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Report to Gisborne District Council

Waste Wood Processing Technologies Review

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July 2022

Summary

Four biomass conversion technologies were reviewed and assessed for potential use to convert the forest waste wood (biomass) in the Gisborne area. These conversion technologies include combustion, gasification, pyrolysis and torrefaction. The assessment is based on the maturity and complexity of the technology, products and applications, production costs and the environmental impact.

The biomass combustion process is a mature technology and can produce heat or combined heat and power (CHP). Heat generation requires local users who can be wood processors or district heating. Power generated can be sent to the grid. Although biomass contains low contents of sulphur and nitrogen, emissions from the flue gas still need to be carefully monitored.

Biomass gasification is a proven technology operating at 700 to 1200°C, although 700-900°C is most common. Both demonstration and commercial biomass gasification plants are available in the world. This technology produces a gas mixture, termed producer gas, with H_2, CO, CO_2 and CH_4 being the major components. The producer gas is expected to contain a significant amount of N_2 if air is used as the gasification agent. On the other hand, the producer gas also contains tar and gaseous contaminants, which need to be removed before the producer gas is further used. The cleaned producer gas can be used for power generation using a gas turbine or gas engine. In addition, the producer gas can be further processed for gaseous fuel (synthetic natural gas, hydrogen) or liquid fuel. In this case, the overall process is complex and capital investment is significantly increased.

Biomass pyrolysis is also a proven technology operating at 400-650°C with demonstration and commercial plants available around the world. In general, biomass can produce products in liquid (bio-oil), gas (non-condensable) and solid (bio-char). The target product in most cases is the liquid bio-oil, which is further processed for liquid fuel. In this case, sophisticated upgrading is needed due to the complex composition of the bio-oil.

Torrefaction is a relatively simple process in which the wood is heated in the absence of oxygen to remove volatiles; thus, only solid char is produced at a yield of 85% or higher. The solid char can be used to substitute coal in combustion or co-firing. Recently, solid char has been applied in ironmaking to replace coal-derived coke.

Based on the assessment of technology maturity, products and market demand, production costs and environmental impacts for the four conversion technologies, biomass torrefaction stands out as a preferred technology to process the forest waste wood to solid char.

Contents

1. Introduction

The forestry slash problem in the Gisborne area has been reported for some time. The forestry waste was often washed away by rain to rivers, into the sea, and then back to the beaches. Kitchin from RNZ stated this problem as a summer eyesore on the beach RNZ [1]. Dr. Murry Cave of the Gisborne District Council concluded that 85% of the waste wood came from plantation forests [2]. Therefore, better forestry management is required to solve the waste wood slash problem and to promote sustainability in the local forestry industry. It has been aware that the waste wood from the forests and residues from logging are potentially valuable resources for energy and materials. There are various types of technologies which may be employed to convert these wastes streams from forests to energy, fuels or other types of useful products.

The primary technologies are combustion, gasification, pyrolysis and torrefaction. Combustion is a mature technology that can use the waste wood as fuel to produce heat or heat and power. Gasification is a process that converts the wood to a combustible gas mixture at high temperatures. This gas product can be used from heat, heat and power or further synthesised for synthetic natural gas, hydrogen and liquid fuel. Pyrolysis thermally decomposes the waste wood in an oxygen absence environment into three products: solid char, liquid oil and non-condensable gas. The Torrefaction is similar to pyrolysis but operates at lower temperatures with solid (brittle) as the target product. In this report, these four technologies are reviewed and discussed. The process mechanism, the products, emissions and possible applications are compared to provide technical information for selecting the most appropriate technology for resolving the wood slashing problem in the Gisborne area.

2. Technology Review

2.1 Biomass combustion

Combustion is one of the oldest and most mature technology to utilize wood for heat or heat and power. The wood combustion process can be separated into four stages: evaporation of moisture in wood; devolatilization of wood components; ignition of volatiles; and combustion of remaining char. The combustion performance of the wood depends on both chemical properties, which are related to wood chemical composition, and the physical properties such as particle size and moisture content. Woody biomass can be in different forms, such as sawdust, wood chips, wood logs, briquettes and pellets. For the forest wastes, the materials are in small logs and branches, thus can be converted into chips for combustion. The chips may be directly used as fuel in furnaces after natural drying. However, controlled drying is needed if the moisture content is too high. Small logs can be cut into pieces for large-sized combustion units. Briquetting and pellets are usually used as fuel for combustion outside the forestry sector [3].

The combustion systems can be classified into discontinuous fuel feeding (charging) stoves and automatic continuous fuel feeding (charging) furnaces when it comes to the heat utilization of woods [4]. For small to medium-scale combustion systems, stoves and boilers are applied.

