in choosing a thermal conversion process.

Gasification versus Combustion

In choosing between gasification and combustion, consider if generating a product gas is an advantage. Also, consider the possibility of achieving higher electrical generation efficiency by burning producer gas directly in either a reciprocating engine or combustion turbine, as opposed to using direct combustion of biomass to make steam for use in a typical steam power generation scheme. If/where carbon emission reductions associated with gasification and CHP energy conversion can be documented as described in following sections, this may also add value in emerging carbon offset markets.

Combustion technologies are well-established and widespread. While gasification has been successfully demonstrated in projects of several megawatts in size over a number of years, it is still an emerging commercial technology. As capital costs drop, operations mature, and the economic value of carbon emission reductions increases, cost effectiveness of gasification compared to combustion is expected to improve.

Gasification versus Pyrolysis

Another promising thermal conversion technology, sometimes confused with gasification, is pyrolysis. While gasification occurs with restricted oxygen, pyrolysis occurs in the absence of oxygen or steam. In pyrolysis, biomass is heated to the point where volatile gases and liquids are driven off and then condensed into a combustible, water soluble liquid fuel called bio-oil (not to be confused with biodiesel.) Bio-oil from fast pyrolysis[4] is a low viscosity, dark-brown fluid with a high tar content and a water content of 15% to 20%. Bio-oil can be burned in a boiler, upgraded for use in engines and turbines, or used as a chemical feedstock. Being a liquid fuel, bio-oil is easier to transport than syngas, but its corrosiveness makes long-term storage difficult.

Both gasification and pyrolysis can produce char, which may be used as a soil amendment, a precursor to activated carbon, or burned. Slow pyrolysis results in a higher percentage of char (up to 35%), if that is a more desired co-product. Some uses of the biochar can provide carbon sequestration benefits (refer to the section “Environmental Advantages” below).

Pyrolysis is a less mature technology compared to gasification. Some manufacturers of pyrolysis reactors include Klean Industries (Canada), Plastic Advanced Recycling Corp (US), and PYREG (Germany). The focus of Klean Industries and Plastic Advanced Recycling Corp is on plastic recycling and generating fuel from plastic waste while PYREG’s technology is compatible with a wider variety of feedstocks [2-4]. For more information on pyrolysis, refer to IEA Bioenergy’s PyNe website at http://www.pyne.co.uk/ and the Bioenergy Technology Group’s website at http://www.btgworld.com/index.php?id=22&rid=8&r=rd.

In choosing between gasification and pyrolysis, one must consider if biochar and/or liquid fuel production are a priority for your application. In particular, a liquid fuel, such as bio-oil, has a higher energy density than syngas, which reduces transportation costs. On the other hand, bio-oil is corrosive, which increases transportation and storage costs.

[4] Fast pyrolysis occurs at a relatively low temperature of around 500°C (900°F) and the biomass has short residence times of 2 seconds or less. Intermediate and slow pyrolysis occur at higher temperatures and have longer residence times. As residence time increases, char content increases (up to about 35%), tar content decreases and water content of the bio-oil increases (up to about 75%).

Table 2. Comparison of Combustion, Gasification and Pyrolysis

	Combustion	Gasification	Pyrolysis
Oxidizing Agent	Greater than stoichiometric supply of oxygen*	Less than stoichiometric oxygen* or steam as the oxidizing agent	Absence of oxygen or steam
Typical Temperature Range with Biomass Fuels	800ºC to 1200ºC (1450ºF to 2200ºF)	800ºC to 1200ºC (1450ºF to 2200ºF	350ºC to 600ºC (660ºF to 1100ºF)
Principal Products	Heat	Heat and Combustible gas	Heat, Combustible liquid and Combustible gas
Principal Components of Gas	CO_2 and H_2O	CO and H_2	CO and H_2

* In stoichiometric combustion, air supply is the theoretical quantity necessary to completely oxidize the fuel. For cellulosic biomass, which has an average composition of $C_6H_{10}O_5$, the stoichiometric air supply is 6 to 6.5 lb. of air per lb. of biomass.

Table 3. Predominant Components of Products from Pyrolysis and Gasification

	Oil and Tars, Water (Liquid)	Char (Solid)	Producer Gas
Fast pyrolysis Medium temperature, T=~500ºC Short residence time (<2 s)	60% to 70%	10% to 15%	10% to 25%
Slow pyrolysis [5] Temperature, T=~620C Heat rate (10C per min)	~43%	~32%	~25%
Gasification Higher temperature, T>800ºC	Up to 20%[1]	Up to +20%[2]	~85%

1. Updraft gasifiers produce 10% to 20% tar, while tar content from downdraft gasifiers is low.
2. Downdraft gasifiers produce 20% or more char, while char content from updraft gasifiers is low.

Principles and Advantages of Gasification

Gasification is a thermochemical conversion process – like traditional combustion – producing both heat and a combustible producer gas. The primary difference between gasification and combustion is that in gasification the producer gas is removed before it can combust, while in combustion, that reaction occurs immediately in the presence of sufficient oxidant (typically oxygen). One method of gasification, referred to as "partial oxidation," is very similar to combustion except that it occurs with insufficient oxygen supply for complete combustion to occur. In a second method of gasification, the biomass is indirectly heated in the absence of oxygen or air, with steam as the oxidizing agent.

Gasification produces either a medium-energy content gas referred to as "synthetic gas" or "*syngas*" or a low-energy content gas often referred to as "*producer gas*."[5] Syngas, which is required for chemical production (such as biomass-based "synfuels") consists primarily of carbon monoxide and hydrogen. Syngas is produced by either indirectly heating biomass in the absence of oxygen or by using pure oxygen to oxidize the biomass ("oxygen-blowing"). In contrast, producer gas oxidizes the biomass using air ("air-blowing"), which dilutes the combustible components of the gas with nitrogen. Critically, such producer gas is adequate for either direct combustion in a boiler or for power generation in specially configured engines. This approach to gasification avoids the energy use and/or attendant costs associated with oxygen production or the complexity of indirect heating and is the approach used in all the gasifiers researched in detail for this report.

Producer gas can be burned in conventional boilers, furnaces, engines, and turbines, or co-fired with natural gas, with engines and turbines requiring producer gas to be adequately cleaned, while boilers and furnaces are more tolerant of impurities. Since both producer gas and syngas have lower heating values than propane or natural gas, enlarging fuel injection orifices and adjusting control settings is typically required as a minimum modification.

A note on terminology: The term "gasifier" is also commonly used in the biomass industry to describe staged-air combustion furnaces and boilers in which producer gas generated in a partial-combustion first stage is further combusted in a second stage of an integrated or closely coupled unit with no provision for separately collecting the unburned producer gas. However, in this guide, the terms "gasifier" and "gasification" are exclusively used to refer to equipment that is designed to obtain primarily a combustible producer gas, and often heat as separate products.

[5] It is quite common and accepted to use the term "syngas" to refer to the producer gas in general, whether syngas or producer gas as defined here. However, other references make a clear distinction in terminology, as does this guide. Some references also use the term "biogas" to refer to the producer gas of biomass gasification. However, this name is easily confused with the methane-rich gas produced by anaerobic digestion, which is more commonly referred to as biogas.

Advantages of Gasification over Other Biomass Energy Conversion Processes.

Use of producer gas in engines increases efficiency of electricity generation from biomass. An important advantage of biomass gasification compared to combustion is its potential to achieve higher efficiencies and lower emissions. Generating a gaseous fuel makes the use of reciprocating engines, gas turbines and potentially fuel cells possible in the generation of electricity. These prime movers produce a higher ratio of electricity to heat than the steam turbines that are most commonly used for generating electrical power with biomass. The electrical efficiency of biomass-fired steam turbine systems are between 20% and 25% with the notable exception of backpressure steam turbines, which can only be employed effectively under specific circumstances[6]. In comparison, producer gas fueled engines and turbines can achieve electrical system efficiencies in the range of 30% to 40%, at many scales, from 25 kW to many megawatts.

Gasification can facilitate combined heat and power. Traditional separate heat and electric power generation result in net delivered efficiency ranging from 40-60 percent while CHP systems regularly achieve efficiencies in excess of 75%. If heat from both the gasification process and electrical generation are recovered, overall efficiencies of up to 90% can be achieved. Because gaseous fuels can be piped over a distance, gasification can facilitate combined heat and power projects in cases where the best use of heat from the gasifier and the best or most convenient use of the producer gas are not co-located.

In the most cost-effective CHP projects, heat recovery is cascaded through a series of applications with each step using a lower temperature. Heat can be recovered from both the gasification process and from electrical generation equipment. Waste heat can be used in a variety of ways, such as generating steam and hot water, space heating, generating power using an organic Rankine cycle power generation, or meeting cooling and refrigerating needs with absorption chillers.

A variety of products are possible with gasification. The gasification process results in co-products that may result in other revenue streams for an operator. The oils, char and ash that are generated in gasification may be captured, depending on gasifier configuration, and sold as precursors for products such as soil amendments, filtration media and cement additive, given proper market conditions. The char in particular can have a high value as a co-product, as discussed in detail below. Syngas can be used as a feedstock to produce other fuels (such as ethanol, methanol, naphtha, hydrogen, gasoline, and diesel) and as a precursor for chemicals (such as acetic acid, dimethyl ether, and ammonia). In this report we focus only on direct use of producer gas for combustion along with capture of biochar and ash as marketable byproducts.

Gaseous fuels are easier to transport than solid biomass. Gaseous fuels may be distributed by pipeline from a gasification plant for direct use in other locations if/as

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[6] Installing a *backpressure steam turbine* for pressure reduction provides an efficient means to generate electric power for biomass where a steam boiler operating at more than 150 psig. is supplying loads that can operate at low pressure (typically less than a third the boiler pressure), with consistently large steam loads. These conditions are becoming uncommon, because of the multiple operational challenges associated with steam heat in general and high-pressure steam in particular.

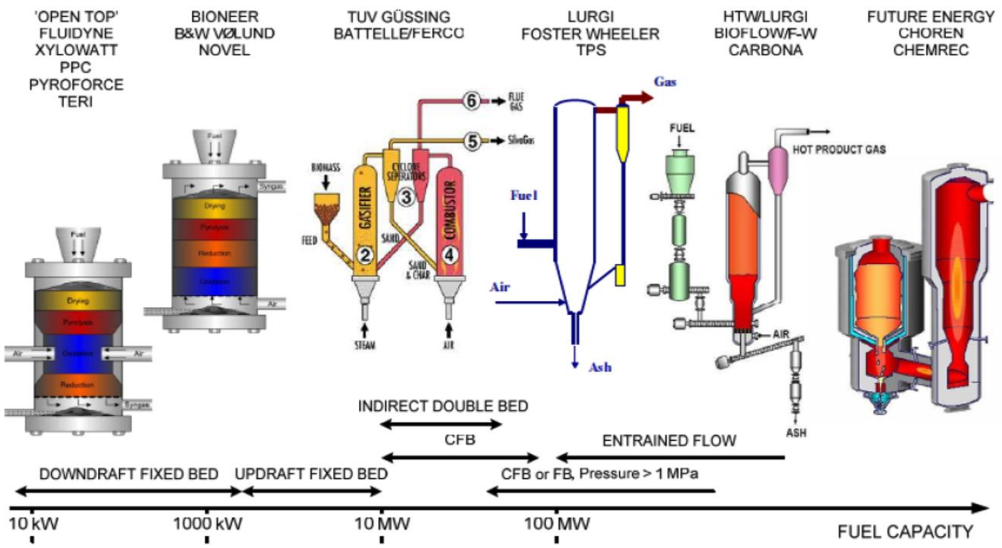
needed. There are various scenarios where this would be an advantage. As one example, a gasifier could be located at the most convenient point of biomass collection with the producer gas piped to users located off site. As another example, available space within a manufacturing facility may prohibit locating a biomass-fired boiler or furnace and its ancillary equipment within the facility. In this case, a gasifier could be located elsewhere with the producer gas piped to the point of use. Whenever possible, the gasifier should still be located where there is a use for its heat to achieve the highest efficiencies possible with CHP systems.

Landfill gas use in the United States serves as an illustration of this potential. Of the approximately 500 landfill gas projects existing in the U.S., about a third pipe the gas in dedicated pipelines to nearby industrial customers to offset fossil fuel use. Biogas pipelines range from 200 yards to more than 20 miles.

Types of Gasifiers

Types of gasifiers currently used in biomass gasification include fixed-bed, fluidized-bed, entrained gas, and indirectly heated steam gasifiers. Characteristics of these types of gasifiers are summarized in Table 4. Other types of gasifiers, discussed only briefly here, include entrained bed, plasma arc, and super-critical water gasifiers. Within these general classifications, there are many different designs that have been developed.

Figure 1: Principal gasifier types [6]



Fixed-Bed Downdraft and Updraft Gasifiers

The most common types of fixed-bed gasifiers are downdraft (or co-current type) and updraft (or counter-current type). Each gasifier manufacturer has their own proprietary design, but even so the core of these designs usually falls into one of these two categories.

Fixed-bed gasifiers typically operate on a smaller scale than other types and so are often the most suitable choice for many types of biomass projects, such as in co-located forestry industries, where both heat and power will be valued. The largest fixed bed gasifier for woody biomass found is currently sized below 2 MW (input fuel rate).

The defining difference between updraft and downdraft gasifiers is the direction of gas flow through the unit, as shown in Figure 1. In downdraft gasifiers, the oxidizing agent (air or pure oxygen with or without steam) enters at the top of the gasifier with producer gas exiting at the bottom. Gas flow is the reverse in updraft gasifiers.

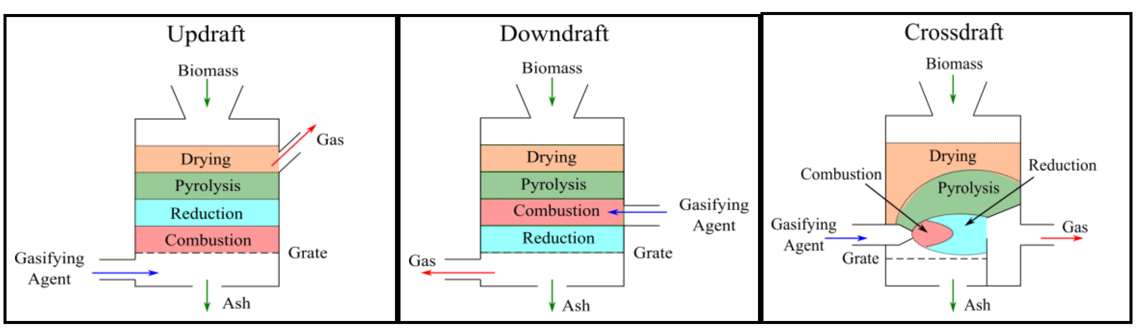
In *downdraft gasifier*, both the gasifying agent and the biomass are simultaneously fed in at the top of the gasifier. It has a moderate range of acceptable feedstock particle sizes from, 1.57 - 3.94 inches (40-100 mm) and accepts feedstocks with up to 30% moisture content [7]. It also has lower carbon conversion capability and lower cold gas efficiency compared to the updraft design. With these limitations, the downdraft gasifier is typically best suited for small-scale, packaged applications (defined here as 10 kW - 1 MW) [7].

This design has the advantage of low tar production and low fugitive exhaust particle content in the producer gas. They have outlet temperatures of 800°C (1450°F) and operating temperatures of 800°C to 1200°C (1450°F to 2200°F). A drawback of downdraft gasifiers is that the feedstock must have a moisture content of about 30% or lower. As discussed in the Section "Feedstock Characteristics and Requirements" below, materials meeting this limit include dry woods, nut shells, and rice husks. Other materials can be dried, but drying moist feedstocks impacts the cost effectiveness of a project because of the cost of the dryer and the energy required for drying.

The *updraft gasifier* has been the principal gasifier used for coal gasification for 150 years. Updraft gasifiers have high thermal efficiency, are also easy to control, and are more tolerant of fuel variability or switching than downdraft gasifiers. In an updraft gasifier, the biomass is introduced from the top side of the vertical vessel reactor (inside of the gasifier where gasification occurs) with the gasifying agent introduced from the bottom side of the reactor. Updraft gasifiers have high carbon conversion (which refers to the percent of carbon in the feedstock that is converted into biochar and other carbon-based products), can handle a wide range of feedstock particle sizes from 0.20 - 3.94 inches (5 - 100 mm), and can handle feedstocks with up to 60% moisture content [7]. As such, this type of gasifier is suitable for small and medium scale applications. Updraft gasifiers also have the highest *cold gas efficiency* (defined as the ratio between the calorific value of the producer gas after all cleaning/processing and the total feedstock energy input), when compared with downdraft and cross-draft gasifiers [8]. However, this type of gasifier also has high tar production and high fugitive exhaust particle content in the producer gas. As such, updraft gasifiers are the least suitable to use in a pre-built and packaged CHP system, since the producer gas needs substantial cleaning before it can be used in an engine [8]

Updraft gasifiers have outlet temperatures of 250°C (480°F) and operating temperatures of 800°C to 1200°C (1450°F to 2200°F). An advantage is that they can handle feedstock moisture contents as high as 55%.

Figure 2. Updraft, Downdraft, and Crossdraft Fixed-Bed Gasifiers* [9]



**** There are many variations in specific designs. For example, solid fuel is not fed from the top in some designs.***

In a *cross-draft* gasifier, the gasifying agent enters at high speed (a jet) through a single nozzle which induces substantial circulation and flows across the bed of biomass and char. This gasifier performs poorly when it comes to tar cracking (the decomposition of tar into non-condensable gases at high temperature) and therefore has high tar production, though its performance is better than the updraft design in this regard [8]. As such, cross-draft gasifiers need minimal producer gas cleaning compared to updraft gasifiers. While this design is the simplest and therefore cheapest of the three fixed bed gasifier designs, it also has the lowest cold gas efficiency, lowest producer gas lower heating value (LHV), and the lowest tolerance for feedstock moisture content and particle size compared to updraft and downdraft gasifiers [8]. As a result of these key limitations, cross-draft gasifiers are not often seen in commercial applications [10].

Floating Fixed Bed Gasifiers

The floating fixed bed gasifier, a cross between a fixed bed and fluidized bed gasifier, is a newer gasifier design. Unlike the fluidized bed design, the floating fixed bed design builds up a stable bulk bed in a pyrolysis chamber that floats on the gasifying agent stream from the inlet. After pyrolysis, the particles move to a second, floating-bed reactor. Because pyrolysis occurs in a separate reactor, particle movement in the floating bed reactor is more controlled than in the fluidized bed design. This allows for longer gas residence times and therefore lower tar concentrations in the producer gas. As a result, the floating fixed bed gasifier design can be used in small-scale applications.

SynCraft is one example of commercial success for this design. The company succeeded in developing a floating fixed bed gasifier in 2007 and has built and sold a few models for applications as small as 220 kWe / 328 kWth.

Fluidized Bed Gasifiers

In fluidized bed gasifiers, the oxidizing agent and fuel are mixed in a hot bed of granular solids. Solid fuel and bed particles are fluidized by gas flow. The bed is usually composed of sand, limestone, dolomite, or alumina. Gases and remaining solids are separated afterwards by cyclone. There are two types of fluidized bed gasifiers: bubbling and circulating. Bubbling fluidized bed gasifiers are appropriate for medium size projects of 25 MWth or less, while circulating fluidized bed gasifiers can range from a few MWth up to very large units.

Fluidized bed gasifiers are especially suited for biomass gasification. They have very good fuel flexibility and so can be considered true multifuel units. Wood waste, straw, and refuse-derived fuel, as examples, can be gasified in the same unit, although the heat output varies with the heat value of the fuel. Fluidized bed gasifiers reduce gas contaminant problems often associated with agricultural biomass. Due to their lower operating temperatures, ash does not melt, which makes its removal relatively easy and reduces problems with slagging. Sulfur and chloride are absorbed in the bed material, reducing fouling and corrosion.