The through-burning stove is commonly used with wood briquettes and coarse wood chips in the discontinuous fuel feeding combustion systems. The warm air-tiled stoves are shown in Figure 1, which require a short charging interval to ensure the combustion quality. Another discontinuous fuel feeding stove is “tiled stove” as shown in Figure 2, which has a longer charging interval. The central boiler is another typical discontinuous fuel charging combustion system, as shown in Figure 3. The suitable retention time for oxidation of the volatiles is the key to ensuring the combustion quality. With appropriate control, the CO emission in the flue gas from combustion can be reduced from 2000 mg/m^3 to 150mg/m^3 [4].

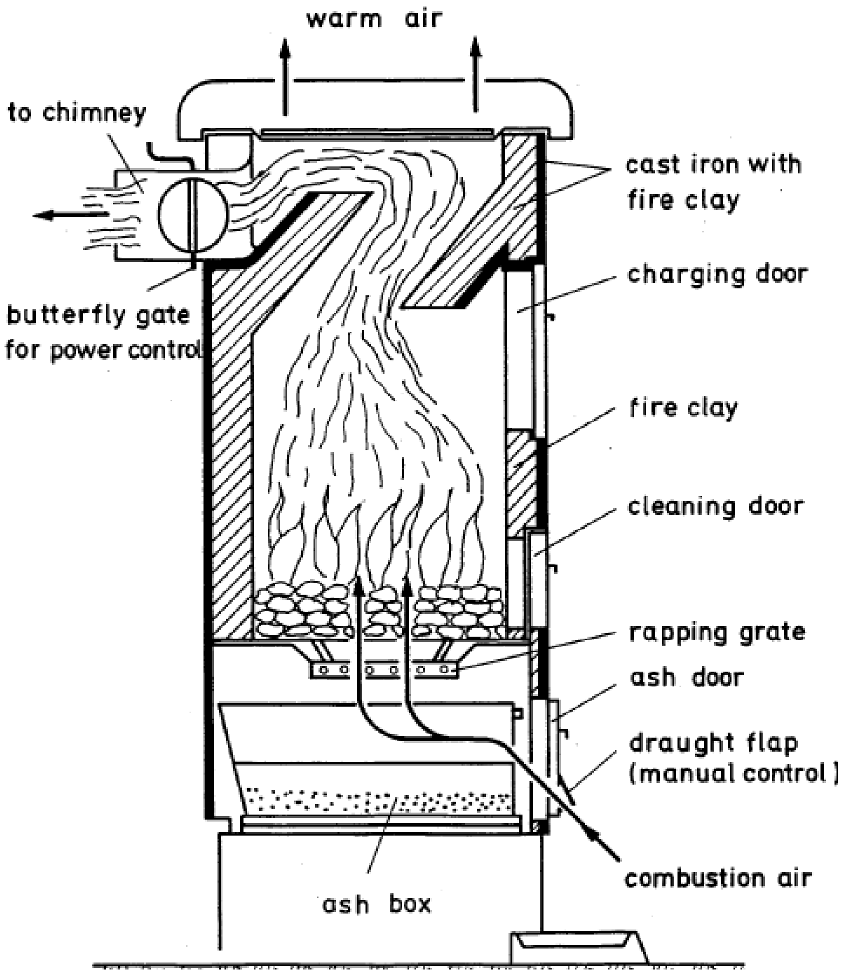


Figure 1. Through-burning stove for short wood logs, briquettes, and coarse wood chips [4].

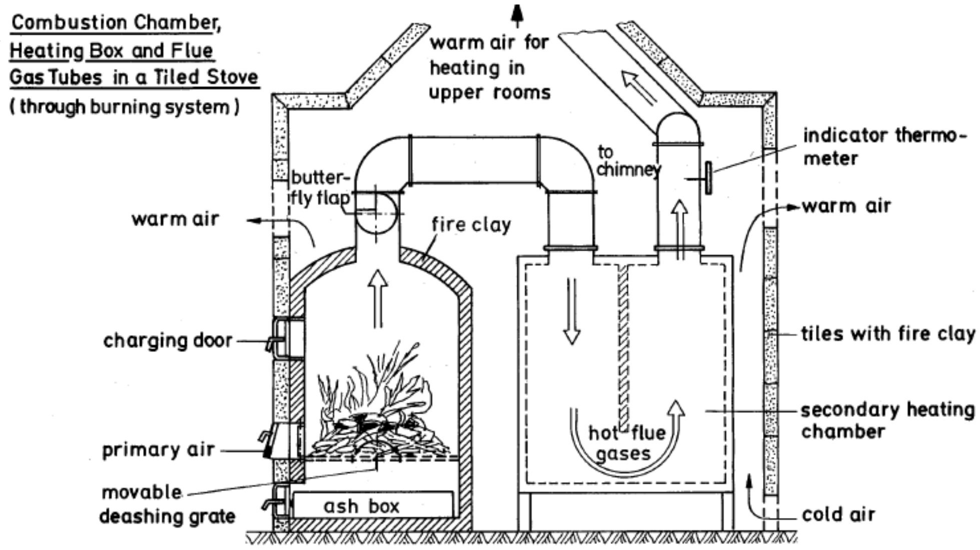


Figure 2. Tiled stoves for warming air [4].

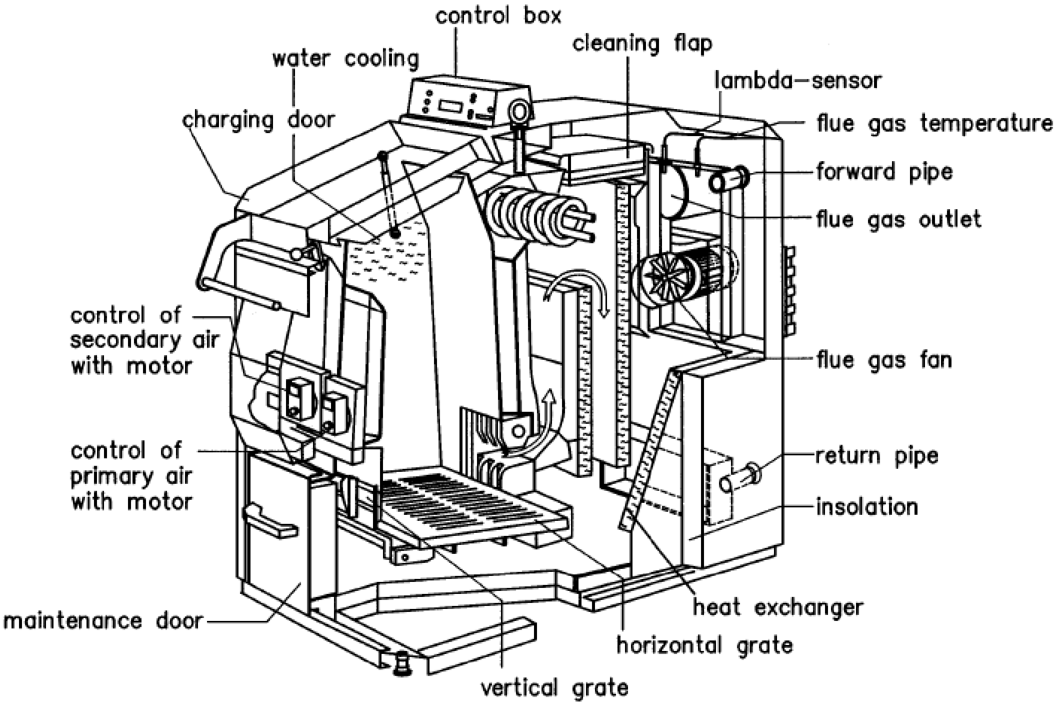


Figure 3. Bottom burning boiler with flue gas fan and top charging [4].

In the continuous fuel-feeding furnace systems, the wood is fed to the combustion chamber with automatic augers or hydraulic cylinders. Fuel preparation and pre-furnace systems are connected to the furnace system, as shown in Figure 4. The fuel preparation units include size reduction and drying using flue gas. The pre-furnace system is designed for wood devolatilization and combustion. The flame and unburnt volatiles from the pre-furnace section flow to the boiler chamber for complete combustion and heat supply. The boiler, in this way, acts as a secondary combustion chamber and heat exchanger.