Fluidized bed gasifiers are more compact per unit power and have higher throughput than fixed bed gasifiers. Their efficiency is lower but can be improved by recirculating gas. The producer gas has low tar content but has a high level of particulates.

Indirectly Heated Steam Fluidized Bed Gasifiers

Indirectly heated steam gasification (also known as allothermal gasification) [11] was specifically designed to take advantage of biomass characteristics such as high reactivity, low ash, low sulfur, and high volatile matter. Additionally, indirectly heated steam gasification is especially well suited for the production of medium calorific value syngas, which allows for pairing of these gasifiers with turbines or for their use in biofuel production [12] .The development of other types of biomass gasifiers was heavily influenced by coal gasification technology so they are not optimum for biomass. For example, the high reactivity of biomass means that greater throughputs (i.e., higher rate of gasification) are possible with indirectly heated steam gasifiers, but the throughputs of other types of gasifiers are very limited. Throughputs of indirectly heated gasifiers can be several times that of other types of gasifiers. While this design would appear ideal for woody biomass gasification, indirectly heated fluidized bed gasifiers have typically been large gasifiers, with smaller pilot scale gasifiers around 50 kWth slowly beginning to emerge [13].

The SilvaGas or Taylor-type indirectly heated gasifier consists primarily of two chambers: the gasifier and the combustor, with both chambers being fluidized beds. These types of gasifiers fall under the broader category of indirectly heated steam dual fluidized bed (DFB) gasifiers [13]. In the gasifier, the biomass mixes with steam and a heated solid medium, such as sand, in a circulating fluidized bed. The biomass is rapidly converted into syngas, char, and tars at a temperature of approximately 1550°F (850°C). The solid particles – char and sand – are separated from the gas stream and directed to the combustor where the char is burned, reheating the circulating sand to 1800°F (1000°C). The reheated sand is then conveyed back to the gasifier to supply energy for gasification of the incoming biomass. The bubbling fluidized bed indirect gasifier developed by Manufacturing and Technology Conversion International, Inc. (MTCI), primarily used for black liquor and paper mill sludges, and is similar in that it consists of two stages, a lower combustor, and an upper steam reforming stage.

Indirectly heated gasifiers are inherently more complicated than directly heated systems due to the need for a separate combustion chamber, and so have a higher capital cost. This is offset to a certain degree compared to oxygen-blown gasifiers because an oxygen separation plant (with its efficiency penalty) is not required.

Indirectly heated gasifiers produce high quality syngas without the need for pure oxygen. The syngas has a higher percentage of methane and higher hydrocarbons, which poses a greater challenge in producing liquid fuels, chemicals, and hydrogen.

Significantly fewer emissions are produced in this process. In particular, not having oxygen in the gasifier makes it impossible to form dioxins if a chlorine-containing feedstock (such as processed municipal solid waste or recycled paper pulp sludges) is used.

The very successful indirect steam DFB demonstration plant in Gussing Austria (2002-2016) produced 8MWth and was inspiration for more recent demonstration plants like those in Oberwart, Austria (2008-2015) (8.5 MWth), Nongbua, Thailand (1 MWth) and Daigo, Japan (1.4 MWth), as well as an upcoming demonstration project in Gaya, France (planned for 2023). The Gussing plant is often cited as a successful example of the DFB indirect steam gasification process and is used as a basis for the design of other DFB plants, which are often said to use the “Gussing Process.” It operated until 2016 and was only shut down due to the loss of a feed-in tariff in October 2016. [13]

Repotec began construction on a combined IGCC and CHP indirect steam DFB gasification plant in Senden Germany in 2009. The plant reached commercial operations in the beginning of 2012. The gasifier is rated for 14 MWth, with 5 MWe going to electricity and 6.5 MWth going to district heating, leading to a total efficiency of over 80%. This plant is one of many inspired by the Gussing plant. It appears that this plant is still operational. [14]

Repotec also built the indirect steam DFB "GoBiGas" plant in Gothenburg, Sweden (32 MWth). This plant was built specifically for biomethane production (20 MW), with an additional 2.5 MWth of district heating coming from the production process. The plant was built from 2010 to 2012 and has been shown to have an efficiency of approximately 65% when producing biomethane. This plant was the first to deliver biomethane to the national grid in Sweden and appears to have been successful in its operation (demonstration considered successful by 2018). Phase 1 had met all pre-set performance goals and demonstrated the technology was ready for commercial use. There was a second phase planned, which would have delivered 80-100 MW of biomethane. However, this never came to fruition and the original plant was mothballed because it could not reach "commercial break-even." [15]

Very recently, papers have been published on a small 50 kWth indirect steam gasifier referred to as an Indirectly Heated Bubbling Fluidized Bed Steam Reformer (IHBFBSR). It was designed, built, and commissioned by the Dutch company Petrogas – Gas Systems in collaboration with the Delft University of Technology. This gasifier appears to be first of its kind. The earliest paper found on this gasifier was published in December 2021, but results from studies are promising.

"Gasifying Boilers" - A Special Case - Close-coupled Gasifiers

"Close-coupled" or "multi-stage" gasifiers[7] are essentially staged-air combustion devices (i.e., boilers or furnaces). Staged-air combustion is a conventional technology that is widely applied in both large and small combustion systems. In any combustion of a solid – whether in a woodstove, furnace, or boiler – volatile materials are first pyrolyzed and gasified followed by full combustion of gases. Most commonly, these processes occur in a single stage. In staged-air boilers and furnaces, thermal conversion occurs in two stages of an integrated unit. In the first stage, the biomass is gasified by restricting air flow and thus oxygen. In the second stage, sufficient air is supplied for full combustion of the gases. Producer gas is not extracted from staged-air combustion appliances as a separate product. In this guide, the term "gasifier" refers only to appliances that produce a combustible gas as a separate product. The primary advantage of staged-air combustion compared to conventional single-stage boilers and furnaces is reduced air emissions.

Leading examples of related modern "close-coupled" gasifying biomass CHP power plants that do not employ gas separation include Dall Energy's installation at Sindal,

[7] Integrated staged-air combustion appliances units are sometimes called "two-stage" or "multi-stage" gasifiers, not to be confused with indirectly heated steam gasifiers, which are also often referred to as "two-stage" or "dual-stage" gasifiers.

Denmark and other locations and HoSt Bioenergy Systems state of the art 15 MW 'bioenergy plant' in Andijk, Netherlands [16-18]

Other Types of Gasifiers

The gasifier types below are either still in development or applicable only to very large or specialized applications. They are unlikely to affect the commercialization of woody biomass gasification in the foreseeable future:

Entrained Bed Gasifiers: In entrained bed gasifiers, fine feedstock particles are suspended by the movement of gas to move them through the gasifier. An example of an entrained bed gasifier is the Chemrec black liquor gasifier. A Chemrec gasifier was installed in 1996 at the Weyerhaeuser mill in New Bern, North Carolina. Entrained bed gasifiers require large scale to be cost effective and so are not practical for many biomass projects.

Supercritical Water Gasifiers: Materials with moisture contents up to 95% can be gasified with the use of supercritical water. This process is still in development but promises to widen the range of possible feedstocks. (For more information on supercritical water gasification, refer to Biomass Technology Group's website at https://www.btgworld.com/en/)

Plasma Arc Gasifiers: In plasma arc gasification, electricity is fed to a torch, which has two electrodes, creating an arc. Inert gas is passed through the arc, heating the process gas to internal temperatures as high as 14,000°C (25,000°F). The temperature a few feet from the torch can be as high as 3,000°C to 4,000°C (5,000° to 8000ºF.) Because of these high temperatures the waste is completely destroyed and broken down into its basic elemental components. Plasma arc gasification has been used in the gasification of municipal solid waste, especially in Asia.

Table 4. Summary of Selected Biomass Gasifier Types

Gasifier Type	Scale	Typical Temperatures		Fuel Requirements		Efficiency	Gas Characteristics	Other Notes
		Reaction	Operating	Moisture Content (%)	Flexibility			
Downdraft Fixed Bed	5 kW_{th} to 2 MW_{th}	1000°C (1800°F)	800°C (1450°F)	<20%	• Less tolerant of fuel switching • Requires uniform particle size • Large particles	Very good	• Very low tar • Moderate particulates	• Small Scale • Easy to control • Produces biochar at low temperatures. • Low throughput. • Higher maintenance costs
Updraft Fixed Bed	<10 MW_{th}	1000°C (1800°F)	250°C (480°F)	up to 50%-55%	• More tolerant of fuel switching than downdraft	Excellent	• Very high tar (10% to 20%) • Low particulates • High methane	• Small- and Medium-Scale • Easy to control • Can handle high moisture content • Low throughput
Bubbling Fluidized Bed	<25 MW_{th}	850°C (1550°F)	800°C (1450°F)	Flexible	• Very fuel flexible • Can tolerate high ash feedstocks • Requires small particle size	Good	• Moderate tar • Very high in particulates	• Medium Scale • Higher throughput • Reduced char • Ash does not melt • Simpler than circulating bed
Circulating Fluidized Bed	A few MW_{th} up to 100 MW_{th}	850°C (1550°F)	850°C (1550°F)	Flexible	• Very fuel flexible • Can tolerates high ash feedstocks • Requires small particle size	Very Good	• Low tar • Very high in particulates	• Medium to Large Scale • Higher throughput • Reduced char • Ash does not melt • Excellent fuel flexibility • Smaller size than bubbling fluidized bed
Indirectly Heated Steam Gasification	Large scale	850°C (1550°F)	800°C (1450°F)	Flexible	• Very flexible, does not require sizing, pelletizing, or drying	Excellent	• High methane yield	• Very high throughput • Low emissions, even with high chlorine feedstocks such as MSW • High capital cost

Gasifier Feedstock Characteristics and Requirements

Almost any carbon containing material can be gasified, provided the material meets requirements of the particular equipment. Moisture content and chemical content of feedstocks should be carefully considered. Also, different kinds of gasifiers have different requirements for particle size and uniformity.

Moisture Content

Moisture content is critical in combustion, gasification and pelletization. Maximum moisture contents required for gasification depend on the gasifier type. Downdraft fixed bed gasifiers cannot tolerate moisture contents above about 20%. Updraft fixed bed gasifiers and fluidized bed gasifiers can tolerate higher moisture contents of 50% and 65%, respectively.

Wastes with very high moisture contents often cannot be dried cost effectively. For these wastes, other conversion technologies may be more suitable.

The moisture contents of some common biomass feedstocks are summarized in Table 5.

Chemical Content

The chemical content of biofuels influences slagging, fouling and corrosion of gasifier and heat exchanger components.[8] For most biomass fuels, silicon, potassium, calcium, chlorine, sulfur and to some extent phosphorous, are the principal elements involved in the fouling of surfaces. In general feedstocks for gasification should preferably have a high carbon-to-nitrogen ratio, low sulfur content, low chlorine content, and low silica content. The ash content of common biomass materials is summarized in Table 5. Tables 6 and 7 give more detail on selected biomass fuels.

Alkali salts, potassium in particular, are responsible for much of the fouling, sulfation, corrosion, and silicate formation found in biomass boilers. Straws, other grasses and herbaceous materials, younger tissues of woody species, nut hulls and shells, and other annual biomass contain about 1% potassium dry weight. The leaves and branches of wood have higher levels of potassium than the mature stem wood. Sodium and potassium salts in ash vaporize at temperatures of about 700^{o}C (1300^{o}F). As a vapor, they are not easily separated by physical methods such as filtration. Condensation begins at about 650^{o}C (1200^{o}F), first on particulates in the gas forming clinkers and then on cooler surfaces in the system as slag.

High silica content is associated with slagging. However, high silica alone does not present much of a problem. It is the combination of high silica with alkali and alkaline metals, especially potassium that can lead to the formation of slag. Thus, rice hulls, which may contain 20% silica by weight but have low potassium content, do not easily slag. But many types of straw, grasses and stover – which have both high silica and potassium – are very prone to slagging.

[8] Slagging occurs when a material is melted and then condenses on surfaces or accumulates as hard, dense particles or "clinkers". Fouling refers to deposits on surfaces that have not melted.

Fouling and slagging seem to be worsened by the presence of chlorine which increases the mobility of inorganic compounds. Also, chlorine is absorbed by metals at high temperatures, rather than just building up on surfaces, and so results in corrosion.

The ash that remains after a material is burned is indicative of the mineral content, i.e., Na, K, etc. Ash is easily measured by burning the material completely and weighing the sample before and after. Hence, much more data is available on ash content than on specific chemical contents. Low ash content also reduces disposal costs, assuming the ash isn't put to a useful purpose such as a soil amendment or cement additive. Gasifiers especially for straw and other biofuels with high alkali and chlorine contents have been developed. Fluidized bed gasifiers are in general better suited for these materials due to their lower operating temperatures. The Purox gasifier, designed for gasification of municipal solid waste, operates in "slagging mode" in which all the ash is melted on a hearth.

Table 5. Typical Heating Value, Moisture Content and Ash Content of Selected Biomass Feedstocks

	Dry Higher Heating Value (Btu/lb.)	**Moisture Content (% Wet Basis)**	**Ash %, dry basis**
Corn Stover	7,700 to 8,000	Dry: 7 to 30 Moist: 50 to 65	6 to 13
Grape Pomace Pellets	8,300	14	6
Coal	10,000 to 14,000	12	8 to 14
Wood: **Logging Residue** **Land Clearing Debris** **Clean Wood, temperate zones**	**7,000 to 10,000**	**Dry: 10 to 12** **Moist: 12 to 40** **Wet: 40 to 60**	 **4** **8** **0.1 to 1**
Bark	8,000 to 10,000	30 to 60	3 to 8
Straw	7,500	15	6 to 10
Switchgrass	8,000 to 8,200	15 to 20	3 to 8

Sources:

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Table 6. Characteristics of Common Biomass Feedstocks

Crop Residues	Ash content: 5% to15 by weight High in silica and potassium (K) Slagging problems at high gasification temperatures (>900°C) Clinker formation Reduce slagging and clinker formation by K removal and feedstock washing
Poultry Litter	Ash content: 15% to 20% by weight High in Silica and K Very high slagging properties Secondary reactions creating cyanide gas
Herbaceous Biomass (Switchgrass, Miscanthus, Reed canary grass, Johnson grass)	High ash High in silica and K
Forest Products Industry Residues	Generally less unwanted contaminants High lignin content, and therefore high tar production Low K and therefore less slagging potential Often low cost, due to proximity to use
Forest Residues	High lignin content, and therefore high tar production High in ash due to soil contamination Low K and therefore less slagging potential
Woody Biomass (Hybrid poplar, Black locust, Maple, Willow, Short rotation woody crops)	Low ash content Low in silica and K Minimal slagging problems High cost of production as an energy crop

Table 7. Chemical Contents of Product Gas Based on Selected Biomass Feedstocks

	C %	H_2 %	S %	O_2 %	N_2 %	Ash %	Cl %	Na (mg/kg)	K (mg/kg)
Wood, coniferous	**51**	**6.3**	**0.02**	**42**	**0.1**	**0.3**	**0.01**	**20**	**400**
Bark, coniferous	**54**	**6.1**	**0.1**	**40**	**0.5**	**4**	**0.02**	**300**	**2,000**
Poplar	**49**	**6.3**	**0.03**	**44**	**0.4**	**2**	**0.01**		**3,000**
Straw, Wheat, Rye, Barley	49	6.3	0.1	43	0.5	5	**0.4**	500	**10,000**
Straw, Rape	50	6.3	**0.3**	43	0.8	5	**0.5**	500	**10,000**
Reed canary grass, summer harvest	49	6.1	0.2	43	**1.4**	6.4	**0.6**	200	**12,000**
Reed canary grass, delayed harvest	49	5.8	0.1	44	0.9	5.6	0.1	200	2,700

From: http://www.ncp.fi/koulutusohjelmat/metsa/5eures/2Training/2_CHP_shulkkonenl.pdf.

Reducing Slagging, Fouling and Corrosion

Combustion and gasification of biomass feedstocks have been more challenging than with coal in part due to problems with slagging, fouling and corrosion. Slagging occurs when ash and other components of the reaction gases melt and condense on surfaces. Fouling refers to deposits that build up on surfaces but have not melted. Strategies for reducing slagging, fouling and corrosion problems in biomass boilers include use of fuel pretreatment, automatic surface cleaning, temperature control, and feedstock selection.

Slagging and fouling problems will be similar in nature in both biomass boilers and gasifiers. Therefore, references on problems in biomass combustion can be useful in considering potential problems and their solutions in gasification.

Fuel Management

Fuel management strategies for reducing slagging, fouling and corrosion include using fuel additives, washing the feedstock, and screening dirty fuels. Some feedstocks may need to be avoided altogether or mixed with less problematic fuels.

Fuel Additives: Fuel additives including limestone, clays, and minerals based on calcium, magnesium and/or iron have been used to reduce slagging in biopower combustion appliances. Examples are magnesium oxide, dolomite, kaolin, kaolinite, clinochlore, and ankerite. Such additives have been shown to be effective particularly in fluidized-bed boilers, which have good mixing. These materials may also be used effectively as bed materials.

One commercial additive that reduces ash fouling in biomass power plants is "CoMate" produced by Atlantic Combustion Technologies (http://www.atlcombustion.com). CoMate is not mixed with the fuel but added directly to the unit on its own in a dedicated feeder. Site ports can be taken advantage of for inlets.

Screening: Trommel screening dirty fuels can dramatically decrease ash and slagging problems in plants that burn field and urban wood residues. In wood fuels, screening out fines reduces problems because ash-forming elements tend to be concentrated in the smaller particles.

Reducing Problematic Fuels: Dirty or problematic fuels can be mixed with cleaner burning fuels to reduce fouling. For example, nuts, shells, and straws might be limited to less than 5% to 10% of the fuel mix. It is important to avoid using feedstocks, especially grasses and straws, in a gasifier for which it was not designed.

Temperature Control

Temperature can be used to control deposits to a certain extent, especially as a short term or intermittent solution. Slagging can be avoided by operating the gasifier in one of two temperature regimes:

- Low temperature operation that keeps the temperature well below the flow temperature of the ash.
- High temperature operation that keeps the temperature above the melting point of ash.

In addition, gas streams throughout the system should be maintained above the dew points of its corrosive contents. In particular, sulfur and chlorine result in low temperature corrosion if they are allowed to condense out on surfaces.

Reducing temperature to control deposits also reduces the capacity and can have undesirable economic consequences.

Product Gas and Its Management

Product Gas Composition

The product gas is primarily composed of carbon monoxide and hydrogen, and if air is used as the oxidizing agent, nitrogen. The product gas will also have smaller quantities of carbon dioxide, methane, water, and other contaminants, such as tars, char, and ash. The percentages of each of these components depends on a number of parameters, including the temperature and pressure of gasification, feedstock characteristics and moisture content, and whether air or oxygen with or without steam is used for the process. Significant methane is only produced at high temperatures. More char is produced at lower temperatures, below about 700°C (1300°F), with a corresponding decrease in energy content of the product gas.

Product gas heating values typically vary from 15% to 40% of natural gas, as shown in Table 8.

Table 8. Typical Energy Contents of Producer Gas, Syngas and Natural Gas

	Energy Content	
	(MJ/m^3)	**Btu/ft^3**
Producer Gas	2.5 to 8	65 to 220
Syngas	10 to 20	270 to 540
Natural Gas	38	1,028

Gas Clean-Up

The major contaminants produced during gasification are particulates, alkali compounds, tars and char, nitrogen containing compounds, and sulfur. Gas cleaning is required before use in engines and turbines, but little or no gas cleaning is required for burner applications. Tars can clog engine valves, cause deposition on turbine blades or fouling of a turbine system leading to decreased performance and increased maintenance. In addition, tars interfere with synthesis of fuels and chemicals from syngas.