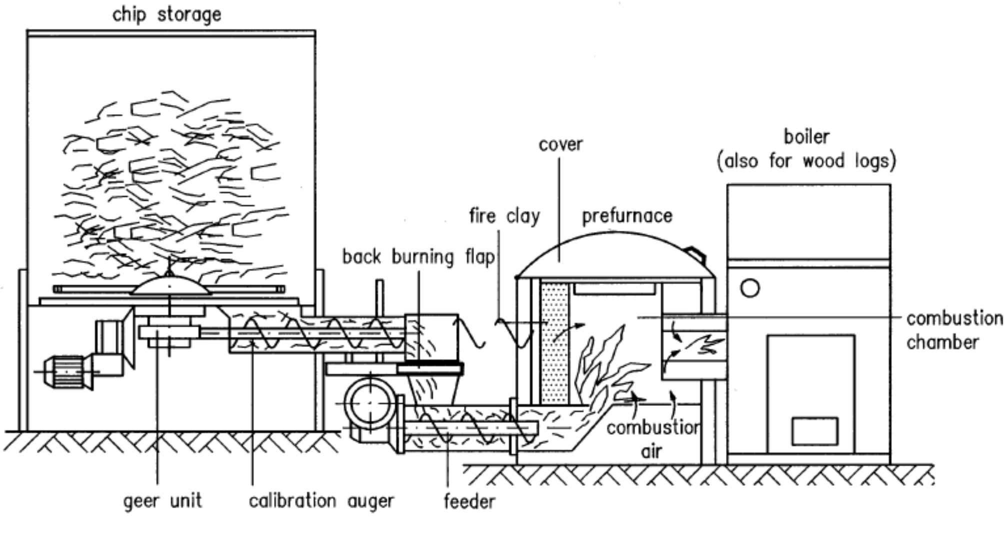
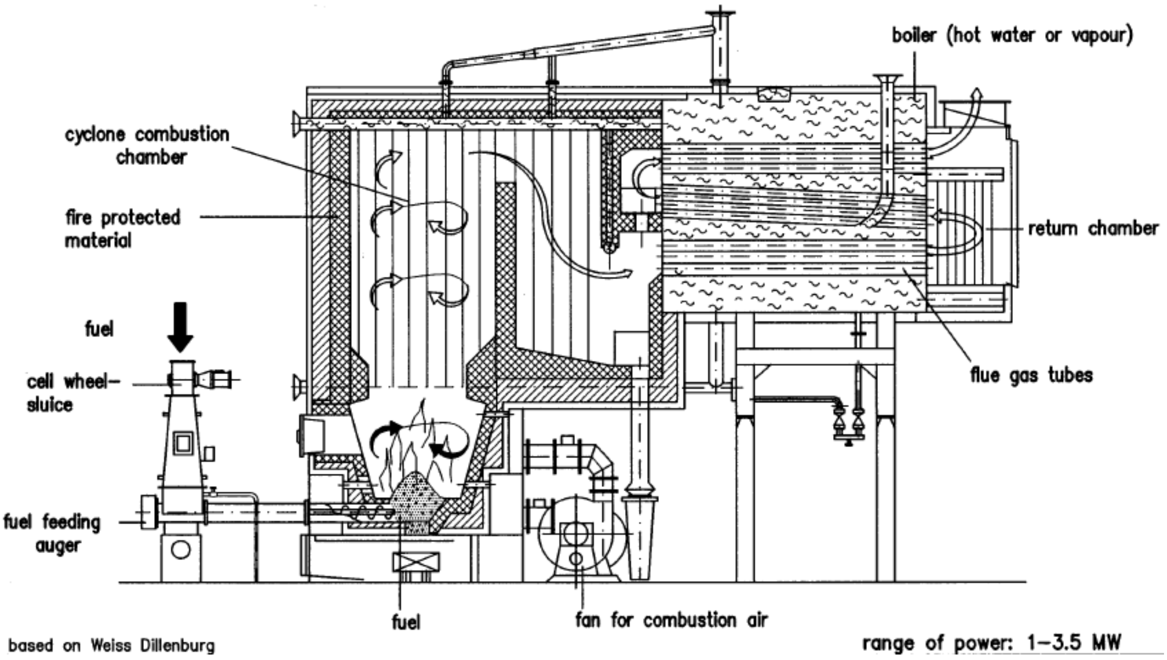


Figure 4. Demonstration picture of the pre-furnace system [4].

A boiler system combined with a furnace requires less space than a pre-furnace system and this system shares the same combustion set as a pre-furnace system. Under-feeding is commonly used for fuel feeding, as shown in Figure 5 below.



based on Weiss Dillenburg

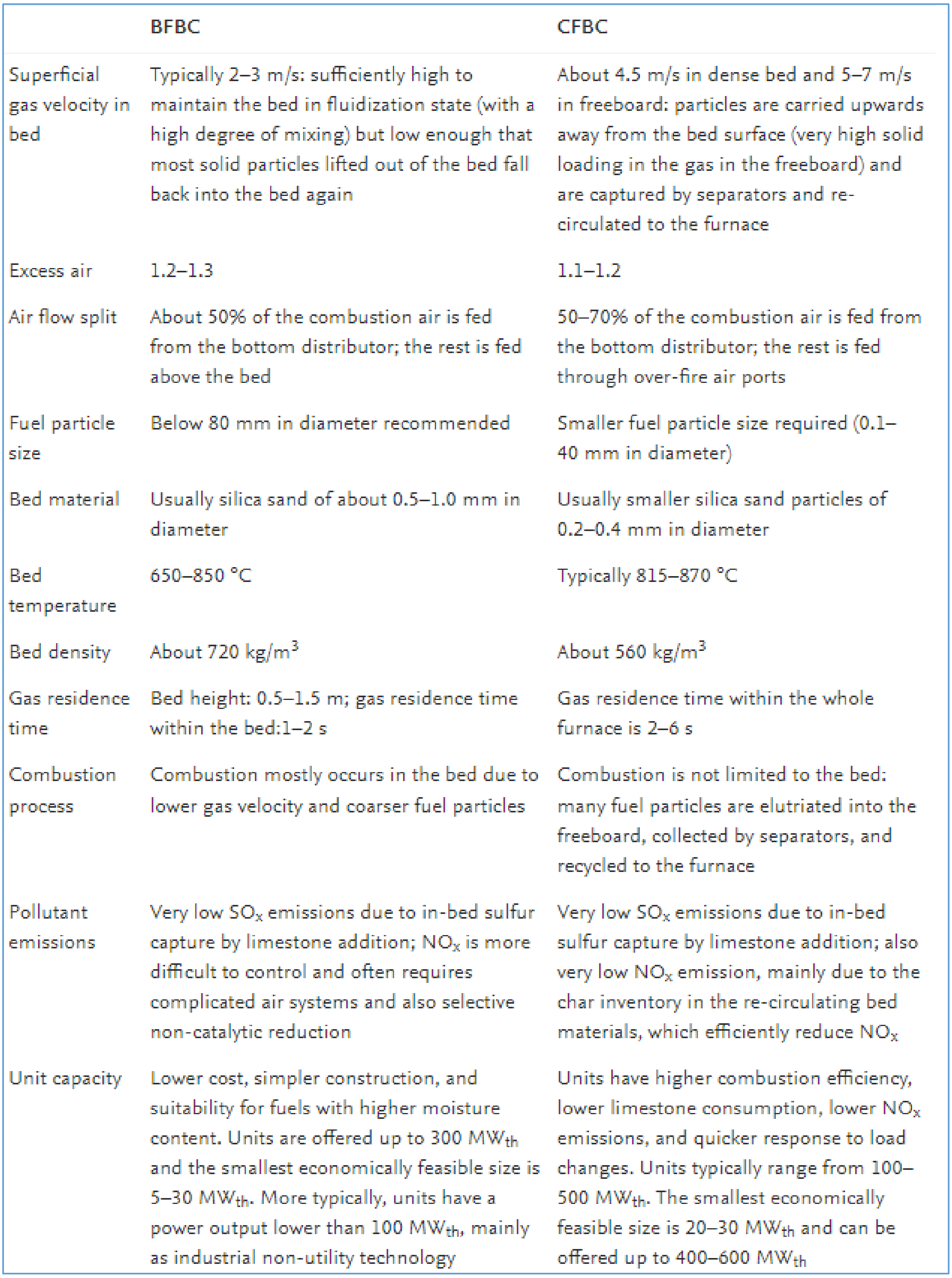
range of power: 1–3.5 MW

Figure 5. Under-feeding system for high-performance furnace with a steam boiler [4].

In large-scale combustion systems, the combustion chamber is usually a fluidized bed reactor using high air velocities to fluidise solid fuels. Combustion occurs in the bed with a very intense mixing of gases and solids. Thus high heat transfer rate and uniform temperature can be achieved [5].

A fluidized bed system can be charged with a wide range of particle sizes for the solid fuel, and the carbon burning efficiency in such a system is high. Another advantage is that the fluidized bed system can reduce NOx formation due to its uniform combustion temperature [6]. However, the disadvantage is the requirement of a high-speed fan system to support the fluidization. Usually, the bubbling fluidized bed and the circulating fluidized bed are the two main types of systems used in the combustion area. The bubbling bed system requires less capital cost than the circulating bed system when the system capacity is lower than 20 MW. In contrast, the circulating bed system has better carbon burnout efficiency, and the SO_2 formation can be minimized by applying limestone [6]. Yin et al. made a detailed comparison of the two types of fluidized bed systems, as shown in Table 1 [5].

Table 1. Comparison of bubbling fluidized-bed combustion and circulating fluidized-bed combustion cited from Yin et al. [5].