Table 9. Typical Tar and Particulate Contents of Gasifier Types

Gasifier Type	**Tar Content (g/Nm^3)**	**Particulate Content (g/Nm^3)**
Downdraft fixed bed	~1 Typically 0.5, ranging from 0.02 to 4	0.1 to 0.2
Updraft fixed bed	~100, Typically ranging from 20 to 100	0.1 to 1.0
Bubbling fluidized bed	~10, Typically ranging from 1 to 15	2 to 20
Circulating fluidized bed	~10, Typically ranging from 1 to 15	10 to 35

Effective, low cost and reliable producer gas conditioning (cooling and cleaning) is one of the major barriers to the commercial development of gasification since it has historically been difficult and expensive [19]. Even so, producer gas cleaning is an essential part of gasification, especially when used for CHP applications; internal combustion engines require a relatively clean fuel gas to prevent rapid deterioration to failure with high tar and to reduce maintenance costs at any level of contamination. A maximum allowable tar content of 100 mg/Nm^3 is typically specified for internal combustion (IC) engines [20]. When comparing gas cleaning strategies, one must carefully consider the producer gas's desired composition, tar content, particle content, heating value, and cold gas efficiency [21].

"Biomass gasification gas cleaning for downstream applications: A comparative critical review" by Asadulla et al provides an overview of existing producer gas cleanup strategies, which are summarized in the following sections of this report.

Cold Gas Cleaning - Dry and Wet: Cold gas cleaning is categorized as either dry or wet. The dry gas cleaning system consists of various proprietary combinations of cyclones, rotating particle separators, fabric filters, ceramic filters, activated-carbon-based absorbers, and sand bed filters. In contrast, wet gas cleaning systems utilize water and typically involve wet electrostatic precipitators (ESP), wet scrubbers, and/or wet cyclones.

Hot gas cleaning has a higher thermal efficiency compared to cold gas cleaning [22]. Hot gas cleaning strategies are described further in the following sections.

Hot Gas Cleaning – Filtration: Hot gas filtration focuses on the removal of particulate matter and tar to minimize producer gas impurities. Most of the particle removal technologies consist of cyclone and ceramic filters which, in hot gas cleaning, are used for high-temperature particle separation. The cyclone and ceramic filter cannot be used for complete cleaning of producer gas but can be used in combination with one or more of the other methods of contaminant removal discussed in this section of the report [22].

Hot Gas Cleaning - Thermal Cracking Hot gas tar removal converts tar to gas through thermal cracking or catalytic cracking. Thermal cracking is the decomposition of large organic molecules to smaller non-condensable gases at high temperatures. The typical temperatures for thermal cracking range from 1832 ˚F - 2372 ˚F (1000 ˚C to 1300 ˚C) within the reactor (most often in the gasifier fuel bed itself, in the 'reduction zone'). The required residence time for the gas within the reactor depends on the temperature being used for thermal cracking. The downdraft gasifier is commonly used with thermal cracking since it can maintain high temperatures within the reactor's combustion zone (see Figure 2b). The gas composition after using this method is typically adequate for use in internal combustion engines, but in some cases may require additional cleaning depending on the temperature and residence time used [22].

Hot Gas Cleaning - Catalytic Cracking Catalytic hot gas cleanup requires a highly reactive and coke-resistive catalyst. This is because tar can be readily converted to coke under the reaction conditions, which can build up on the surface of the catalyst and impede the tar reforming process. The catalyst must be able to transfer oxygen to the carbon deposited on the catalyst to clean up the surface through a fast oxidation reaction. The catalyst developed for tar reforming is classified into four groups: (1) mineral, (2) nickel based, (3) noble metal catalysts, and (4) iron-based catalysts.

Compared to non-catalytic tar removal, the catalyst produces highly combustible gas with minimum tar and other poisonous gases [22]. However, the required temperature range where the producer gas exits the reactor is 1382 - 1652 ˚F (750 - 900 ˚C), so this method is typically limited to larger-scale applications using fluidized bed gasifiers [23]. While downdraft gasifiers maintain high temperatures in the combustion zone of the reactor, the reduction zone (where the producer gas exits the reactor and where the catalyst is located - see Figure 2b) does not meet the above temperature requirement for catalytic cracking.

Government Regulations Expected to Affect Gasifiers

Emissions and Air Quality Regulations

Since 2018, the US EPA has treated biomass from managed forests as carbon neutral when used for energy production at stationary sources [24]. As such, wood gasification is a carbon neutral means of energy generation in federal regulatory terms; state and local officials may consider it differently, and many environmental scientists have objections to this classification.

Currently, there are no emission standards specific to biomass gasifiers in the United States. However, the national emission standards for reciprocating internal combustion engines may be relevant for CHP gasification systems. The specific compliance requirements vary depending on the internal combustion engine's size, type, and whether the engine is located at a major source or an area source of hazardous air pollutants (HAP) [25]. (Note that the Clean Air Act (CAA) defines a "major source" as "a stationary source or group of stationary sources that emit or have the potential to emit 10 tons per year or more of a hazardous air pollutant or 25 tons per year or more of a combination of hazardous air pollutants"; all other stationary sources are considered an "area source" [26].)

While there are currently no regulations specific to gasification units, this may soon change. In September of 2021, the EPA issued an advanced notice of proposed rulemaking (ANPRM) to potentially develop regulations for pyrolysis and gasification units [27]. The ANPRM provides an opportunity for stakeholders to provide information on the details of pyrolysis and gasification units and processes before the EPA decides on how best to regulate the pyrolysis and gasification units. In December of 2021, the National Association of Clean Water Agencies submitted comments urging the EPA not to place gasification and pyrolysis into existing Clean Air Act (CAA) categories because the processes are "inherently different from other thermal treatment methods...currently regulated by the EPA" since neither process involves combustion as defined in the CAA [28]. They also argue that when used to manage municipal biosolids, they should be regulated under CAA section 112 rather than CAA section 129; since CAA section 129 applies to the combustion or incineration of solid waste, this would not be appropriate for gasification or pyrolysis since neither process involves combustion. Meanwhile, CAA section 112 would allow the EPA to distinguish between "major sources" and "area sources" of HAP.

Applicable Gasifier Equipment Safety Standards

Municipal building codes in the United States require appliances — and therefore small-scale gasification units — to meet certain safety standards and regulations before they can be installed. Manufacturers must prove they have complied with building codes by acquiring safety certifications from a nationally recognized testing laboratory (NRTL). In the US, the most widely recognized testing lab is Underwriter's Laboratory (UL), so most municipalities require UL safety certifications to satisfy building codes. It is important to note that requirements vary across municipalities, so one must check local building codes or consult with a professional when certifying equipment for distribution in the US.

Very few safety marks are federally required in the United States; OSHA only requires electrical equipment to be listed and labeled by an NRTL. Local municipalities generally have stricter safety requirements, meaning that municipalities call for safety certification and marks that are considered “voluntary”, which can be misleading. Additionally, users are more likely to choose and trust equipment with safety marks over those that do not have them, which is why it is important for manufacturers to have their equipment and its parts safety certified regardless of whether it is required even at the municipal level.

Most municipalities require safety marks for the entire system and/or its individual parts. For gasifiers specifically, the authors assume UL marks would generally be required for the system’s individual parts only. Municipality building codes generally require that UL listed electrical components are used in all appliances. The listings for the electrical components center around the UL508A standard for industrial control panels intended for general industrial use. In the case of most gasifier systems, this encompasses the boiler controls. This standard typically requires that all components be UL Recognized in addition to having the UL508A standard.

Other gasifier components that would need certification (other than the control panel and the electrical components) would be pressurized components (if any), which would need ASME certification. For reference, here is a list of the different kind of certifications that UL offers [29]:

- UL Certified Mark: The UL Certified Mark can be used for products certified under UL’s Listing and Classification services and for UL certifications for certain geographies.
- UL Listed Mark: UL Listing means that UL has tested representative samples of a product and determined that the product meets UL safety requirements, and the manufacturer claims that the product continues to meet those requirements.
- UL Classified Mark: UL Classification typically means that UL has tested and evaluated samples of a product with respect to certain properties of the product, a limited range of hazards, or suitability for use in specialized conditions. UL classified products to applicable UL requirements or standards of other organizations.
- UL Recognized Component Mark: UL Component Recognition means that UL has evaluated components or materials intended for use in a complete product or system. These components are intended only for end-use products that may be eligible for UL certification. Consumers rarely see this mark, as it is used for components that are part of a larger product or system.
- UL Performance Verified Mark: UL Performance Verification means that UL has tested and evaluated samples of a product, typically against a specific performance standard. UL performance Verifies products to National or international industry performance standards, manufacturer’s proprietary (internal) standards, or UL requirements.

Below is a list of safety certifications and listings available in the United States [30].

Table 10: United States Certifications and Listings

Name	Requirements	Mandatory/Voluntary	Additional Requirements
Functional Safety Listed	Safety (functional safety)	Voluntary	UL Mark Required
UL Listing Mark US	Safety	Voluntary	N/A
HAZLOC Certification	Safety	Mandatory	N/A
UL Recognized Component Mark US	Safety	Voluntary	N/A
California Energy Commission (CEC) Certification	Energy Efficiency	Mandatory	N/A
Department of Energy (DOE) Certification	Energy Efficiency	Mandatory	N/A
Federal Communications Commission Mark	EMC/Wireless	Mandatory	N/A
Cool Roof Rating Council (CRRC) Certification	Energy Efficiency	Voluntary	N/A
Combined UL Recognized Component Mark for US and Canada	Safety	Voluntary	N/A

"Functional safety" is the part of overall safety which depends on the correct functioning of safety-related control systems and software.

Here is a list of safety certifications and listings available in Canada [30]:

Table 11: Canadian Certifications and Listings

Name	Requirements	Mandatory/Voluntary	Additional Requirements
Functional Safety Listed Canada	Safety (functional safety)	Voluntary	UL Mark Required
UL Listing Mark Canada	Safety	Voluntary	N/A
NRCan Certification	Energy Efficiency	Mandatory	N/A
UL Recognized Component Mark Canada	Safety	Voluntary	N/A
ISED Canada	EMC/Wireless	Mandatory	N/A
Combined UL Recognized Component Mark for US and Canada	Safety	Voluntary	N/A

As a thermochemical energy conversion system, fire safety is an important consideration when crafting and installing gasifiers. The US National Fire Protection Agency (NFPA) creates safety standards and regulations for such systems where fire safety is a concern. The US NFPA database is a great resource for investigating existing safety standards and regulations that may be applicable for a given system. Their database contains the following regulations that are expected to be relevant for gasifier systems [31]:

- NFPA 85: Boiler and Combustion Systems Hazards Code. Contributes to operating safety and prevents explosions and implosions in boilers with greater than 12.5 MMBtu/h, pulverized fuel systems, and heat recovery steam generators. While this is much larger than the systems characterized in this section of the report, it may be relevant for large-scale gasifier systems.

- NFPA 37: Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines. Criteria for minimizing the hazards of fire related to the installation and operation of stationary combustion engines and stationary gas turbines that use liquid or gaseous fuels and are used as prime movers for emergency generators, fire pumps, and stand-by and peak power systems.

In conclusion, for gasifier manufacturers looking to expand into the North American market, these are some of the regulation and policy requirements that must be met before a gasifier system can be sold and used in North America. The only small-scale gasifier system that the authors are aware of that are marketed in the United States and meet US requirements is All Power Labs' Power Pallet systems. Bioenergie Wegscheid is starting to market and sell their systems in the United States, though the authors are unsure if they have completed the process of meeting US regulations and policies. Volter has not expanded into the US market, but they do currently manufacture and market their systems in Canada and as such meet their requirements. These and other small-scale gasifiers and their manufacturers are discussed in the "Small-Scale Wood Gasifier Development and Commercialization" section below.

History of Gasifiers and their Development Since 2010

At the turn of the 21st century, most gasification projects were large demonstration plants and were not anticipated to be commercially viable — relying heavily on subsidies from various governmental organizations. Many plans for gasification plants were conceived around this time, some of which were never built due to economic or political reasons. Of the plants that were constructed and began their demonstration operations, many were mothballed due to economic difficulties, such as the loss of feed-in tariffs or scarcity of feedstock, while some others shuttered due to technical difficulties like feedstock quality and purity issues, as well as poor sub process suppliers, all leading to slagging, corrosion, and destruction of gasification plant components. In truth, a minority of plants from this era achieved commercial operation and have maintained it until the present day.

The successful plants from this period and earlier have certain commonalities. Financial viability or subsidization has been required for success. Lack of finances often shutters fully functional and reliable gasifiers. Good sub process suppliers are also a must. When it comes to woody biomass, tar cleanup is especially important, and there are a range of ingenious solutions to this including reformation and tar cracking. The viability of a plant is often dependent on how well suited the plant is to its perceived customer base and surrounding infrastructure. There have been a handful of gasification plants that have benefited from providing heat and electricity (CHP) to towns with preexisting district heating infrastructure (see project profiles on Skive and Harboøre in Denmark, described in a section below). Lastly, a well-paced project appears to have been beneficial for gasifiers from this era. This is especially true regarding demonstration plants, which are experimental by nature. Evaluating operating characteristics and producer gas quality during a preliminary phase before adding sensitive components like engines or turbines has proven to lead to good outcomes, although it often requires large initial capital. This last piece will likely become less necessary over time.

New History … The Emergence of Packaged Small and Micro-Scale Gasifier CHP Systems

Washington State University Energy Program's 2010 study found a handful of small-scale gasification demonstration projects and pilots, but none at the time offered commercial products. In the decade since that study, European gasifier manufacturers have successfully established themselves in markets abroad. Despite their commercial success and demonstrated viability, the authors found only one small-scale manufacturer actively marketing its gasifier products in the United States. Having noticed this discrepancy, the authors investigated potential causes such as market barriers, policies, and regulations that could be serving as roadblocks to North American market expansion.

Small-Scale Wood Gasifier Development and Commercialization: Information from Leading Manufacturers

Our research team reached out to various leading wood gasifier manufacturers who offer systems for small-scale applications (less than 500 kW). We investigated and reached out to seven manufacturers, three of which we were able to contact for interviews regarding their systems. We sent each manufacturer a set of questions regarding the operations, maintenance, and technical details of their systems. We also asked about the perceived market barriers for North American markets. The information gleaned from these interviews and technical documents shared with us are included in the following sections of our report.

Table 12: Contacted Vendors' Gasifier Operation Data

Name	Assembled in the US?	Size kWe	Size kWth	Effici - ency	Type	Loading	Operation	Cleaning
APL Power Pallet	Yes	25 / 50 / 130	40 / - / -	-	Downdraft	Manual	Not Continuous	Dry filter
Froling Wood CHP	No	46 / 50 / 56	95 / 105 / 115	85%	Fixed Bed	Auto	Continuous.	Dry filter
Spanner Biomass Power Plant	No	35 / 45 / 49	70 – 4,000		Crossdraft	Auto	Continuous.	Filter
Volter 40	No	40	100	78%	Downdraft	Auto	Continuous.	Filter
Bioenergie Wegscheid	No	65 / 82 / 133	130 / 165 / 250	83% - 86%	Downdraft	Manual	Continuous.	Hot Gas Filter
RESET SyngaSmart (PowerSkid, CHP, GAS Unit)	No	50 / 100 / 200	73 / 146 / 292		Downdraft	Auto	Continuous.	Filter
Syncraft	No	220 / 400 / 500	123 / 227 / 250 (50 ◦C)		Floating Fixed Bed			

Table 13: Contacted Vendor Fuel Requirements

Name	Accepted Fuels	Moisture Content	Ash Content	Particle Size
APL Power Pallet	Wood chips (Pine, Oak), walnut / hazelnut shells	5% - 30%	<5%	0.39 – 1.57 in (10 – 40 mm)
Froling Wood CHP	Natural wood chips			
Spanner Biomass Power Plant	Natural wood chips	<13%		0.12 – 2.52 in (3 – 16 mm)
Volter 40	Natural wood chips	<18%	<1%	0.31 – 1.18 in (8 – 30 mm)

			(dry)	
Bioenergie Wegscheid (65 – 133)	Wood chips (glued, painted, coated OK)	<10%		1.18 – 2.76 in (30-70 mm)
Bioenergie Wegscheid (82)	Wood pellets (DIN EN Plus 6 mm A1)	N/A	N/A	N/A
RESET SyngaSmart (PowerSkid, CHP, GAS Unit)		< 15%		Wood chips: 1.18 – 1.57 in (30 – 40 mm); Briquettes: d 1.18 x h 0.79 in (d 30 mm x h 20 mm)
Syncraft	Wood chips, all forest residues	< 50%		0.24 – 1.26 in (6 – 32 mm)

Table 14: Contacted Vendor Biochar Production and Global Installations

Name	Biochar Max Production Rate	Biochar Quality	Number of Global Commercial Installations	Logged Global Operating Hours to Date
APL Power Pallet	Unknown	Unknown	Unknown	Unknown
Froling Wood CHP	N/A	N/A	Unknown	Unknown
Spanner Biomass Power Plant	Unknown	Unknown	Unknown	80,000,000
Volter 40	Unknown	Unknown	Unknown	1,500,000
Bioenergie Wegscheid (65 – 133)	N/A	N/A	120 (all models)	100,000 (all models)
Bioenergie Wegscheid (82)	N/A	N/A	120 (all models)	100,000 (all models)
SyngaSmart (PowerSkid + CHP)	1.6 kg/hr. (19 kW) – 16.8 kg/hr. (200 kW)	High porosity, no TAR contamination, Carbon content ~ 70%	30 as of 2022	~ 4,900 hrs./yr.
Syncraft	1.98 m^3/day (220 kW) – 4.7 m^3/day (500 kW)	Unknown	Unknown	Unknown

All Power Labs: The Power Pallet:

The Power Pallet is a personal scale wood gasifier-generator that uses wood feedstocks to generate electricity and heating (CHP). One of the byproducts of this system is biochar. According to their website, All Power Labs (APL) has designed the Power Pallet to serve as "a personal scale waste-to-energy appliance" that brings "the machine to where the fuel already is, right where the users and needs already are" [32].

Currently the Power Pallet outputs AC electricity and can be adapted to provide take-off (PTO) shaft power (a PTO is a device that transfers an engine's mechanical power to another piece of equipment, common in agricultural equipment). In the future APL plans to have the Power Pallet produce "additional outputs including... cooling/refrigeration... water purification, alternative char/ash-based building materials, and... liquid fuels" [32]. APL is also focusing on making the unit fuel agnostic with respect to wood species and non-wood biomass fuel types according to interviews with APL staff. Additional details about the Power Pallet are in Tables 12-14.

The following two sections contain information on APL's power pallet and APL's perceptions of market barriers as derived from interviews with APL staff:

1) APL Lab Tests: The California Energy Commission's (CEC) Energy Research and Development Division sponsored and conducted a project in 2021 in coordination with All Power Labs, as described below. The researchers produced a final report for the project titled, "Innovative Microscale Biomass Gasifier Combined Cooling, Heating, and Power System" [33].

The goals of the project were to reduce natural gas and electricity consumption and associated costs, mitigate greenhouse gas (GHG) emissions, and advance the technology to help reach statewide energy policy goals and demonstrate a replicable, scalable gasifier for use in the commercial and light industrial sectors. To do this, All Power Labs developed the Combined Cooling, Heat, and Power (CCHP) PP30 Power Pallet, a micro-scale CCHP system with an electrical generation capacity of 25 kW. This modified system improved the previous version of the All Power Labs' Power Pallet by integrating a more robust CHP and an absorption-cycle cooling system. Some of the major system modifications included changing the engine used (which increased power output from 18 kW to 25 kW) and implementing a hot gas filtration system. The researchers installed and tested this pilot system at a community micro-grid facility in the fire-risk community of Malibu in southern California, using wood waste left behind after the 2018 Woolsey fire as well as walnut shells. Ontario Agricultural Commodities and Skysource LLC made the pilot site operational for testing. Note that APL is not currently offering this CCHP design for sale as it was developed specifically for this project.