	BFBC	CFBC
Superficial gas velocity in bed	Typically 2–3 m/s: sufficiently high to maintain the bed in fluidization state (with a high degree of mixing) but low enough that most solid particles lifted out of the bed fall back into the bed again	About 4.5 m/s in dense bed and 5–7 m/s in freeboard: particles are carried upwards away from the bed surface (very high solid loading in the gas in the freeboard) and are captured by separators and re-circulated to the furnace
Excess air	1.2–1.3	1.1–1.2
Air flow split	About 50% of the combustion air is fed from the bottom distributor; the rest is fed above the bed	50–70% of the combustion air is fed from the bottom distributor; the rest is fed through over-fire air ports
Fuel particle size	Below 80 mm in diameter recommended	Smaller fuel particle size required (0.1–40 mm in diameter)
Bed material	Usually silica sand of about 0.5–1.0 mm in diameter	Usually smaller silica sand particles of 0.2–0.4 mm in diameter
Bed temperature	650–850 °C	Typically 815–870 °C
Bed density	About 720 kg/m^3	About 560 kg/m^3
Gas residence time	Bed height: 0.5–1.5 m; gas residence time within the bed:1–2 s	Gas residence time within the whole furnace is 2–6 s
Combustion process	Combustion mostly occurs in the bed due to lower gas velocity and coarser fuel particles	Combustion is not limited to the bed: many fuel particles are elutriated into the freeboard, collected by separators, and recycled to the furnace
Pollutant emissions	Very low SO_x emissions due to in-bed sulfur capture by limestone addition; NO_x is more difficult to control and often requires complicated air systems and also selective non-catalytic reduction	Very low SO_x emissions due to in-bed sulfur capture by limestone addition; also very low NO_x emission, mainly due to the char inventory in the re-circulating bed materials, which efficiently reduce NO_x
Unit capacity	Lower cost, simpler construction, and suitability for fuels with higher moisture content. Units are offered up to 300 MW_{th} and the smallest economically feasible size is 5–30 MW_{th}. More typically, units have a power output lower than 100 MW_{th}, mainly as industrial non-utility technology	Units have higher combustion efficiency, lower limestone consumption, lower NO_x emissions, and quicker response to load changes. Units typically range from 100–500 MW_{th}. The smallest economically feasible size is 20–30 MW_{th} and can be offered up to 400–600 MW_{th}

Advantages of biomass combustion:

- It is a simple and mature technology.
- Proven knowledge and experience are available for design, construction, and operation.
- Heat supply application is economical.

Disadvantages and challenges of biomass combustion:

- It generates high levels of emissions in comparison with other alternative technologies, as discussed in Sections 2.3 – 2.5.
- Overall efficiency is low due to the heat loss from flue gas.
- Heat and power systems are expensive for small to medium systems. Large-scale systems require large quantities of wood supply, which may not be viable.

2.2 **Heat and power systems**

Combined heat and power (CHP) can be generated simultaneously from two processes. One is from a boiler using high-temperature steam through a steam turbine, and the heat is from post-turbine steam condensation. The other heat and power generation process is to use combustible gas from biomass gasification through a gas turbine or internal combustion engine. The heat provided in this system is the heat recovered from the post-turbine or post-engine flue gas. Recently, a new system termed an integrated combined cycle (ICC), or heat recovery steam generator (HRSG) has been developed in which the heat in high-temperature flue gas from a gas turbine is recovered in a steam boiler, and the steam is further used in steam turbine for generation of the second stream of power. As these systems are relatively independent, these are described here in a separate section.

The gas turbine is widely used in the power generation plant to extract energy from combustible gas with various gaseous fuel choices [7]. An extensive review has reported that gas turbines are most suitable for the combined heat and power generation at a large scale since the high-pressure steam can be regenerated from the high-temperature exhaust gas and is able for second stream power generation through steam turbine [8].

For the gas turbine itself, the number of shafts can be used to configure the gas turbine as a single, dual or triple shaft turbine. Forsthoffer studied these three types of gas turbines and stated that most modern gas turbines are triple shaft turbines due to their high efficiency [9]. The advantages and disadvantages of different gas turbines are shown in Figure 6 [9].

A single shaft turbine has a gas generator and a power turbine on one shaft, while a dual shaft turbine has them on an individual shaft. A single shaft turbine has a low starting load which makes the single shaft turbine only suitable for generator driving applications, while a dual shaft turbine suits for mechanical driving, pump and compressor [9]. The configuration of a triple shaft turbine is studied by Ying, as shown in Figure 7 [10]. The three shaft turbine contains one low-pressure compressor (LPC), one high-pressure compressor (HPC), one combustion chamber (B), one high-pressure turbine (HPT), and one low-pressure turbine (LPT), and one power turbine (PT). The LPC uses the power output from the LPT to condense the inlet air, while the power output from the HPT is consumed by the HPC to condense the air from the LPC further. The shaft connecting the LPC and the LPT is called the low-pressure shaft, while the shaft between the HPC and HPT is called the high-pressure shaft. Then the high-pressure air is sent to the B with fuel supply, and the combustion product is used in the HPT, the LPT and the PT sequentially. The turbines are pushed to produce power. Eventually, the power output of the PT drives the generator to produce electricity.