The Schatz Energy Research Center tested and validated the CCHP PP30 Power Pallet. Researchers collected data for more than six months of operation. Two units were developed for the project, one undergoing testing in a controlled environment and one undergoing testing in the field. Operating hours between the two units totaled to 750 hours. Results showed that the total system efficiency was 80%, an increase from 25% once thermal energy was captured. Additionally, fuel efficiency improved from 1.2 kg/kWh to 1.0 kg/kWh, 22 kW continuous electrical output was produced, 48 kW of heat was captured, and 25 kW heat was used for the absorption chiller. The chiller produced 9 kW of cooling, resulting in a coefficient of performance (COP) of 0.38. Independent analyses of the system confirmed these results.

The biggest roadblocks to complete success were non-technical challenges such as navigating policies that hindered R&D and testing of new technologies. For example, the permitting process was "onerous, expensive, and protracted, representing the largest hurdle related to market penetration" with air quality permits for the two systems taking 8 months and $10,000 each to procure [33]. Overall, the project was successful and met the goal of 80 percent total system efficiency in a controlled setting. The biggest technical challenge of the project and for gaining wide-scale adoption in the future is widening the range of acceptable feedstock types and reducing biomass pre-processing. Other areas of improvement discussed in the report include reducing operation and maintenance needs, improving automation, and developing user-friendly interfaces.

2) Technology Assessment: The following information was derived from interviews with Silvia Sandri, Director of Business Development at All Power Labs.

For fuel handling, APL's Power Pallet has an automated fuel feeding system available for purchase that delivers fuel to the reactor in batches. However, by default the fuel loading is manual. Setting up a continuous fuel feeding system to replace the automated batch-delivery system is not currently a priority for APL since the Power Pallet requires operators to be nearby to monitor for safety alerts indicating a malfunction. While the operator needs to be in the vicinity to address malfunctions, they do not necessarily need to actively manage the equipment during that time.

Startup and shutdown need to be performed manually. For startup, either a hot coal or a heat gun is used to ignite the fuel, though a handheld torch can be used as well. Startup time varies depending on climate conditions but is generally between 10-20 minutes. During emergency shutdown, gas is manually flared from the system. Cleanout is not generally required for emergency shutdown but may be necessary depending on the type of malfunction.

The Power Pallet accepts all types of wood and some nut shells as well, primarily walnut or hazelnut shells. The particle size limits for fuel are 20-35 mm (0.75-1.5 in) and moisture content must be 5-30%. The wood must be appropriately chipped and sifted to remove both fine particles and large particles. The wood must not be shredded as it does not flow well in the fuel hopper or the gasifier reactor. The Power Pallet is not designed to run continuously because the biochar catchment needs to be regularly emptied. Additionally, the reactor needs to be checked every 140 hours which requires the reactor to be cooled. While startup and shutdown are manual, remaining processes are automated. The longest that the system can run uninterrupted is 24 hours, but it is designed to run 12-16 hours per day. In terms of maintenance, trainable operator tasks are performed an aggregate 400 hours per year, with technician tasks performed 5 hours per year.

In addition to generating electricity from fuel produced through gasification, the Power Pallet generates biochar (though this feature appears to be optional). Notably, APL's biochar is certified by the International Biochar Institute (IBI) [34].

A note on the IBI's biochar certification program: The IBI certification "provides biochar manufacturers the opportunity to demonstrate that their biochar(s) meet the minimum criteria established in the most recent version of the IBI Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil" [35]. These standards assert that the biochar's concentration of potentially toxic elements is under the maximum levels set in the standards and the certification lasts for one year. The IBI Biochar Certification Program does not certify biochar systems, only the biochar itself. This means that a customer that owns an APL Power Pallet is not necessarily generating IBI certification quality biochar. Even so, customers are still able to sell their biochar, use it as compost in gardens, or exchange it for carbon credits.

The director of business development noted that the Power Pallet does not require water scrubbing for their gas cleaning process. Instead, the Power Pallet uses paper sleeve filters to collect tar, which sticks to the walls of the filter. According to APL's maintenance schedule, the filters are removed and cleaned every 140 hours while the ash and particulate collection cans are emptied every 24 hours. Ash and tar are the only waste byproducts produced by the Power Pallet.

The All Power Labs Power Pallet is distinguished from other gasifier units by its compact size. It includes a CHP system, gas filtration, biochar recovery, automated feed system, catalytic exhaust, a soundproofing enclosure, and grid tie electronics for feeding electricity into the grid. The Power Pallet is also capable of supporting a microgrid. As of this writing, APL is in the process of making the Power Pallet UL compliant.

The Power Pallet is notably covered by a 30-day 100% money back guarantee. Additionally, APL gasifiers and related mechanical components are covered for 2 years from date of delivery. All electronic parts are covered for 1 year from date of delivery. The engine and reactor are covered by a 2-year (or 4,000 hours) warranty and the engine auxiliary components are covered by a 1-year (or 2,000 hours) warranty. APL will repair or replace, at their discretion, any part that is proven to be defective in material or workmanship under normal use during the applicable warranty period. [32].

Power Pallets located in North and South America are serviced directly from headquarters in Berkeley, California. For EU and Africa, equipment is serviced by technicians in Italy. Equipment in Asia is serviced by technicians in the Philippines.

3) Perceptions of North American Markets and Market Strategies: Currently, All Power Labs' priority sales regions for their Power Pallet system include the North American west coast, Europe (Italy, Spain, Portugal, UK, Ireland), West Africa (Liberia, Ghana, Benin, Nigeria), and Island Southeast Asia (Philippines, Indonesia, Malaysia) [32]. Africa has historically been one of the larger markets for the Power Pallet, but the price point of the system for commercial sales is too high for most of the consumers in the region (For reference, the retail price of the Power Pallet 30 unit was ~$66,000 in November of 2019 [32]). Currently, APL sells 30-40 machines annually, both in the US and abroad.

APL is currently the only small-scale gasifier manufacturer currently selling small-scale systems in the United States according to the authors' research. Most Power Pallet sales have been for use in lab research settings rather than residential, industrial, or commercial projects. In fact, when asked about perceived market barriers in the authors' questionnaire, APL replied that they see their lack of projects in productive (non-testing) use cases as an obstacle – APL is aiming to rectify this in the future to "prove the Power Pallet's reliability to their customer base." Other measures that APL believes would mitigate market barriers would be to activate leasing or hire/purchase options to mitigate client technological risk, scale up to reduce pricing, and increase installation/maintenance network countrywide. The company is planning to reduce the price of their units by doing a design freeze and begin scaling up their operations. Other marketing roadblocks include fuel type limitations and the high level of operator skill required to maintain the system.

Unfortunately, the authors were not able to obtain comments from APL regarding perceived regulatory barriers or their experience navigating the safety certification process in the US and Canada.

Froling:

Froling is not currently marketing their systems in North America and thus declined our request for an interview. As such, information for this report on Froling's gasifier was limited to that available on their website. Based on that source, Froling has one CHP fixed bed gasifier system commercially available, referred to as "Wood combined heat and power CHP". It has an overall efficiency rating of 85% and comes in sizes of 46-, 50-, and 56-kW electrical output [36]. The system comes in a pre-commissioned container that is claimed to be ready for installation and use, typical of "packaged CHP" systems. The wood gasifier and CHP unit are both assembled and pre-installed on a steel platform. The entire system is stored in a container and ready to operate immediately upon delivery.

Operation of the Froling unit is advertised as fully automated, with wood chips transported by the stoker screw into the gasifier, so no manual loading is required. Fuel must be prepared (dried and filtered) outside of the system. The control cabinet monitors all functions and controls the process, offering end-to-end analysis and optimization. The unit operates continuously at full load for maximum efficiency. The coal and ash accumulated are transported by feed screws from the gas filter, through an ash lock and into a supply bin. Technical specifications provided on the Froling CHP wood gasifier are in Tables 12 and 13. Due to the limited information available, the authors were not able to obtain data regarding number of globally installed commercial systems or whether or not their wood gasifiers produce biochar.

C. Spanner Re$_2$:

Spanner Re$_2$ is a German engineering company that manufactures biomass gasifier systems. One of the systems they offer is a "Biomass Power Plant", which is a combined heat and power (CHP) system consisting of a wood gasifier and an electric generator [37]. The heat generated during the gasification process can be used for heating buildings, drying grain, and biomass, or for district heating. Due to the modular design of the units, up to 4 MW of electricity can be produced by installing multiple units, as has been demonstrated in Japan. Spanner also manufactures conveyors and fuel-drying systems for automatic fueling from wood chip feedstocks. This system does not produce biochar.

Spanner Re$_2$ gasifier technology produces heat and electricity from almost any type of natural wood. The accepted biomass feedstocks are listed below:

- High-quality wood chips
- Forest residue wood
- Processed roadside greenery
- Shredded fruit crates, industrial pallets
- Beech veneer

Spanner also offers a briquette press for creating briquettes that can be used with their gasifier; the briquettes are 0.79 inches long and 1.18 inches in diameter (20 mm long, 30 mm in diameter). The press makes these briquettes from sawdust or wood shavings.

Producer gas is cooled by a heat exchanger and passes through a filter with integrated self-cleaning at the gasifier unit. Spanner Re$_2$ biomass power plants also have a second, emergency filter for optimal plant security. The cooled wood gas passes through these two filter systems before driving the system's engine, which produces electricity and heat.

These small-scale (35-49 kWe) units have demonstrated good availability and have an average running time per year of 8,000 hours and a maximum of 8,200 hours. Overall annual availability is around 85% for all operating units. Countries where Spanner units have been installed include Germany, Italy, Austria, UK, Canada, Japan, Honduras, Slovenia, Poland, Latvia, Belgium, Croatia, Chile, and Switzerland [37]. They do not currently sell their systems in the United States. Further details about the Spanner Re_2 Biomass Power Plant are found in Tables 12-14.

1) Technology Assessment: The following section contains information on Spanner's gasifier units as derived from interviews with their staff.

Spanner has over 900 machines sold since first marketing in 2005 with installations and sales on every continent. These installations have generated a total of 80 million operating hours according to the company's response to the authors' interview questionnaire. Their "Biomass Power Plant" CHP system sizes range from 35 kWe (70 kWth) to over 2 MWe (4 MWth). The gasifier's thermal energy is generated in the form of 90 ˚C hot water. The generator's electrical interconnection with the grid is UL-1741 compliant and the system is micro-grid capable as well.

Spanner's gasifier CHP system accepts a wide range of feedstocks. All types of wood (soft wood, hard wood, etc.) are acceptable as well as some kinds of waste wood. While no sand should be in the wood, the gasifier does have a rock separator in case rocks make it into the gasifier. Some of the restrictions for feedstocks used with the system include a maximum allowable moisture content of 13%, a wood chip size range of G30 - G40 or about 3mm-16mm (0.1-0.6 in) [38] and a maximum bark content of 6% by weight. With the standard Biomass Power Plant setup, fuel loading is continuous and automatic. The gasifier system's proprietary design claims to make it so that there is no tar waste generated by the system.

Depending on the financial requirements of the customer, gasifier operations can be fully automated. This is in part thanks to remote performance monitoring; gasifier performance is monitored through remote access to the cabinet with internal storage of operation data. The gasifier also has both an auto-start sequence and an auto-shut-down sequence. Startup time is around 30 minutes, and since startup uses the producer gas there is no requirement for external fuel. There is no cleanout required after emergency shutdown. Since operators can monitor performance remotely, they do not need to always be in the gasifier's vicinity. There is a daily average of approximately one hour of work for the operators.

Maintenance frequency is weekly, and the cost of spare parts and other maintenance expenses are on average 1.7 Eurocent per kWhe. It is important to note that this expense estimate is an average of data from the past 20 years.

When asked in the authors' questionnaire about perceived trends in the industry, Spanner replied that they have observed an increase in gasifier demand for large scale CHP projects. They have also noticed increased use of producer gas without CHP in industrial processes as an alternative gas fuel.

D. Volter:

Volter offers the “Volter 40” gasifier-generator (CHP) system in packages suitable for indoor and outdoor applications. The unit produces enough electricity and heat for the annual needs of a farm, an entire small housing estate or small business. It can be scaled up to multi-unit installations to meet the needs of growing energy demand across diverse applications. Electricity is produced by gasifying biomass in the form of wood chips or pellets. The single packaged Volter 40 CHP unit – which is their ‘module’, replicated for larger systems — is delivered factory tested and ready for use.

Volter CHP systems have an automation system that continually measures on-going activities and allows the CHP unit to automatically adjust operations according to the changes. The CHP unit can be remotely controlled from a computer or smartphone and technical support and upgrades are easily accessible online. Volter also offers access to a cloud service where the plant parameters and sensor data are stored.

Fuel is loaded into the system through an external spring agitator and chain conveyor. The spring agitator has steel arms connected to a rotating disk; whenever fuel is being removed from its hopper, the sprung steel arms rotate to keep fuel flowing out of the hopper and prevent build-up or clogging. A fuel conveyor is available for purchase as well.

Volter provides customers with basic training on equipment and maintenance and provides distributors and engineers with advanced training to handle problems and provide maintenance. Waste disposal is available as an auxiliary service, where personnel come to the site and pick up the ash. Details about the Volter 40 unit are in Tables 12-14.

1) Lab Tests: CanmetENERGY of Ottawa (a Canadian government testing agency) assessed Volter’s biomass CHP technology in a northern climate setting, after it was purchased by Yukon College in Whitehorse, Yukon Territories [39]. The unit tested was Volter’s standard 40 kWe / 100 kWth wood chip fueled indoor CHP unit, manufactured by Volter Oy. It was initially installed at the CE-O labs west of Ottawa, Ontario. The installed system included a fuel hopper and auger, Volter CHP system, flaring and engine stack, a simulated micro grid, and a closed glycol loop for heat extraction. Testing was performed over a 2.5-month period during winter of 2017 / 2018. Each week involved 2-3 days of operation with 8-10 hours of daily runtime. Fuel used included wood chips from two sawmills, one providing softwood and the other providing hardwood. Major findings of the lab test report are summarized below [39]:

- The Volter unit can operate 24 hours per day unmanned with up to 78% overall efficiency.
- The heat to power ratio reaches as high as 3:1 but degrades with decreasing capacity.
- Reliability depends on whether the feedstock meets the manufacturer’s quality specifications.

- Wood chips conforming to specifications are not readily available in Canada. The size requirement can be met, but wood chips require drying to meet moisture content requirements.
- Maintenance requires trained operators.
- NOx emissions may require additional controls to meet Canada's emission regulations.
- The system requires connection to an existing grid. External power was required for start-up of ancillary equipment and operation of heating equipment.
- The unit is best suited for supplying heat and power to a constant load with little change in demand.

Recommendations resulting from the lab test include [39]:

- Improved fuel flexibility and suitability to reflect variations in North American wood chip quality and consistency (species, particle size, moisture content).
- Improvements to feed system and its controls, and automation of ash removal.
- Additional measures to increase the health and safety aspects of the unit, such as integrated carbon monoxide monitoring, feed system improvements, shielding of wiring, etc.

The following two sections contain information on Volter's gasifier units and Volter's perceptions of market barriers as derived from interviews with their staff:

2) Technology Assessment: The Volter 40 gasifier is a fixed-bed downdraft gasifier. The gasifier has a producer gas output of 150 kWth and includes a CHP system with a capacity of 40 kWe and 100 kWth in the form of heated water. The indoor model also provides 20 kWth of heated air - this heat is removed from the generator, which is air-cooled. The system has islanding capability and therefore can support a microgrid, although the generator's electrical interconnection with the grid needs to be specified with each utility company. As such, Volter develops slightly modified versions of the system for each country and state, province, or region where the system is installed, depending on interconnection regulations.

The system does not require an operator to be present to monitor the unit; performance is monitored by remote access through Volter's cloud-based data logging and monitoring system, called "Volter Space". The system has an auto-start and auto-shutdown sequence with a startup time of 45 min to reach full load. An integral electrical resistor in the reactor produces heat to start the process, so no additional fuel is needed for startup. There are no specific shutdown requirements for the system and no issues identified with the emergency shutdown process.

Fuel loading is automatic through a fuel conveyor system that feeds in fuel from the silo. Volter 40's fuel consumption rate is approximately 4.5 m^3/24hr (38 kg/h) at full load.

Wood species acceptable as feedstock include both coniferous and broad-leaf trees. The wood must be forest, plantation, or other virgin wood which includes wood from forests, parks, gardens, plantations, and short-rotation forests. "Thin" (from smaller trees) is apparently acceptable, although exact specifications were not available. Wood feedstock must not have dirt, rocks, or sand as the gasifier does not tolerate non-biomass impurities. The wood also cannot be rotten and must be natural (untreated) wood. The maximum allowable moisture content of the feedstock is 18% with a recommended moisture content of 15%. When chipping wood for use in the gasifier, note that the wood chips must be square-shaped - chipping dry timber tends to produce stick-shaped chips, which cannot be used as feedstock.

The Volter 40 produces approximately 500 L/week of ash. It has a dry ash filter with automatic cleaning and ash removal. An optional ash bin is also available for purchase. The system produces no tar; ash is the only byproduct and has been used as forest fertilizer by clients. The system's producer gas has a calorific value of 154.33 Btu/ft^3 (5.75 MJ/m^3). The nominal producer gas composition is below:

- CO 25%
- H2 17%
- CO2 8%
- CH4 2.5%
- N2 47.5%

The Volter 40 system has a maximum annual run time of 7800 hours (90% availability). Overall, the model has total logged over 1,500,000 cumulative operating hours including past, current, and international installations. A typical unit can operate continuously for up to one week and the longest period of time that the model has operated continuously without shutdown or failure is 1200 hours. The most common causes of shutdown or failure are low fuel quality, gasifier cleanout, and high temperature sensor faults, respectively. Maintenance requires weekly checks and simple maintenance tasks monthly, and gasifier cleanout every 4800 hours of operation.

The system is a CE-marked product, has CSA certifications, and has a 1-year parts warranty. Volter currently markets the Volter 40 system in Canada but has yet to enter the US market with UL certification considered as the primary market barrier. Other issues historically encountered when selling products include the time it takes to enter a new market, limited availability of wood in some areas, and adjusting to the regulations and policies unique to each region.

Emissions analysis of exhaust gas found dust concentrations ranging between 0.27-0.24 mg/m^3 (0.00027-0.00024 ppm). Mass concentrations of greenhouse gas emissions, with uncertainties of the measurements, are listed below. Measurements were taken by Centria University of Applied Sciences.

- CO 147 ± 27 mg/m^3 (0.147 ± 0.027 ppm)
- NO 461 ± 88 mg/m^3 (0.461 ± 0.088 ppm)
- NO2 15 ± 6 mg/m^3 (0.015 ± 0.006 ppm)
- SO2 10 ± 2 mg/m^3 (0.010 ± 0.002 ppm)
- CH4 16 ± 4 mg/m^3 (0.016 ± 0.004 ppm)
- C6H6 1.6 ± 1.4 mg/m^3 (0.0016 ± 0.0014 ppm)
- NOx 721 ± 140 mg/m^3 (0.721 ± 0.140 ppm)
- O2 2.9 ± 0.2 vol % (dry)

Notably, Volter has recently added an option to further reduce NOx and carbon monoxide (CO) with an automatically controlled exhaust stream selective catalytic reduction (SCR) system for use in more tightly regulated areas. Volter indicates this option will reduce up to 80% of NOx and up to 90% of CO, depending on fuel characteristics.

Scheduled spare parts for up to 7800 hours of operation total to 6,823.76 € ($7,376.83) according to a quote acquired in November of 2020.

3) Client Experience: One Volter client from Japan who installed a 40 kWe gasifier system shared their experience installing and operating the system. The client identified two major benefits of their system, which were that "the output of power generation is small and free, and the total efficiency is high." However, they also identified two major downsides as well; the maintenance frequency is relatively high, and the cost of the system is also higher than they would like. To avoid increased maintenance frequency, the customer noted that it is important to pay attention to feedstock quality and ensure it meets Volter's feedstock specifications.

The client shared that they had a hard time operating the system at first due to difficulty adjusting to the required feedstock quality, which is different from what is available in Japan. In Japan, there are various tree species from north to south, which means that the system's maintenance requirements change depending on the location of the installation. In addition to wood species, the client found that the location that the feedstock is sourced from is important as well; chips harvested and manufactured from volcanic soil areas formed many "clinkers" in their gasifier, which are particles that aren't fully combusted during the gasification process. Another complication is wood chip size standards; because there is no wood chip size standard in Japan, the client had a hard time adjusting the wood chip size to meet the gasifier's needs during the chipping process. With these complications, the client found it is necessary to consult with the feedstock supplier to meet Volter's feedstock quality standards.

Currently the client's feedstock supplier procures feedstock from within a 30 km radius of the site. To prepare the feedstock, the client runs it through a Woodtek dryer to reduce moisture content. The dried feedstock is then loaded into the gasifier using the dryer's sieve auger. After gasification, there is almost no tar generation and the average ash generated is 10t / year. The client believes the biochar that the gasifier generates will be a valuable resource and is considering ways to effectively make use of it.

The client chose Volter because their equipment has a small installation area and is easy to maintain. The temperature control system is also "very good" and "the design is the best". The remote performance monitoring has helped the client understand the characteristics of CHP and solve problems when they arise, and the client has found that Volter's client support is "responsive and supportive".

The client shared the following cost information for their installation:

- Capital cost: 45,000,000 yen ($330,494.75)
- O+M:1,000,000 yen ($7,344.33)
- Pay Back: 15 years
- Fuel: 10,000 yen/t ($0.03/lbs.)

For the client's installation, they needed the permission of Japan's Ministry of Economy, Trade, and Industry (METI) as well as their electric power company to implement a feed-in tariff. For small generators, only the permission of the fire department is required. When asked what advice the client had for other prospective gasifier buyers, this customer emphasized that it is important to understand the gasification process before investing in a system of their own. Overall, the client is satisfied with Volter and would not change vendors if given the option; the gasifier system meets their needs and they have not come across any problems with the system that cannot be fixed or resolved. The client does hope that Volter can loosen its fuel quality standards in the future.

4) Perceptions of North American Markets and Market Strategies: When asked about market barriers in North America, Jarno Haapakoski, CEO of Volter Canada, shared that Volter has not taken a deep look but has some awareness of existing barriers, based on their experiences in Canada. The biggest barriers there have been that there are no standards for CSA regarding gasifier technology. Built units need to meet CSA requirements for individual parts instead, though Volter has had no major issues receiving approval here. Canada also accepts UL listed products and CE certified products. As a result, there is generally a mix of UL and CSA listed in Canada. While CSA in Canada is interested in electrical components having listings, they do not require the rest of the product (or unit as a whole) to be listed. Mr. Haapakoski noted that in Canada there is no standard for CHP units.

For the US, Volter did start towards US certification 4-5 years ago and worked with consultants talking through the process to get approval. The consultants laid out the steps required, but it would have required a significant investment of resources to go through with certification. There was also a continuous annual fee to keep the certification valid. Volter would have needed more confidence in the US market to go through with the investment. When asked what the investment would be, Volter clarified that building a UL certified gasifier unit would have a 15-20% price increase compared to building a CSA certified unit.

In the US, most (if not all) local municipalities require that units be "listed" by a nationally recognized testing laboratory (NRTL). Federally required listings and voluntary listings are summarized in Table III for the US and Table IV for Canada. NRTL listings are relatively standard in the US, but US municipalities have the authority to accept foreign listings from entities that are not US-based NRTLs at their discretion. Business-to-business and industrial arrangements generally are less strict compared to commercial arrangements, which are more likely to require NRTL listing of parts.

Fuel handling has also been a big consideration. In total, Volter has delivered 150 units globally. Limitations for the gasification process need to be known for gasifier operations to be successful. The most important limitation for prospective buyers to understand is the fuel; the Volter 40 gasifier is built to handle wood chips, so it cannot use sawdust, bark, or wood pellets.

In the US there are opportunities at sites where wood waste is produced. In Europe sawmill scraps are one such source of wood waste, but this is not available in large quantities. As such, wood waste is not often used as fuel. Volter does not recommend chipping paper grade or timber grade round wood for use in their gasifiers. The woods they do recommend are younger trees collected from forest to keep the forest healthy. Haapakoski indicated that with such thinning cut trees, bark is often left on; bigger trees have thick bark that might pose an issue when using the wood for fuel.

For drying wood, Volter has pre-dryer units sourced from a supplier and have been delivering these dryers to clients alongside the Volter units. So far there are not any sites with a sufficient source of dry chips available. While it would be convenient to chip dry wood, dry wood is difficult for the chipper and the chips tends to come out stick-shaped rather than the desired rectangular shape. In Japan and the UK, groups of installations create a reliable source of chips with clients sharing dryers. The radiant heat from the unit can also be used for drying, but commercial dryers all have a water circulation system and use the radiant waste heat from the gasifier to warm the water.

Volter's primary installation locations include Canada, Norway, Sweden, Finland, Estonia, UK, Italy, Australia, Japan, and South Korea.

E. RESET – SyngaSmart:

RESET is a biomass gasifier CHP manufacturer headquartered in Rieti, Italy [40]. The company's core business is renewable energy / circular economy technology design and development, and as such they have developed their original SyngaSmart biomass gasification system. The design is a modular downdraft gasifier, and the CHP models can produce between 20 and 200 kWe depending on the model. There are two CHP gasifier integrated models: one model is called the PowerSkid, which is designed for indoor generation, and the other model is simply called the "CHP", which is designed for outdoor generation. Both the PowerSkid and the "CHP" models produce biochar in addition to thermal energy and electricity. They also offer alternate versions of both of these models (PowerSkid HEAT for indoor use and HEAT for outdoor use) which produce only thermal generation and biochar using a gas burner and boiler. Both HEAT systems have a rated thermal production of 150 kWth. Lastly, they offer a "GAS Unit" model that only generates producer gas generation and ranges from 130 to 520 m^3/hr. of gas production. Details regarding three of the system sizes are in Tables 12-14.

The SyngaSmart gasification CHP systems produce hot water at 80 - 85 ˚C (176 - 185 ˚F) using heat recovered from the engine's coolant and flue gases. Ash particles and condensate are removed through the system's cyclone, heat exchangers, biomass filters, and a scrubber. Approximately 5% of input biomass becomes biochar, which is automatically extracted and collected. For reference, every 20 kg of feedstock produces 1 kg of biochar, containing 680 g of carbon.

Each SyngaSmart model that RESET offers consists of a different series of equipment. The PowerSkid consists of a feedstock hopper, up to 4 gasification units, gas cleaning and cooling components, automatic biochar extraction, a single or double genset with thermal recovery, an electrical panel, and management software. The "CHP" model includes all of the above as well as a biomass storage container. Lastly, the GAS Unit, which comes either skid-mounted for indoor use or containerized for outdoor use, includes one or more gasification units, gas cleaning and cooling components, automatic biochar extraction, an electrical panel, management software, and gas supply system

For operations, the plants are equipped with pressure and temperature sensors, valves, probes, gearmotors, augers, pumps, and inverters for remote management and monitoring through the systems' software. Operating parameters are recorded and logged on a dedicated cloud platform. Despite automation, the system still requires the availability of a properly trained operator for daily operations, with an average commitment of 2 - 4 hours per day depending on the complexity of the installation and presence of additional equipment. This is needed for timely intervention in the case of a system malfunction.

Biomass feedstocks are fed into the system automatically from a thermos-ventilated loading tank. Regarding the feedstock itself, SyngaSmart gasifiers accept wood chips, nutshells, and briquetted organic waste as long as they meet system specifications. Wood chips need to be rectangular and 30 - 40 mm (1.2 – 1.6 in) in size, while briquettes need to be 30 mm (1.2 in) in diameter and 20 mm (0.75 in) in height. The moisture content can be no more than 15%. These and additional feedstock requirements are listed in Table 13.

The PowerSkid and "CHP" SyngaSmart gasifier models generate biochar as a valuable byproduct. The biochar that SyngaSmart gasifiers produce have a carbon concentration of approximately 70%. As far as the authors know, this biochar has not been tested and certified outside Italy, where it is already listed in the soil amendment registry issued by the Ministry for Agriculture and Forestry.

For service and maintenance, RESET has a service program called ReCare. This program provides services including feasibility studies, staff training for plant operation, after-sales services, and spare parts supply.

1) Technology Assessment: RESET's SyngaSmart technology uses a fixed-bed downdraft gasifier design and has chosen to use air as their gasifying agent. When asked in the interview questionnaire how they differentiate themselves from their competitors, RESET responded that they focus on three aspects of their gasifier technology to stand out. The first is biochar quality; the gasifier's design automatically separates the gas flow from biochar production and removal, which results in high porosity and quality while minimizing the presence of polycyclic aromatic hydrocarbons, which are harmful to humans. The second differentiator is feedstock variability; RESET has designed their system to operate with standard wood chips, but in the last two years, they have worked towards including densified lignocellulosic feedstock (plant biomass containing cellulose) as an acceptable feedstock. Organic municipal solid waste, sewage sludge, digestate, and chicken manure have also been successfully tested, though the authors were unable to find any published testing results. The third differentiator is plant flexibility; RESET customizes each system to the needs of their customers and the biomass feedstock available. Readers should note that all other vendors interviewed for this report customize their systems in this way as well.

Biomass feedstock loading is automatic. External feedstock supply systems are designed according to customer needs. Feedstock storage options include a storage silo, a tank, a dryer container, or even just large bags. RESET can also custom design the feedstock transportation system upon request. The feedstock itself should ideally have a moisture level of 10-12 %. While the systems are capable of operating with feedstock moisture contents of 20-25%, this results in lower efficiency and higher cleaning demands. According to their interview questionnaire responses, RESET sees their feedstock moisture content requirements as the primary reason for operating under 7,200 hrs./yr. at customer installations. To address feedstock quality issues RESET has recently started including a dryer in their installations as default. In addition to low moisture content, the feedstock must meet shape requirements (G30-G40 wood chips, large pellets, or 3 cm (1.2 in) diameter briquettes) and cannot contain rocks, which tend to clog the gasifier and damage the motion mechanism of the hot charcoal bed. As such, rocks must be sifted out of the feedstock prior to use in the gasifier. Other impurities such as inorganic compounds (sometimes found in dirt) tend to cause ash formation, which may fuse inside the gasifier depending on its melting point.

RESET's gasifier system has a thermal capacity of 270 kWth with a mass flow rate of 60 kg/h. The gasifier itself delivers 130 m^3 of producer gas (which they refer to as "BioSyngas"). The heat and electrical outputs for the CHP system has a ratio of 1.2 kg of dry wood chips to produce 1 kWe and 1.46 kWth of useful energy. Unit power capacity ranges from 50 to 200 kWe in modular and scalable units. Heat output temperatures are typically 80-85 ˚C (176-185 ˚F).

Both the PowerSkid and "CHP" systems allow for grid-tie connection for electricity exporting to the local grid. The generator's electrical interconnection with the grid is not yet UL-1741 compliant since the company has not expanded to the US, but the system is microgrid capable. However, when using the system to power a microgrid, RESET recommends matching the system with an energy storage unit.

SyngaSmart system performance is monitored through a proprietary SCADA software called "ReMotica", an HMI with remote desktop control. For startup, the plant is turned on with dry wood chips and a blower —no additional fuel is required. The startup time is about 30-45 mins. For shutdown, the operator must empty the gasifier by using the flare after the generator set(s) are switched off in order to avoid additional cleaning. Both the traditional PowerSkid and CHP models as well as their associated HEAT models have an auto start and auto shutdown sequence.

The gasifier system operates continuously as long as the plant is regularly maintained and operated with standardized fuel; complete shutdown is only necessary under extreme circumstances. An operator can run the system for up to 24 hours before the system must be temporarily stopped for maintenance (daily biomass filter replacement); however, on 50 kW models, the system remains operating at 50%, since the system is equipped with at least 2 gas generators and 2 engines. While operator presence is not required at all times during operation, having an operator close by limits downtime due to system malfunctions.

The maximum number of operating hours a client can expect annually is 7,200, though most sites do not meet this maximum target. Currently, the average annual operating hours for all site installations is approximately 4,320 hours. (Note that this data is only for the more recent installations that have performance monitoring systems in place and includes issues caused by biomass quality or missed maintenance.) Achieving the maximum availability of 7,200 annual hours is only possible with one or more dedicated operators on site. However, larger plants have higher maintenance needs than smaller plants, and therefore may not be able to achieve the maximum of 7,200 annual hours even with dedicated operators on site.

RESET does not have enough operating data to estimate the mean time between failure for the gasifier, but the plant in the testing facility has been operating for 2+ years without failure. The most critical component of the system is the ash scraper, which works at high temperatures, but replacement takes approximately one day of plant shutdown. The longest period of time that any of the gasifier models have operated without shutdown or failure (excluding the testing facility unit) is 5 days. The most common causes of shutdown or failure are: 1) Issues with biomass quality, 2) Missed maintenance, and 3) Mechanical issues such as a loading valve block or dirt stratification in the heat exchangers.

RESET's maintenance schedule is relatively complex due to the "cascading" design of their larger systems (i.e., their standard 100 kWe unit has twice the generation equipment of the 50 kWe unit). Time to repair is about 1 day/week of plant shutdown for regular maintenance. Regular daily maintenance tasks take around 20-30 mins to complete each day. The maintenance cost of the system varies, but on average is about $50 per MWh which includes spare parts, labor, and consumables. The most expendable or high-wear parts are gaskets, which are replaced each time a component is disassembled for cleaning. For the engine, the most expendable or high-wear parts are lube and air filters.

To address the contribution of high maintenance times to limited annual availability, RESET has developed and are currently testing automatic biomass filter replacement that would decrease daily maintenance. Likewise, a self-cleaning heat exchanger system has been developed and is currently under testing.

For producer gas cleaning, the gas undergoes several cooling and cleaning stages including cyclones for dust removal, high temperature HX, low temperature HX with condensate collection, recyclable biomass filters, and a final small scrubbing stage with an engine guard filter. The whole system has a proprietary design and is constantly under improvement; gas cleaning is crucial in gasification and there is always room for improving process quality. Producer gas energy content (lower heating value (LHV), assuming a feedstock with a moisture content of 6.6 % by volume) is approximately 4.6 MJ/kg, or 5.2 MJ/m^3. The cold gas efficiency is approximately 72%.

As with all gasifiers, waste disposal is an important consideration. For RESET's SyngaSmart gasifier, tar and condensates are collected in a buffer; normally they are disposed of as waste, but tar can be reused in several ways, including during gasification itself. Condensates contain wood vinegar that can also be recovered for further uses, but the amount of wood vinegar that can be extracted is minimal, so it is usually disposed of. The amounts of tar and condensates generated are limited thanks to the Imbert downdraft gasifier design; the design limits scalability but minimizes tar production. The frequency with which the waste must be disposed of depends on plant size (i.e., amount of biomass used) and humidity, but normally the waste is collected in typical 1000 L tanks and are disposed of during weekly maintenance. The condensates and the scrubber blowdown are automatically collected to a storage tank and are disposed once a week or more depending on the storage capacity and the wood moisture content.

As an alternative to the current open-loop scrubber blowdown system, RESET is currently testing a closed-loop scrubber blowdown system. In this closed-loop system, the scrubber blowdown is sent to the wastewater treatment system to remove the suspended solids and tar, which are collected and sent back to the gasifier while the cleaned water is recirculated to the scrubber. This would remove the need to dispose of collected waste on a weekly cadence.

Producer gas composition (% volume, dry):

- 4% CH_4
- 20% CO
- 15% H_2

- 14% CO_2
- 47% N_2

Emissions information is the following:

- Dust: 0.6 mg/m^3
- Nitrogen dioxide (NO_2): 176 mg/m^3
- Carbon monoxide (CO): 297 mg/m^3

Typical unit equipment, installation, and commissioning cost ranges between $5,500 and $6,500 per kWe installed. Warranty is standard on faulty parts for 12 months. RESET emphasizes that before investing in a system, customers understand that the SyngaSmart gasifier systems are small-scale refineries and will need to be attended to accordingly.

2) Perceptions of North American Markets and Market Barriers: RESET has not yet entered North American markets and, in fact, currently has no international sites. Since there are currently no plans to enter the North American market, RESET has not investigated applicable regulations or policies in those markets. When RESET does choose to enter the market and finds a local partner capable of market development and post-sales services, it fully plans to make its products compliant with US regulations. For the markets they do operate in, RESET gasifiers are CE marked and have a TÜV certification.

RESET has found that in selling its products so far, the sales process has been "complicated and long-lasting." However, considering the positive outcomes they have found the time and effort to be worthwhile. Some of the roadblocks they have encountered during the process include 1) feedstock specifications, since each biomass requires specific pre-treatment modules that RESET must design on a case-by-case basis; 2) high capital costs serve as a barrier for many customers; 3) operation requirements, as customers sometimes see the level of commitment needed as a hassle.

F. Bioenergie Wegscheid [41]

Bioenergie Wegscheid is a German biomass CHP manufacturer that has been producing and selling gasifiers for over 10 years. As of April 2021, Bioenergie Wegscheid became part of the ENTRENCO Group. The company manufactures downdraft fixed bed CHP wood gasifiers in three sizes: 65, 82, and 133 kWe. Each has an average annual runtime of 8,200 hours, or 93% availability. As of this writing there are 120 units in the field, and they claim to be the only gasifier manufacturer whose products have accumulated over 100,000 operating hours. Units are sold primarily to Germany, Great Britain, and Japan. Currently none of their gasifier units produce biochar.

Multiple units can be connected together in a "cascading" formation to increase overall generation capacity. The units operate continuously, and the wood feedstock is loaded mechanically, using a screw conveyor. Gas is cooled using water, which collects the heat for re-use in hydronic heating or other purposes. The cooled gas then goes to the engine, which generates electricity.

Before it is used in the engine, the producer gas from the system is filtered through hot gas filtration using metallic filter cartridges. Further remaining micro particles are filtered from the gas in the unit's safety filter. Low amounts of micro-particles and filter tears guarantee the longevity and constant running of the 12-liter engine. This ensures a high level of plant availability and reduces the need for on-site personnel. The unit produces little ash, and the ash is clean of toxic materials. There is no additional cost for ash waste disposal. Ash goes into the ash bin and ash box until time for disposal.

Annual "major" maintenance is performed by the service team while smaller maintenance tasks are done by operators. Customers receive intensive training on operation and routine maintenance during commissioning. The average daily maintenance time is 30 mins. All systems and its current operating parameters can be monitored by the control center. In case of any issues, the 24/7 help desk can support the operator.

The following two sections contain information on Bioenergie Wegscheid's gasifier units and their perceptions of market barriers as derived from interviews with their staff:

1) Technology Assessment: The 133-kW gasifier system that Bioenergie Wegscheid offers has an auto-start sequence and an auto-shutdown sequence. The generator's electrical interconnection with the grid is UL-1741 compliant. The system can support a micro-grid if the client requests it, however this requires a separate set of controls. The outputs for this system are 133 kWe, 250 kWth, and it has a hot water flow temperature of 88˚C (190 ˚F). Performance is monitored through a remote maintenance system. For startup, the system requires 60 liters of charcoal and has a startup time of 1 hour. The system has an emergency shutdown sequence as well as a safety shutdown sequence. Operation is automated.