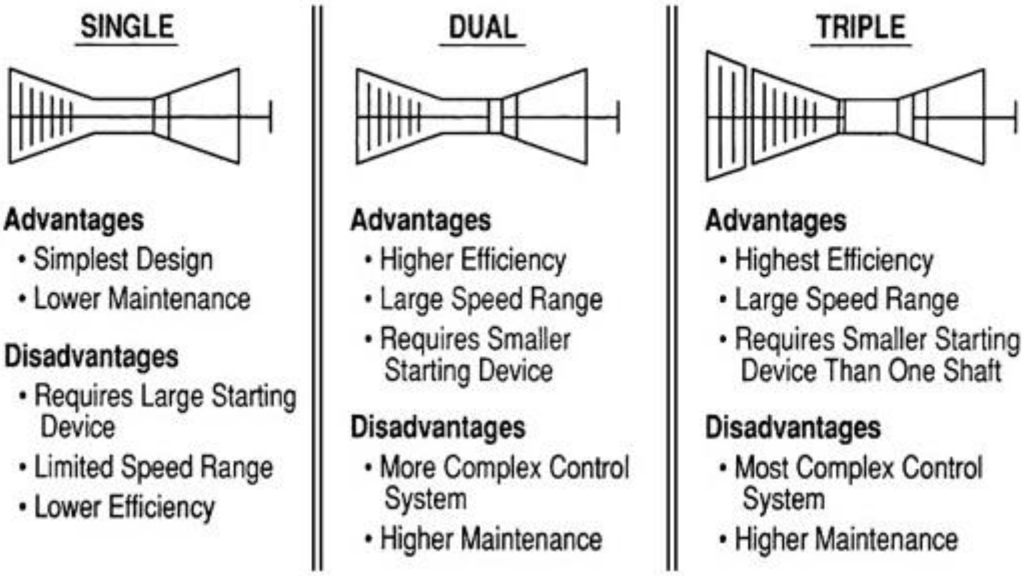


Figure 6. Advantages and disadvantages of different types of gas turbines.

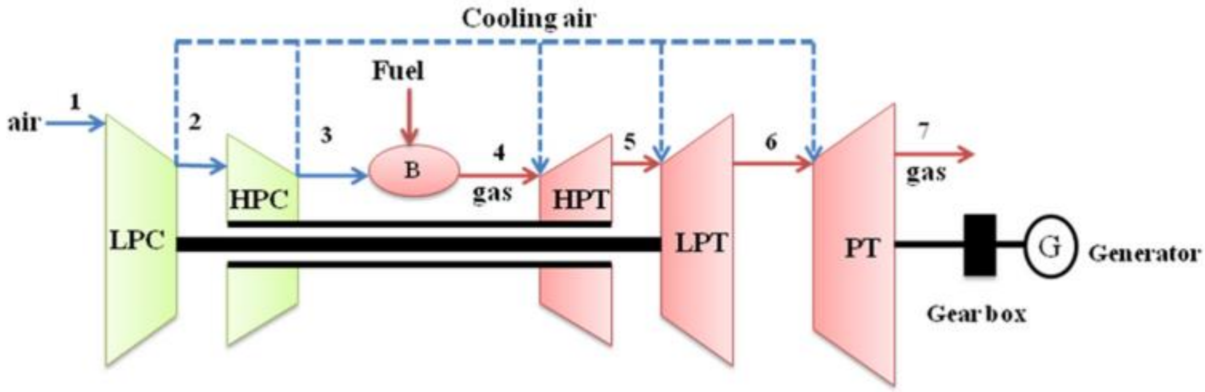


Figure 7. Configuration of triple shaft gas turbine [10].

The heat recovery steam generator (HRSG) can generate a second stream of power, thus increasing the power efficiency. However, this will need additional costs, which are only feasible for large-scale plants. There are four zones or four components in the HRSG system [11]. The first component is the economizer, which captures the heat from the exhaust gas close to the exit and heats the water returning from the steam turbine. The second component is the evaporator which further heats the hot water from the economizer to the boiling point under pressure. The third component is the steam drum working as a steam separator from water, and the water is recycled back to the evaporator. Finally, the fourth component is the superheater which dries the steam and increases the steam temperature.

There are multiple variants of HRSG systems with different arrangements of tubes (vertical tubes vs. horizontal exhaust gas path) and circulating regimes (forced circulation vs. natural circulation). Usually, the system becomes more complicated to increase the overall efficiency [12] further. Figure 8 shows the heat exchanger tubes in the vertical arrangement of the HRSG system, which is popular considering the low footprint [12].