For a 133-kW wood gas unit, system efficiencies are:

- Engine: 30.9% electrical efficiency
- CHP: up to 89% overall efficiency
- Engine: 58% thermal recovery efficiency
- Engine specific wood requirement: 0.71 kg/kWhe
- Gasifier: 81-83% efficiency
- Gasifier specific wood requirement: 0.79-0.84 kg/kWhe

For a 133-kW wood gas unit, operating at full capacity, energy generation is:

- 250 kW CHP heat
- 30 kW of uncoupled hydronic heat
- 33 kW of CHP heated air
- 30 kW of uncoupled heated air

The gasifier requires mechanical feedstock loading by means of a plug screw that continuously feeds the biomass into the reactor. A variety of wood species can be used as feedstock, though the system has low tolerance for impurities such as dirt and no tolerance for rocks. Producer gas filtration is a combination of hot gas filtration via stainless steel filter and dry filtration. Waste is disposed of every three days, though this depends on container size. Removing the collected ash takes around 20 minutes. Shutdown is not required during this process. Ash is the only potentially desirable byproduct.

The combustion engine emissions for the 199 kWe gasifier unit were measured to be the following while running at 80% nominal power:

- NOx: 121 mg/m^3

- NO: 77 mg/ m^3
- NO2: 3 mg/m^3
- CO: 1 mg/m^3
- CO2: 6.8% Vol.
- SO2: <1 mg/m^3
- Total Dust: 2.1 mg/m^3
- Benzene: 1.19 mg/m^3
- Ammonia: 3.2 mg/m^3
- Volatile Organic Carbon: 27 mg/m^3
- Exhaust Air Quantity: 796 m^3/h

The overall CHP system emissions were measured to be the following:

- CO: 63 ± 2 mg/m^3 (0.063 ± 0.002 ppm)
- NO2: 253 ± 25 mg/m^3 (0.253 ± 0.025 ppm)

The manufacturer indicated that the gasifier has proven to have the highest percent annual availability (8300 annual hours of operation) for its performance class. The cost for a system deployed in a container is about $828,000 ($6,226/kW), not including installation costs. The system has a 1-year warranty after delivery, which is typical for German-manufactured products.

Since the operator or technician must shut the gasifier down for engine oil changes, the longest the system can operate without stopping is 500 hours. With remote monitoring, the operator does not have to be on site while the system is running. The most common causes of shutdown or failure are 1) wood chips sticking to sensor and causing the system to falsely display message that the combustion chamber is full and 2) Insufficient heat removal causing overheating of the power plant engine.

In terms of auxiliary equipment, Bioenergie Wegscheid offers hot water buffer storage tanks, dryers, and sieves to separate fine parts and wood chips that are too large, as well as supplying briquetters. For the dryers, three types of in-house dryers are available for feedstock prep. Screening, storage, and conveying of the wood chips can also be tailor-made by a system of in-house products if needed. Typical consumables for the gasifier include oil, filter candles, and spark plugs. There is remote monitoring infrastructure in place to support all pieces of equipment 24/7.

Additional details about the gasifier operating parameters and feedstock requirements are in Tables 12 and 13.

*2) Perceptions of North American Markets and Market Strategies***:** Bioenergie Wegscheid plans to market their gasifier system in the US in the future and distribute their systems through Wisewood Energy. Currently their systems have CEE certificate, VDE-AR-N-4110 medium voltage certificate and are certified for explosion prevention. They are working on getting the necessary certifications for distribution in the United States as of this writing.

Overall, Bioenergie Wegscheid has had positive experiences selling their systems to customers. However, in their interview they noted that it is important that biomass specifications are followed, and that the customer is willing to be trained in operation and maintenance.

When asked about the roadblocks they have encountered in marketing and selling their gasifiers, Bioenergie Wegscheid identified inadequate wood quality, limited wood supply, sloppy maintenance practices by customers, insufficient grid space, and slow or contradictory government regulations as primary issues.

G. SynCraft

SynCraft is an Austrian gasifier manufacturer headquartered in the city of Tyrol. The manufacturer's gasifier design is self-developed and patented; their proprietary system is based on a floating fixed bed design that was first developed in 2007 [42]. In a floating fixed bed gasifier, the producer gas flows upwards (rather than downwards in the more popular fixed bed design). The upward flow of producer gas keeps the char in the gasifier loosened and permeable. By loosening the char, the design reduces compaction of the fuel bed and increases feedstock flexibility in terms of particle size and shape.

The SynCraft gasifier produces biochar during pyrolysis, which can be used as soil substrate, manure additive, in building materials such as concrete, gypsum or clay. It sequesters about half the carbon from the wood feedstock. The biochar quality allows it to be used as a base to produce Terra Preta (black earth), as an animal feed supplement to stabilize digestion, or as high-quality wood BBQ charcoal.

As with all gasifiers, this system produces undesirable waste that must be dealt with when the gasifier is serviced. Because of its feedstock flexibility, foreign bodies from the feedstock must be addressed inside the gasifier. These foreign bodies accumulate at the base of the floating fixed bed reactor, where they need to be regularly removed and disposed of during maintenance intervals. In addition to providing service for regular system maintenance, SynCraft provides clients assistance with planning, support with approval processes, delivery, installation, and system start-up.

SynCraft's wood power plants are packaged, cogenerative units; they work entirely stand-alone and do not require any auxiliary materials. Each system includes a gas generator, an engine, a controller, a walkway, and a gas flare. Optional auxiliary equipment includes a dryer, a bunker, and a biomass feeding system, a low temperature usage packet, and a big bag filling station for the biochar. For the heating loop, each is designed based on customer needs. They include high and low temperature loops (supply and return), consisting of steam and water, respectively. There are a total of four system sizes: 220, 400, 500, and 1000 kWe. For every 1 kW of feedstock, the systems produce approximately 0.3 kWe and up to 0.62 kWth. Information about the three smaller systems are depicted in Tables 12-14. Note that the largest system size is 1 MWe and therefore not quite "small-scale."

As mentioned previously, the floating fixed bed gasifier design reduces compaction and increases feedstock flexibility regarding particle size and shape. As such, SynCraft gasifiers allow feedstocks consisting of any and all forest residues. Examples include wood scraps and sawmill by-products. For wood chips, they must have 60 – 100% of particles between 6 and 32 mm in size, though unlike many other gasifiers including fine fraction and bark is acceptable. Wood chips must also have less than 50% moisture content. However, the wood chip feedstock must have less than 10% moisture content once it reaches the gas generator inlet; there is an optional upgrade that ensures the feedstock is sufficiently dry at this point in the gasifier.

Some of the countries where SynCraft gasifiers have been installed include Japan, Germany, Switzerland, Italy, and Croatia. This list is not comprehensive, but provides an idea of the scope of markets that SynCraft currently operates in.

Successful Medium-Scale Gasifier Projects (1 MW and Greater)

While small gasifiers have enjoyed a rapid move to commercialization, medium scale projects have continued to be developed at a similar pace to the turn of the 21st century. This slower pace is likely due to their bespoke nature and large cost, gearing them more towards large municipalities or industrial clients. There are many medium-scale biomass gasification projects in various phases located around the world, as summarized in Tables 18 and 19. Numerous gasification projects that do not burn the gas in engines or turbines have been in operation for decades, but projects generating electricity in combustion turbines and reciprocating engines have much shorter histories. The ongoing development of robust gas clean-up technologies like tar reformation and electrostatic precipitators has likely made internal combustion engine driven plants more viable recently. Also, our research indicates that it requires significant commissioning time to ensure that the gasifier will operate correctly and produce acceptable fuel for internal combustion engines gas prior to installing gasifier-fueled engine-driven power plants.

The status of three notable medium-scale gasifier projects are profiled here; these sites were previously described in the WSU Energy Program 2010 study of gasifiers, and it was decided to revisit these projects to provide updates, especially as all three are still operating. The first two detailed project profiles below demonstrate entirely different but successful gasification and gas clean-up technologies with generation of electricity by burning the producer gas in an internal combustion engine: The Babcock Wilcox Volund gasifier in Harboøre, and the Andritz pelletized wood gasifier in Skive, both in Denmark. Common to both projects are committed operators, designers, and constructors with solid support from their local and national governments, as well as a staged approach to plant development and utilization of preexisting district heating.

Harboøre, Denmark – Babcock & Wilcox Volund Gasifier

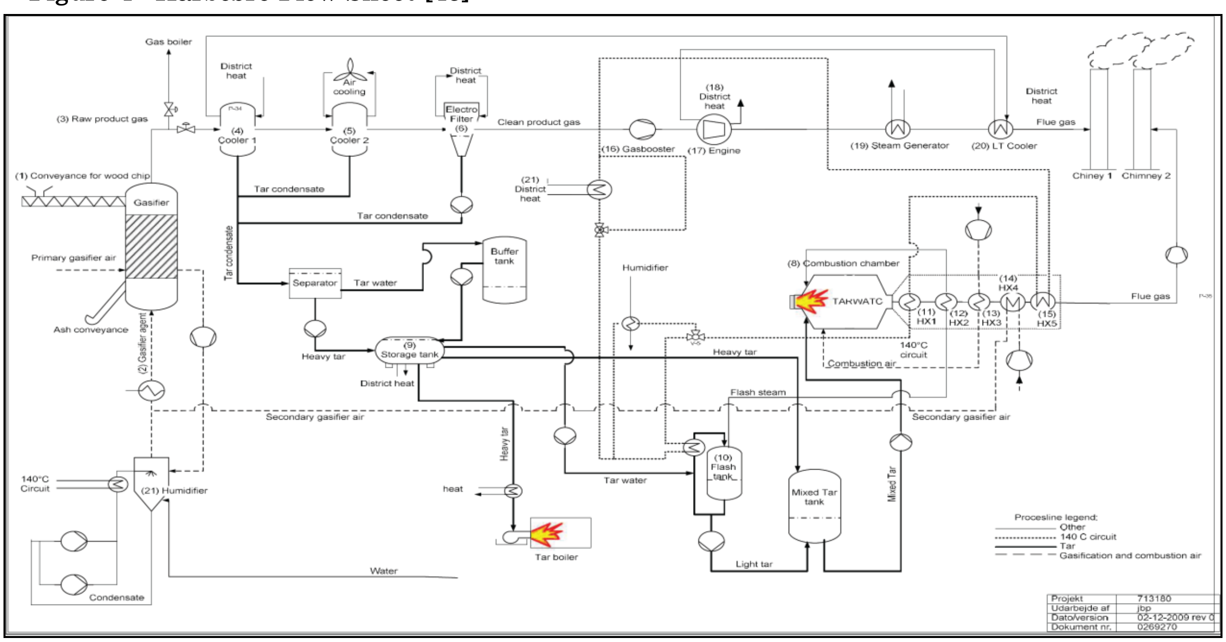
Summary: At this 1.5 MWe project, wood chips are gasified in an updraft gasifier. The gasifier has been operating since 1994, providing district heating. Since 2005, it has also been generating electricity by burning producer gas in two engines. Gas cleanup is accomplished by cooling the gas and then passing it through a wet electrostatic precipitator (ESP). Treating the tar-contaminated water from the wet precipitator was problematic, but a successful solution was developed, and the plant has been operating successfully since its construction, with partial support from Danish government renewable energy subsidies. Harboøre demonstrates that megawatt-scale woody biomass is a viable technology.

Figure 3: Harboøre wood gasifier CHP Plant [43]

System Details:

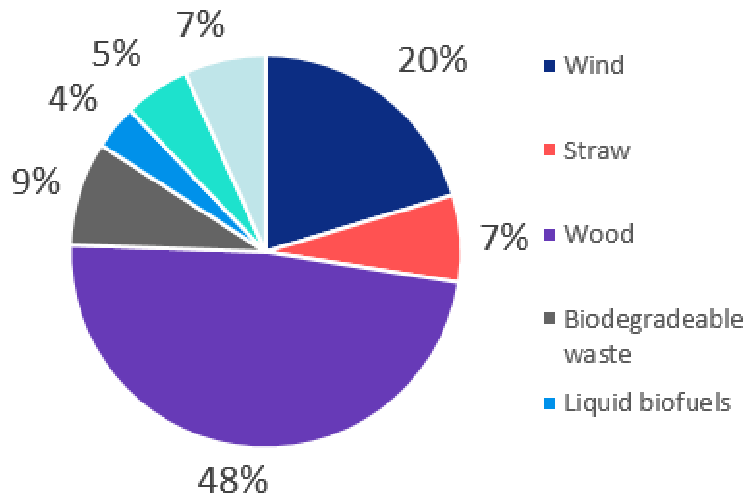
The Harboøre gasification plant uses an updraft fixed bed gasifier to gasify woody biomass, applying the 'producer gas' in a combined heat and power system [44]. The plant is primarily used for district heating [44]. A flowsheet of the plant is shown below, with numbers corresponding to components that will be referenced throughout this section [45]:

Figure 4: Harboøre Flow Sheet [45]



The feedstock for the gasifier is unadulterated wood chips, which are stored in a nearby building [44]. In Denmark, bioenergy accounts for 64% of renewable energy, with woody biomass accounting for 48%, as shown in Figure 5. Forest covers over 10% of the land in Denmark, but most of it is protected after forests nearly went extinct in the country at the beginning of the 18th century. The Danish Energy Agency indicates that more than half of the woody biomass used in the country is imported [46]. This mainly consists of wood pellets and chips originating from Baltic countries, the US, Russia, and other European countries [46].

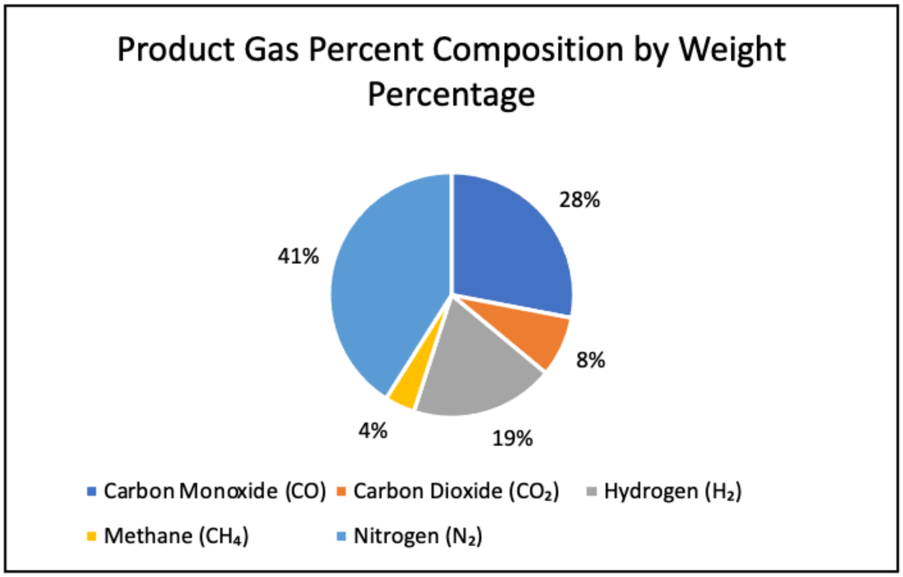
Figure 5: Danish Renewable Energy Breakdown [46]



The gasifier is tolerant of feedstock moisture content (MC) between 35-55%, although the upper limit has not been tested and the feedstock is typically around 42% MC [47]. These wood chips appear to be fed into the gasifier via a worm conveyor dumping through a rotary grate and wood chip distributor (#1) at an energy rate of around 7 MW (1800 – 2500 kg/hr. or 4000-5500 lb./hr.), and the woodchips have an LHV around 10.02 MJ/kg (4300 Btu/lb.) ([47] and [45]).

The updraft fixed bed gasifier partially combusts the wood using outside air combined with recirculated, heated, and humidified air [45]. Heat for the combustion air comes from a heat exchanger connected to the "Tarwatc" tar water cleanup system, as well as the gasifier itself (#2) [45]. The composition of the producer gas is specified in the pie chart below. Both woody biomass feedstocks and updraft gasifiers in particular are associated with high tar content. This gasifier produces large amounts of tar as a result. Downstream of the gasifier, the rate of tar removal (#4-6) – in energy values – is typically around 1.4 MW (4.8 MMBtu/hr.), which is quite large considering the rate of producer gas entering the engines is typically around 4 to 5 MW (13.6-17.1 MMBtu/hr.) ([47] and [45]).

Figure 6: Producer Gas Composition



At the bottom of the gasifier ash is conveyed out, while raw producer gas exits the top (note that #3 – #19 here and following reference the flow diagram in Figure 4) [45]. Next, the producer gas is fed through two gas coolers, with the first producing district heat (#4) and the second being air cooled (#5) [45]. Note that the gas can also be diverted to a boiler before the coolers, although this function does not appear to be used (a relic of the pre-CHP era of this gasifier) [45]. After the gas coolers, there is a wet electrostatic precipitator (ESP) (#6) that cleans the gas of tar and other contaminates by means of an induced electrostatic charge that draws out particulates from the exhaust gas stream ([47] and [46]). The water used in the ESP also adds to the production of district heat in the plant [45].

After the electrostatic filter, the producer gas proceeds to a gas pressure booster where it is brought up to the operating pressures of the reciprocating engines (#16) [45]. These GE Jenbacher engines are about 38% efficient and produce about 648 and 768 kWe (#17), respectively, although they have been shown to output more power depending on feedstock input ([44] and [45]). Waste heat from these engines and their flue gas is used for district heating (#18-19) [45]. From all components of CHP process, the district heating is around 1.5 MWth [45].

The two coolers and the ESP generate tar condensate due to filtering and cooling of producer gas [45]. This condensate is then passed through a separator, yielding heavy tar and tar water [45]. The tar water mix from the separator is then fed to a buffer tank, while the heavy tar is pressurized and goes straight to a tar storage tank (#9) [45]. The tar water is pressurized and fed into the top of the same storage tank, with the storage of the two likely being stratified in the tank so that both can be retrieved individually (#9) [45]. The heavy tar from the storage tank can then be burned in a heavy tar boiler to generate district heating, although it is typically reserved for peaks in district heating demand ([45] and [47]). The mass of heavy tar collected per unit fuel is 0.055 kg/kg and the mass of tar water per unit fuel is 0.577 kg/kg. The heavy tar at this plant has a LHV of 27,952 kJ/kg and the tar water has one of 2,014 kJ/kg [47].

As mentioned above, one of the constituents of the condensate from gas cooling and cleaning is tar water. This tar water is quite toxic and cannot be dumped into the sewer, which is why this plant incorporates the Tarwatc system (#8). The Tarwatc system was developed by Babcock & Wilcox Volund [47] and directly incinerates the tars, while also recovering additional chemical energy for district heating and plant processes from these constituents through a series of heat exchangers (#11-15) ([47] and [45]). This system appears to function similarly to a boiler except that mixed tar (heavy tar and light tar) are combusted in the same chamber as flash steam in order to distill some of the steam (#8), while the rest likely comes out with the flue gas [45]. This distillation process is assumed to drive off light volatiles that must be destroyed in combustion.

'Upstream' of the Tarwatc, some tar water from the storage tank is fed to a flash tank (#10), while the rest is fed to a mixed tar tank. Before the flash tank, there is a heat exchanger carrying heat from the Tarwatc. This heats the tar water traveling to the flash tank enough that the water evaporates, and light tar is left behind in the tank. The newly created flash steam is then heated up further after passing through another heat exchanger in the Tarwatc (#12), and then added to the Tarwatc with combustion air and mixed tar from the mixed tar tank (#8). The mixed tar tank ingests tar water from the storage tank (#9), heavy tar from the storage tank (#9), and light tar from the flash tank (#10) [45].

Commissioning and Plant History:

In 1993 Harboøre Varmeværk created a demonstration gasification plant based on developments achieved at pilot scale by their gasifier supplier Babcock and Wilcox Vølund [44]. In 1997 the gasification process was considered commercial, gas engines were added in April 2000, and in 2001 it was converted to CHP and taken into commercial operation [44]. Due to the use of a wet electrostatic precipitator, the plant needed a good water cleanup system. Several were evaluated, including osmotic filters and centrifuges [44]. The Tarwatc system was chosen and implemented between 2002 and 2003 [43-44]. The plant has operated about 8000 hours per year since then and now supplies heat to 698 customers through a hot water district heating distribution system [44].

Operation and Maintenance:

The Harboøre gasification plant operates year-round [44]. The plant has a one-week annual maintenance period, during which bio-oil is burned [44]. The plant is controlled by district heating demand [48]. The plant is typically operated by two employees working 40 hours per week each [47].

Financing and Operational Costs:

According to the operators, the budget price for the Harboøre plant was 10 million euros in 2009 [47]. This price comprised "delivery, construction and commissioning of a gasifier supply" [47]. This price excludes "all civil work, foundation, building, site clearing, and dry storage area" [47]. Additionally, in 2009 the estimated operation and maintenance cost for the 2MWe unit was 350 thousand euros per year excluding the cost of personnel [47].

Reasons for Success:

Biomass appears to be well suited for use in district heating and CHP applications as a low GHG fuel. When implemented using gasifiers to provide fuel for internal combustion engines, this is an excellent, efficient energy conversion strategy, assuming the project is cost effective and reliable, as has been demonstrated in the case of Harboøre. The gasification CHP plant in Skive, Denmark is very similar in its application and history to the one in Harboøre. Significantly, both plants started as strictly district heating plants, allowing the operators to assess the quality of the producer gas while receiving revenue from district heating. This was possible because boilers are generally more tolerant of producer gas impurities than reciprocating engines. The steady revenue from district heating likely allowed operators the time to determine viable gas cleanup methods. This gradual transition into CHP probably allowed ample time for the selection of good subprocess suppliers and a well vetted design for plant expansion, as well as learning effective operational practices particular to gasifier-based biomass energy conversion—all leading to an eventual success that has been sustained through today.

Challenges:

The choice to use an updraft fixed bed gasifier makes sense from several perspectives including maintenance, cost, and complexity. However, these gasifiers are known for producing large amounts of tar, especially when combined with woody biomass. Furthermore, using this combination of gasifier and feedstock in a CHP application necessitates the development of a robust producer gas cleanup system that can adequately protect the reciprocating engines (or other prime movers) from tar and other impurities. The use of an ESP along with the Tarwatc system has clearly been successful, although it is notably more complex than the gas cleanup systems necessary at plants using different types of gasifiers, like Skive. It appears that there is a tradeoff between gasifier complexity and gas clean up complexity.

Besides technical challenges, time and money are always some of the largest impediments to success regarding large boundary pushing energy projects. Harboøre wouldn't have evolved into its current state if it were not for grants and subsidies, as well as a dedicated team.

Implications for Future Gasification Plants

It might be advisable for most gasification plants to focus on process or district heating initially because of the higher difficulty involved in gas cleanup for electricity production in reciprocating engines or turbines. Plants can typically be expanded into CHP without needing to retrofit the gasifier.

Skive, Denmark – Fluidized Bed Gasifier

The Skive gasification plant is primarily for district heating, with electricity as a byproduct. It contains a pressurized bubbling fluidized bed (BFB) gasifier integrated with a CHP system. Heat is pulled from the producer gas cooling before gas goes to three GE Jenbacher engines, each producing 2MW electrical (MWe) and further heat. This leads to 12MW thermal (MWth) and 6MWe in total. The plant was commissioned in 2007 and has been operating ever since, with availability steadily increasing over the years [49]. The plant is pictured below.

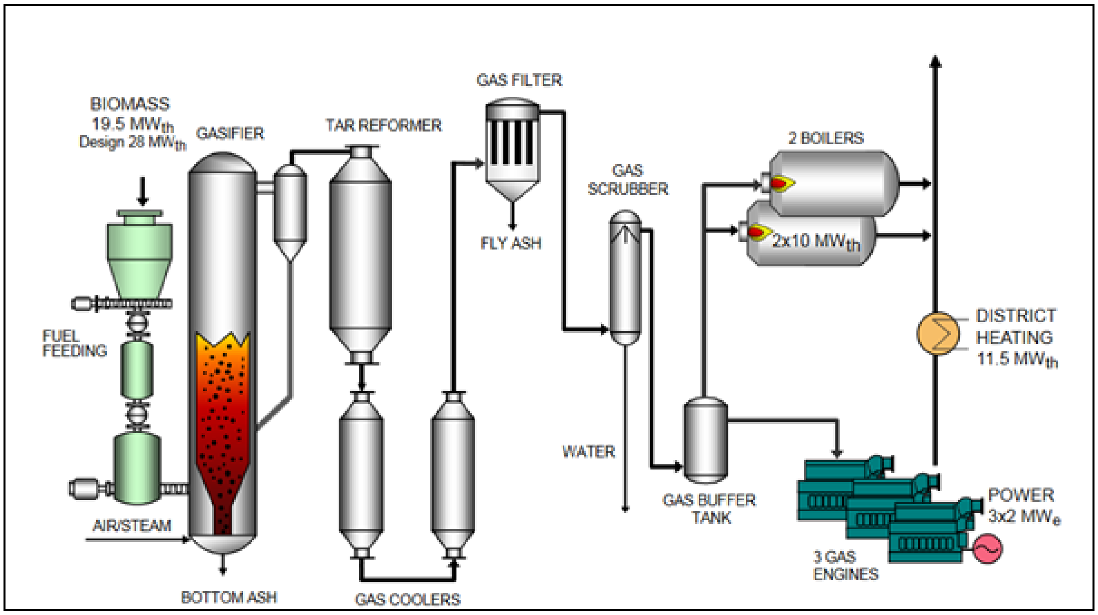
Figure 7: Skive District Heating Plant [44]

Gasifier System Details:

The CHP plant operation is primarily controlled by district heat demand and can have a maximum *cold gas efficiency*[9] of 76% and a maximum *hot gas efficiency*[10] of 93% using wood pellets ([49] and [44]). The plant also has two backup boilers allowing for an increased thermal output of 20MWth [44]. A conceptual flow sheet of the plant is shown below [44].

[9] Cold gas efficiency is the ratio of the calorific value of the producer gas to the LHV of the feedstock—only the chemical energy of the producer gas is considered, ignoring the increase in sensible heat [50].
[10] Hot gas efficiency considers both the sensible heat and calorific value of the producer gas and compares it to the LHV of the feedstock [51].

Figure 8: Skive Plant Diagram [44]



The system was designed to intake either wood pellets or chips, with moisture contents of <10% and 30%, respectively [44]. The plant typically operates on pellets with a diameter of 8mm and a length of 20-40mm, despite its ability to accommodate fuel within the tolerances of P45 wood chips. The feedstock impurity tolerances are shown below in the table [49].

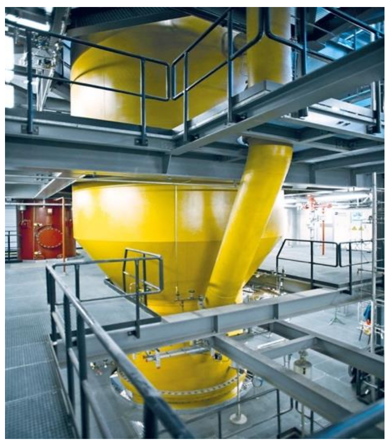
Table 15: Feedstock Tolerances

System Tolerances [49]	
Substance	**Weight Percentage**
Fuel Ash	< 2.5% of exhaust
K_2O	< 8% of fuel ash
Na_2O	< 2% of fuel ash
Feedstock	
Dust (<2000µm)	< 5% of feedstock
Rocks	None
Debris	None
Bark	Tolerant

Pellets are stored in a covered wood pellet storage site next to the gasification plant. They are then fed through two lock hopper systems by feeding screws into the lower section of the fluidized bed. Fuel feeding screws are typical of pressurized gasifiers [44].

The Carbona gasifier (pictured below), supplied by Andritz was initially designed for coal gasification, but has been modified for use with biomass [52]. It can use air, oxygen, or steam as the oxidizing agent ([49] and [44]). Only air is used at Skive. The oxygen and steam blown configurations of the Andritz Carbona gasifier have been demonstrated by other entities for syngas production in biorefinery projects as a precursor to biofuels [49]. In Des Plaines, IL, there is a pilot plant that gasifies wood pellets into gasoline using the Andritz-Carbona gasifier, tar reformation, morphysorb acid gas removal, and the Haldor Topsøe TIGAS gasoline synthesis process (Haldor Topsøe also responsible for methane production in GoBiGas plant) [53]. Although the Andritz-Carbona gasifier can function as a constituent of a biorefinery plant, oxygen and steam blown gasification is not conducted at Skive and syngas production has not been demonstrated there ([49] and [53]). The gasifier is operated at 2 bar over atmospheric pressure and 850 °C. Dolomite is used as the fluidized bed material, which is a common cement aggregate and tends to react with acids ([54] and [44]). While this gasifier could produce a useful biochar under the right conditions, Skive does not do so because the filter ash output (which would be where char would be collected) contains too much char for use as soil amendment [49]. However, the filter ash from this plant is moisturized for transportation and incinerated in a cement mill [49]. Also note that none of the byproducts of this plant are toxic [49].

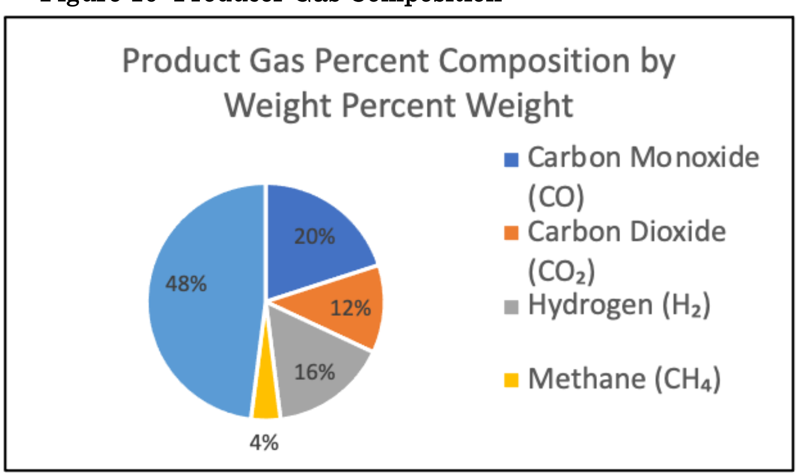
Figure 9: Carbona Gasifier [52]



Producer Gas – Composition and Clean Up:

The producer gas from the gasifier flows at 2.5-3 kg/s (5.5-6.5 lb. /s), has a heating value of 5 MJ/Kg (2150 Btu/lb.), and its composition by volume is shown in the chart below (data from [49] and [44]):

Figure 10: Producer Gas Composition



Gas clean-up at Skive begins with a novel hot gas catalytic tar cracker supplied by Haldor Topsøe ([44] and [54]). Operators queried call it a "catalytic reformer"[i]. In this step, the tar is reformed into mostly hydrogen and carbon monoxide [44]. After tar reformation, the producer gas passes through a gas cooler and subsequently through bag house filters to remove dust [49]. Lastly, the producer gas is passed through the water scrubber, which conducts additional cooling to 30 °C and dries the gas ([49] and [44]). Trace amounts of residual tar are extracted from the producer gas with condensed wastewater in the water scrubbing step. When processed, the gas has a relative humidity of 80% and is then sent to one of three GE Jenbacher engines, each capable producing 2 Mwe [44].

Waste heat absorbed from gas cooling is used for district heating along with heat from the engines' exhaust, lubrication oil, and jacket cooling [49]. All of these heat recovery processes happen in separate heat exchangers [49]. Additionally, to bolster district heating at peak times, gas can also be used to produce up to 20MWth district heating from two auxiliary gas boilers for meeting peak thermal loads and if/when any of the engines are not operating [44],[49].

According to the Task 33 IEA report from 2016 [44]:

> "The plant is designed to operate at between 30% and 140% load, corresponding to 28 MW of fuel heat input. Operation with all three gas engines running at 13 bar cylinder pressure is considered as 100% nominal load. Initially, the engines are expected to operate at 10 bar cylinder pressure, corresponding to 80% load. The 130% load also corresponds to the full load operation of the boilers, which provide operational flexibility when the engines are not available due to regular maintenance."

District heating demand controls the CHP plant capacity and the plant's performance is monitored by fuel feed rate, reactor temperature, reactor pressure, fluidization velocity, and gas composition ([49] and [44]). Additionally, the plant can be operated as an island, but it has never been operated this way in practice [49].

Commissioning and Plant History:

Skive Fjernvarme is the local district heating company and has been responsible for component integration and operation of the plant [43]. The plant was initially a first of its kind demonstration project [49]. It was commissioned in September 2007, with gasifier start-up and first gasification happening later the same year. The start-up was tested with just the gasifier, gas cooler, bag filter, and boiler at first. This was to validate the gasification system. This initial system supplied gas to the boilers, which in turn provided hot water to the town [44].

Next, a new gas clean-up line was commissioned. The performance of the gasification system was tested in early spring 2008, with all of its components being optimized separately. Prior to adding gas engines, the plant was optimized while gas was being fed to the boilers. The producer gas was tested thoroughly before it was deemed ready for testing with the first GE Jenbacher engine. As a result of this careful staging, it was possible for the engine to achieve full load and be connected to the grid a few days later. More analysis of the plant operation was conducted with the first engine in place [44] and in the summer of 2008, two more engines were added.

Andritz now cites the Skive plant as an optimal use case for their Carbona gasifier. They say: "The main application for pressurized air-blown BFB gasification would be to fuel a Combined and Heat Power (CHP) plant with gas engines like the one in Skive, Denmark." [52].

Operation and Maintenance:

Liquid fuel oil (LFO) is used to start up the plant. Final heat up is by wood combustion. The startup time to full load is about 40 to 50 hours [49].

The plant typically operates for 90 days between maintenance. The plant has had high availability of about 88-90% and annual operation hours of 7200 hours. In total, the engines have operated 60,000 hours by summer 2021 [49].

As indicated above, system maintenance typically occurs every 90 days. During this down time, the dipleg (cyclone return pipe) and fuel feeding screws are cleaned. Additionally, the plant goes down for 6 weeks during the summer, when general maintenance is conducted [49].

Financing:

The Skive gasification plant has been funded by the US Department of Energy (DOE), European Union (EU), and the Danish Energy Agency (DEA). The initial capital costs were subsidized by the DOE and EU [44]. Financing is also carried out by selling energy to Skive Fjernvarme customers. The project was expected to pay back in about 10 years. This funding was likely a prerequisite for this project's success.

Reasons for Success:

The operators of the plant indicated that the plant's success was likely due to good subprocess suppliers, the Carbona gasifier, and especially the devotion of Skive Fjernvarme to the project. Using the Carbona gasifier in this set up was ideal because this CHP application has a very high overall process efficiency, which allows for reasonable energy production costs. Furthermore, the catalytic tar reformation appears to play a large role in the success of this plant. Woody biomass produces higher amounts of tar than other feedstocks, so gas clean-up for tar is especially important—with reformation arguably being better than removal.

Besides what operators have indicated themselves, there may be more that is critical to the plant's success. The application of CHP in conjunction with gasification in an area with preexisting district heating infrastructure is likely critical from a cost and efficiency standpoint. Furthermore, gasification with CHP is arguably a more ideal application than IGCC or district heating alone. Additionally, the feedstock appears to be a perfect match for the gasifier and gas clean-up technologies. The wood pellets are likely refined to the point that there is not much concern for slagging due to high silica or other mineral content coming from dirt or debris. Also, the bed material could play a role in neutralizing corrosive compounds due to its tendency to react with acids. Slagging, corrosion, and tar are often the culprits for failure. To have a successful plant, these problems must be mitigated or dealt with, which Skive has been successful at handling.

Challenges:

Per the 2016 Task 33 IEA report, some of the challenges have included scale up to commercial operation, lack of long-term data, integrated plant control, missing details from design documents, and a long and expensive commissioning period during which equipment was tested. Due to the expense of the novel plant, government grants and subsides are necessary. Currently the nature of the contract to build and operate this plant is not known. Other challenges included fuel availability, renewable energy prices, and government carbon emission reduction targets. Additionally, the stakeholders in the project may have had differing incentives: “the owner of the project wants to produce cheap electricity and heat and the equipment vendor to demonstrate new technology” [44].

Implications for Future Gasification Plants:

This project’s success shows that gasification plants, which are still arguably an emerging technology, must be financially nurtured to be successful. Good financial backing likely leads to an environment in which diligence and perfection is encouraged, reducing the risk of introducing new components prematurely, which can lead to plant failure. Skive benefited from existing district heating infrastructure and a staged approach to implementing CHP. Their staged approach to building up the plant shows that it is advantageous for gasification plants to have time-period where producer gas and feedstock quality is analyzed before any impurity sensitive equipment is introduced. Another benefit of this approach is that it allows time for a more informed selection of gas cleanup subprocess suppliers that considers compatibility with preexisting plant infrastructure. This period could only take place with adequate funding and/or existing revenue from heating.

Lahti Energia – Kymijarvi Projects - Lahti, Finland [55-60]:

Waste materials as well as producer gas are co-fired with coal at the Lahden Lämpövoima Oy’s Kymijärvi I (350 MWth) power plant at Lahti, Finland. Paper and textiles, wood, and peat, as well as shredded tires, plastics and municipal solid waste are gasified in a Foster Wheeler air-blown circulating fluidized bed gasifier that was installed in 1997. The plant has a total maximum capacity of 167 MWe. On an annual basis, approximately 15% of fuel needs are met by gasification. Capital cost of the gasification plant was $15 million.

The hot producer gas is led through an air preheater to two burners, which are located below the coal burners in the boiler. The bottom ash extraction system was designed to remove the non-combustibles from the municipal solid waste, as well as nails and other metals from urban wood waste.

The gasifier has been in operation since 2002. Availability increased consistently in the first few years and in 2005, 2006 and 2007, the gasifier was available more than 7000 hours of the year and the engine, more than 6000 hours.

In 2012, the Kymijärvi II demonstration gasification power plant was inaugurated by Lahti Energy. It cost 160.5 million Euros, receiving 15 million Euros from the Finish Ministry of Employment and the Economy, as well as 7 million Euros from the EU. This plant runs on solid recovered fuel (SRF), which is essentially trash that has been shredded, dried, and rid of metals. In this particular case, the SRF is made up of commercial and building site waste, as well as household waste. The SRF is largely prepared by waste management companies in Southern Finland. Some sources also indicate the plant runs on supplementary woody biomass. This plant is completely separate from the Kymijärvi I powerplant, which ran on coal and producer gas, while Kymijärvi II relies solely on gasification of SRF and some waste wood.

The Kymijärvi II plant produces 50 MWe of electricity and 90 MWth of district heating with an organic Rankine cycle. Startup uses natural gas. The plant has extensive gas cleanup preceding the boiler, with the boiler operating at 540 °C and 120 bar (1004 °F and 1740 psi). The gas cleanup is touted for being responsible for the solution to slagging and corrosion that often results from gasification of SRF containing metals like sodium in addition to other harmful compounds. Some impurities are removed during cooling and initial filtration, taking the gas from 900 °C to 400 °C (1652 °F to 752 °F), causing the impurities to solidify into ash. After this step the gas is led to ceramic filter pipes where unwanted particles stick to the pipe walls. Sediment build-up is removed at regular intervals using "nitrogen pulses." The gas is then sent to the boilers. It's important to note that most of the problems with this plant have been surrounding the gas purification process, although there don't appear to have been many.

Due to this plant's replacement of 170,000 tons of coal per year with 250,000 tons of SRF per year, it was awarded Finland's "Climate Act of the Year" Award in 2012. Valmet appears to have supplied the majority of the components including the gasifier, gas cooling and cleaning, steam boiler, and flu gas cleaning system. According to sources, this plant is still running.

In 2016, Lahti Energia Oy received a loan of 75 million euros for the construction of the 150-180 million Euro Kymijärvi III plant, which had been planned to start in 2014. Interestingly, this plant is a woody biomass CHP plant and does not appear to incorporate gasification in any capacity. The plant is nearing completion as of January 2022, with testing taking place over the following six months. The plant had already delivered first heat to Lahti's district heating network as of 2019. The plant has a heat capacity of 193 MWth and is intended to replace the Kymijärvi I plant, which is still running uses coal for the most part. Kymijärvi II is intended to continue running alongside Kymijärvi III.

Tables 16-19: Projects Reviewed in 2010 and 2022

Tables 16 through 19 below are included in this report to provide a broad view of biomass gasifier technical and market developments over the last 10 plus years; in the authors' view, a unique perspective that may offer value to the industry.

When the Washington State University Energy Program published "*Clean Heat and Power Using Biomass Gasification for Industrial and Agricultural Projects"* with funding from the US Department of Energy's Clean Energy Application Center (CEAC) program in February 2010, a substantial table of gasifier projects was included to expand the detailed project profiles with an overview of representative leading gasifier projects – mostly demonstrations – to help readers appreciate the breadth of the development front for this technology. The current report draws on that earlier report throughout, so including, updating, and expanding on that survey of projects appeared a logical opportunity to provide industry stakeholders with the 'long view': how the gasifiers have both evolved and persisted in many cases.

The picture is optimistic, in our opinion – gasifier technology has changed, but many of the decades-old projects included in these tables have continued to operate successfully, boding well for a future where efficient use of biomass for thermal and electric power production is expected to have increasing value.

Table 16. Examples of Recent U.S. Packaged Micro-Scale Biomass Gasifiers

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Malibu, CA	Atmospheric water distillation, electricity, and heat generation	All Power Labs	Downdraft	30 kWe	-	N/A	Installed Jan, 2019. Provided to the Skysource / Skywater Alliance to power a prototype atmospheric water distiller.
Fresno, CA	Wildfire risk mitigation, electricity generation	All Power Labs	Downdraft	20 kWe	Woody biomass	N/A	Installed June 2019. Provided to the Sierra Resource Conservation District, which manages and protects more than 3000 square miles of forest and foothills in the Sierra Nevada and Central Valley.
NW Montana	Biochar generation for production of soil regenerating biostimulants	All Power Labs	Downdraft	30 kWe	-	N/A	Installed March 2022. Added to Regenitech's regenerative agricultural facility, specifically their EPL biorefinery system.

Table 17. Examples of Recent International Micro-Scale Biomass Gasifiers

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
White River, South Africa	Macadamia nut drying, electricity and heat generation	All Power Labs	Downdraft	30 kWe	Macadamia nut shells	N/A	Installed Oct. 2019. Provided to Ambermacs, a macadamia nut processing plant. The plant dries, processes, packs, and supplies raw macadamia kernels.
Kenya, East Africa	Reduce diesel fuel consumption, electricity generation	All Power Labs	Downdraft	10 kWe	-	N/A	Installed Mar. 2012. Provided to the Turkana Basin Institute, which gives support to researchers doing fieldwork in the Lake Turkana Basin.
Miyazaki, Japan	Heat is used for heating greenhouses; electricity is sold to the grid through a feed-in tariff.	Volter	Downdraft	40 kWe	Woodchips	N/A	Provided to Hamatech Co. Ltd. There are substantial forest resources in the Miyazaki prefecture, so Hamatech harvests wood from their forests to power their gasifier and sells the electricity to generate revenue.
Jaunjelgava, Latvia	Electricity and heat generation.	Spanner	Crossdraft	45 kWe (x10)	Wood	N/A	Installed in 2014 at a power plant. The energy system consists of wood gasifiers and wood gas CHP units, which are connected in a cascade. In 2018, the 5.7-litre CHP engines were converted from 1,500 rpm to 3,000 rpm. This enables an increase output from 45 to 54 kWel to be achieved.
Muhlbach, South Tyrol	Generates electricity from process heat.	Bioenergie Wegscheid	Downdraft	125 kWe	Wood Briquettes	N/A	Installed in Oct. 2013 at a glue laminated beam manufacturer. The gasifier has an average annual operating time of 8600 hours/yr.
Emsdetten, Germany	Generates heat and electricity, produces 500 tonnes of biochar	Syncraft	Floating fixed bed	500 kWe	Residual forest wood / landscape management	N/A	Provided to Bioenergie Ahlintel (a wood power plant). The system is a CW1800-500 system and has an average annual operating time of over 8000 hours/yr.

	per year				material		

Table 18. Examples of European Biomass Gasification Projects: 2010 with Status Updates to 2022 -(Updated from 2019 IEA report unless otherwise specified)

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Harboøre, Denmark – Demonstration (1993 – 1997) - Commercial (1997 – Present)	CHP (2001 – Current) and District Heat (1993 – Current)	Babcock & Wilcox Voland	Updraft	1.5 MWe 1.6 MWth	Non-Pre-treated wood chips Wood Chips (35%-55% MC, typically 42% MC)	Operation of 2 GE Jenbacher gas engines on producer gas began in 2001. Plant availability up to 8000 hrs. /year operation by 2006. District heating has been provided for more than 70,000 hours of operation between 1994 and 2005. Has wet electrostatic precipitator and "Tarwatc" tar removal system. Heavy tar fired boiler used for peak district heating demand. Auxiliary producer gas fired boiler also available for engine downtime.	The plant is still in operation after implementing CHP in stages. Subsidies assisted with the project cost.

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Lahti, Finland (Kymijärvi I)	Electricity and District Heat	Foster Wheeler	Circulating Fluidized bed	167 MWe	Peat, wood, tires, and trash	A 200-megawatt coal-fired plant that added a 40 MWe fluidized bed gasifier. Successful operation.	This plant is still operational. However, it will be replaced by Kymijärvi III once it becomes fully operational. Kymijärvi III is a wood biomass fired CHP plant without a gasifier. Kymijärvi III is currently finishing up testing.
Location	**End Use**	**Gasifier Manufacturer**	**Gasifier Type**	**Electric Power Production**	**Feedstock**	**Notes (Pre 2010)**	**Notes (2010-2022)**
Lahti, Finland (Kymijärvi II)	Electricity and District Heat	Valmet	Assumed to be Fluidized Bed	50 MWe 90 MWth	"solid recovered fuel" (solid wastes), and sometimes supplementary woody biomass	N/A	Kymijärvi II was completed in 2012. It cost roughly 160.5 million Euros. Info on this plant is in an above section. This plant has extensive gas cleanup, as well as nitrogen pulsing. To deal with the impurities of the SRF feedstock and sediment build up, respectively. This plant displaces about 170,000 tons of coal and is hailed as a great success in Lahti's efforts towards carbon neutrality. This plant will continue operating alongside Kymijärvi III.

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Moissannes, France - Demonstration	Electricity	PRM Energy	Updraft.	1.0 MW	Wood Chips and Pomace	Successful operation in 2006 and part of 2007, but not running now due to permit problems. Uses the OLGA organic solvent gas clean up.	Plant shut down in 2007 but was considered a successful demonstration.
Värnamo, Sweden	Electricity and Liquid Fuels	Foster Wheeler	IGCC	6 MWe	Wood chips	Plant availability up to 6500 hours by 2005. Restarted in 2006 for condition assessment with liquid fuel production starting in 2007.	Plant appears to have been shut down for non-technical reasons, such as the end of its demonstration period. It may have been repurposed, but information is scant.
Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Gussing, Austria	Electricity, mixed alcohols, heat	Repotech	FICFB or Indirect steam DFB	2 MWe	Local wood	Plant availability up to 6500 hours of operation by 2005. GE Jenbacher gas engines. Beginning pilot of Fischer-Tropsch synthesis to produce biodiesel and syngas. High grade producer gas. Plans for a fuel cell. Demo plant in operation from 2001-2016. Inspired plants in Oberwart, Senden/Ulm, and Goteborg.	Also inspired plants in Nongbua, Thailand, and Daigo, Japan, as well as an upcoming plant in Gaya, France. The Gussing plant is often cited as a landmark indirect steam DFB plant such that subsequent plants across the world have said they use the "Gussing Process." Shut down for economic reasons (fully functional) in 2016. Feed in tariff went away in October 2016. Plant itself had no technical issues. Indirect steam works well but is high in capital costs.

Oberwart, Austria	Electricity. Biomethane	Repotech	FICFB or Indirect Steam DFB	2.7 MWe	Wood	Operational in 2008. Design based on demonstration at Gussing. Electric efficiency of 32%. GE Jenbacher gas engine. Organic Rankine Cycle will recover heat from gasifier to generate electricity. Possibility of biomethane production. Operated from 2008 – 2015.	No up-to-date information on this gasifier.
Spiez, Switzerland	Electricity	Pyroforce	Dual zone /Fixed bed downdraft	200 kWe	Commercially shredded wood	Operational since 2002. As of June 2008, plant has 15,000 hours of run time on GE Jenbacher gas engines.	No updates available.
Location	**End Use**	**Gasifier Manufacturer**	**Gasifier Type**	**Electric Power Production**	**Feedstock**	**Notes (Pre 2010)**	**Notes (2010-2022)**
Kokemäki, Finland	Electricity and District heat	Condens Oy / Novel	Fluidized Bed	1.8MWe	Wood	Commissioned in late 2006. Startup of one JMS 316 engine in 2004/2005 and two more in 2005/2006. District heat output of 4.3 MWth. Fuel is dried to less than 30% by waste heat from the existing Kokemäki district heating plant.	No up-to-date information

Skive, Denmark	District Heating (electricity is secondary)	Andritz / Carbona	Bubbling Fluidized bed	6 MWe 12 MWth	Wood pellets with a diameter of 8mm and a length of 20-40mm Designed to accept wood chips as well.	Commissioning September 2007. Gasifier startup and first gasification happened in late 2007. In 2008 plant provided DHW with 2 auxiliary gas boilers to the town while the plant was being optimized. Official opening delayed until April 2009. 3 GE Jenbacher gas engines installed. Unique design of tar reformer. Total investment cost is 30 million Euros. Expected pay-back time was ~10 years.	Still operating. IEA report says it has been subject to “public funding”. R&D Stage funded by Danish Energy Agency, European Commission, and US DOE. Improvements have been made in fuel quality and catalytic tar reforming, allowing the plant to have high availability. Tar reformation appears to be best in class. Similar to Harboore, this plant has benefited from a stage approach to CHP implementation, along with a preexisting district heating network.
Location	**End Use**	**Gasifier Manufacturer**	**Gasifier Type**	**Electric Power Production**	**Feedstock**	**Notes (Pre 2010)**	**Notes (2010-2022)**
Rossanno, Italy	CHP	PRM	Updraft	4 MWe	144 tpd olive waste	Operating since 2002 but in 2005 experimental tests were still on-going due to gas clean-up problems. Six Guascor gensets, model 560 FBLD.	2016 IEA report indicates briefly that plant is still operating. However, the current status in unknown.

Tondela, Portugal	Electricity	Milena	CFB + BFB	1 MWe	Chicken Manure, RDF, and Wood Chips	N/A	Gasifier started in 2011 and used chicken manure as feedstock. Used Milena gasification process and OLGA gas cleanup technology. Operated from 2011 to 2015 and shut down due to removal of subsidies in 2012-2013. Plant was sold to another company.
Senden, Germany	IGCC and CHP	Repotec	Indirect Steam DFB	6.5 MWth 5 MWe	Logging Residues	N/A	This plant began construction at the end of 2009, with commissioning at the end of 2011. Commercial operations began in 2012. The plant was around 80% efficient. Incoming logging residues were diverse, unaltered, and brought minerals. This plant stopped operating in 2018, although it is unclear why.

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Gothenburg, Sweden (GoBiGas)	Biomethane Production (small district heating)	Repotec	Indirect Steam DFB	20 MW Biomethane 2.5 MWth	Woody Biomass	N/A	Construction for this plant began in 2010 and operations began in 2012. Its efficiency was 65% for methane production (including gasification and methanation processes). Haldoore Topsoe and Jacobs were responsible for the methanation process. The plant was very successful in demonstrating biomethane production. A second phase was planned that would generate 100 MW of biomethane, but it was never constructed. The original plant was mothballed in 2018 due to its inability to break even.

Table 19. Examples of North American Biomass Gasification Projects: 2010, with Status Updates to 2022

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Joseph C. McNeil Generating Station Burlington VT	Electricity	Future Energy Resources Company (Silvagas) Silvagas Bought by Rentech. Can't find any mention of Gasifiers	Indirect steam	7 MW	76 tons per hr. forest thinnings and waste wood	Silvagas technology successfully demonstrated in Phase 1 (1996 to 2001) in which producer gas was supplied to the existing 50 MWe biomass boiler, adding 6 to 7 MWe capacity. Phase 2 involving gas clean-up and use of gas turbines was stopped in 2001 due to pending bankruptcy of FERCO. FERCO Enterprises became Silvagas in 2006.	Phase 2 of the plant never happened due to Ferco's bankruptcy. McNeil appears to have reverted the plant to just wood combustion with ORC.
Biomass Gas and Electric Forsythe, GA	Electricity	Future Energy Resources Corporation	Updraft	28 MWe	Wood waste, sawmill residue, and herbaceous agricultural waste from adjacent land fill	Planned as of August 2007. Will generate electricity by steam cycle. Not online as of 2011. Energy policy in Georgia does not incentivize biomass.	Appears to have never been built due to lack of biomass incentives.
Biomass Gas and Electric Tallahassee, FL	Electricity. Methanated biogas	Future Energy Resources Corporation (Silvagas)	Indirect steam	42 MWe	Wood chips	Construction to begin January 2009. Will use Silvagas technology demonstrated at McNeil Generating Station. BG&E estimates it can deliver electricity at 7 cents/kwh.	Project canceled due to environmental justice concerns
FruitSmart: short term demo Prosser WA	Syngas offset propane use in dryers.	CPC Biomax	Downdraft	Thermal Only	Various	Ended due to slagging of gasifier with straw feedstock	N/A

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
FruitSmart: long term demo Prosser WA	Electricity.	CPC Biomax	Downdraft	500 kWe	Grape pomace	Planned demonstration of biomass pelletization and gasification at Prosser Wine and Food Park. Design complete but put on hold waiting for funding. Project has received a federal appropriation that has not yet passed.	No up-to-date information available.
Gady Farm Spokane, WA	Electricity. Liquid fuels.	Taylor Biomass Energy and WRI	Dual-bed indirect air	300 kW	Grass and straw	Cleaned producer gas will be burned in engine. Biochar used in field as soil amendment. Energy used to run seed drying and cleaning mill. Everything here seems to be in a big cycle all products and energy are basically used on site. Partially government funded.	Appears to still be in operation as of 2017.
Tallon Lumber	Electricity for on-site use and sale. Heat for lumber kiln.	Pudhas Energy		320 kW	Wood	Commissioning 2005 but operation stopped due to gas clean-up problems. Original electrostatic precipitator was replaced with a venturi wet scrubber in May 2008. The startup testing and system shakedown is planned for the 1st quarter of 2009.	No up-to-date information available
Mount Wachusett Community College Gardner, MA	Electricity, Campus heating & cooling	CPC Biomax	Downdraft	50 kWe	1.5 tpd of green wood chips	This small $1.2 million plant was funded by the DOE Golden Field Office and Congressman John Olver of	Appears to be used for research applications. Could not verify if it is still in operation.

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Siskiyou Opportunity Center Mt Shasta, CA	Electricity	Community Power Corp. (CPC)	Downdraft	25 kW	Woodchips and nutshells	Reports that project was terminated due to "feedstock problems". In 2007 the Biomax 25 unit was returned to CPC "after not living up to expectations."	N/A
Tolko plywood plant Heffley Creek BC	Syngas for drying kilns	Nexterra	Updraft	Thermal only 28 MMBtu/h	13,000 bone dry tonnes per year of wood residue	Successful operation producing 38 MMBtu/hr. of net useable heat. Opened in 2006. Reduces GHG emissions by 12,000 tonnes annually.	Gasifier is still listed on Nexterra's website and is said to have operated for over 50,000 hours.
Domtar Paper Mill Kamloops, BC (Pilot Project)	Syngas for lime kiln (8 MMBtu/h)	Developers: Nexterra, Weyerhaeuser and Paprican (Now FP Innovations)	Updraft	Thermal Only 8 MMBtu/h	Hog fuel	Successful 8 MMBtu/h pilot scale project to demonstrate technology for commercial scale project at the same site.	Unknown status.
University of South Carolina, Columbia, SC	Electricity and Steam	Nexterra / Johnson Controls	Updraft	1.4 MWe		Completed performance and emissions tests in 2009. The 72 MMBtu/hr. system provides 60,000 lbs. /hr of steam and 1.4 MWe of electricity.	Decommissioned in 2011 due to repeated equipment failures. Operated from 2007-2011.
Grand Forks Truss Plant, Grand Forks ND	Electricity and Heat, also syngas production	EERC Center for Renewable Energy	Downdraft	50 kW	Wood waste, sawdust. 4 to 6 cubic yards daily	Planned as of July 2007	No updates on this plant after 2007.

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
Dockside Green, Victoria BC	District heating and hot water	Nexterra	Updraft	2 MWth	Urban wood waste (20 – 55% MC)	The 8 MMBtu/hr. system has been completed and is undergoing commissioning in 2009.	Functional according to Nexterra's website. It is Canada's first urban gasifier and is "ideally suited" to this because the gasifier produces little noise or pollution.
Kruger Products Tissue Mill, New Westminster BC	Steam for mill	Nexterra	Updraft	Producer gas for use in boiler to produce steam. 40,000 lbs./hr steam	Wood residue from mill and local construction debris	Scheduled for completion Q4 2009. Opened in 2009. Operational. Urban setting benefits from use of syngas rather than burning biomass.	Still operational. Produces 40,000 lb. /hr of steam.
Oak Ridge National Labs in Oak Ridge Tennessee.	District heating	Nexterra / Johnson Controls	Updraft	60 MMBtu/hr	Municipal wastewater biosolids	Scheduled to be operational in 2011. 60,000 lb./hr steam.	In 2011, ORL were reaching completion on a computer simulation intended to inform the design of the gasifier. In 2012 the plant was completed. In 2013, the plant was shut down, and in 2015 the plant was permanently decommissioned.

Location	End Use	Gasifier Manufacturer	Gasifier Type	Electric Power Production	Feedstock	Notes (Pre 2010)	Notes (2010-2022)
University of Northern British Columbia Prince George, BC	District Heating	Nexterra	Updraft	4.4 MWth	Sawmill Wood residue and hog fuel	Planned	Successful plant startup in May 2011. It has offset 80% of fossil fuel use for the campus. The plant achieved LEED Platinum in 2013 and the Canadian Green Building Award in 2014. The plant cost about $15.7 million and heats ten campus buildings. Plant consumes 6000 tonnes/yr. of fuel. Plant assumed to still be running.
Chippewa Valley Ethanol Company Benson, MN	Syngas for ethanol production	Frontline Bioenergy		Ethanol feedstock only	Wood chips and corn cobs Phase 1: 100 tons/day Phase 3: 300 tons/day	Opened 2008. Currently operating in first of three phases of implementation. When 3rd phase is implemented syngas will displace 90% of plant's natural gas.	No up-to-date information. Unclear if phase 3 ever happened.

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