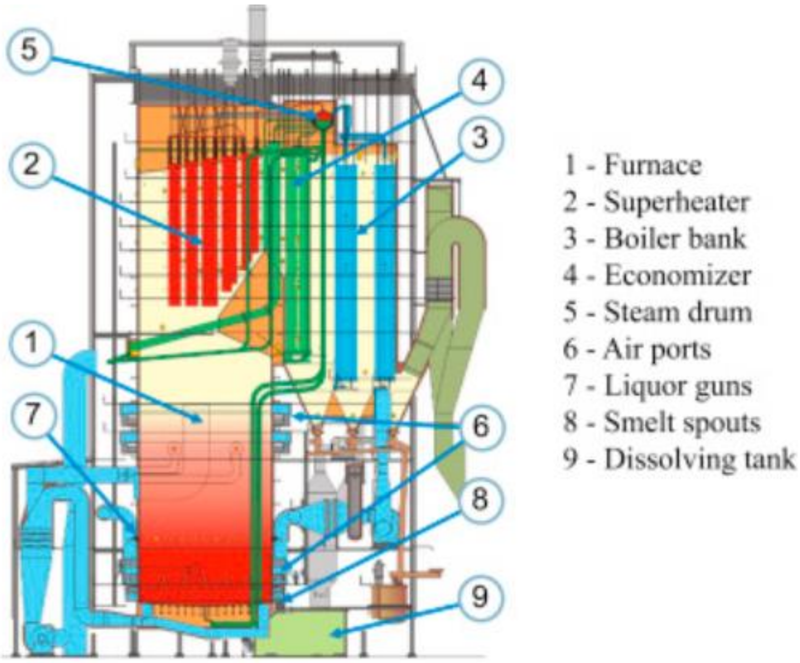


Figure 8. A boiler with a vertical HRSG design [12].

Comments:

- The power generation integration with biomass combustion or gasification is economically feasible only for large-scale plants, namely, 50 -100 MWth. This is equivalent to 80,000 to 160,000 tonnes per year of dry biomass.

2.3 Biomass gasification

Gasification is a partial oxidization process that converts biomass into a gaseous mixture known as producer gas or product gas. The gasification process can be divided into four stages within the gasifier [13]:

(1) Vaporisation of moisture in the wood (drying) occurs at temperatures below 150°C.

(2) Devolatilisation of the dried biomass in which the wood decomposes into volatiles, tar (heavy organic compounds) and char.

(3) Oxidation reactions among volatiles and fed gasification agent (oxygen, air, or steam), and these reactions are called homogeneous reactions.

(4) Reactions between gases and char.

For commercial biomass gasification operation, the required moisture content for the biomass is in the range of 15 to 25% (dry-based), considering the gasification performance and energy consumption in drying. The particle size may vary with the type of gasifier selected, although in most cases, the size of pulp chips usually has a dimension of 15 to 40 mm [14].

The producer gas from the biomass gasification consists of H_2, CO, CO_4 and CH_4, which can be used for heating purposes through combustion or used as the feedstock for further synthesis of gaseous and liquid fuels. When air is used as the gasification agent, nitrogen in the air is carried into the gasifier and then remains in the producer gas [14].

One of the technical challenges in biomass gasification is gas cleaning. There are tar species in the producer gas with a concentration of 2-10 g/Nm^3, which are groups of heavy hydrocarbons with a molecular weight greater than benzene. Most tar species have boiling points lower than 250°C; thus, when the gas is cooled down, these tar species condense to viscous liquid and cause blockage in the pipe lines and machine parts. In addition, gaseous contaminants in the producer gas include NH_3 (500-1000 ppmv) and H_2S (50-150 ppmv). The N and S in these gaseous species are originated from the feeding biomass. Thus, their concentrations vary with the biomass type. For example, Radiata pine wood has low contents of N and S ;therefore, these gaseous contaminants in the producer gas from gasification of radiata pine are not prominent.

Effect of gasification agents:

Gasification agents are used in biomass gasification as reactants to enhance producer gas generation. The gasification agents can be air, oxygen and steam or a mixture of two. Air is a common gasification agent due to its low cost and easy accessibility. However, the N_2 in the air stream will dilute the producer gas and reduce the heating value of the product [15]. The oxygen and steam can produce the producer gas without the presence of the N_2, leading to a higher heating value. The heating value of the producer gas using air as the gasification agent usually is 4-7 MJ/Nm^3, and that using oxygen or steam as the gasification agent is 10–18 MJ/Nm^3 [16].

Although using oxygen as the gasification agent can produce the producer gas with a higher heating value, oxygen production is expensive and highly energy intensive, which makes the process not economically viable [17]. On the other hand, steam offers a higher yield of hydrogen and avoids the requirement of oxygen separation [18]. However, the overall gasification reactions with steam as the gasification are endothermic; thus external heat supply is needed to maintain the operation at the required temperature. The other benefits of using steam for gasification are high hydrogen content and internal steam generation from heat recovery, the steam biomass gasification has attracted significant interest in the past 20 years, and some demonstration scale plants have been built in European countries.

The gasifier type also affects the producer gas composition and gasification efficiency, including fixed bed gasifiers, fluidised bed gasifiers, and entrained flow gasifiers. The following part will provide more technical information on the gasifiers.

Gasifiers

The fixed bed gasifier is the oldest type of gasifier in which there is a stationary grate in the reactor. Solid biomass is fed from the gasifier top. It moves down slowly under the gravity in the bed above the grate where biomass contacts with the gasification agent and is gasified [19]. There are four zones in a fixed bed gasifier: drying, devolatilisation (also called pyrolysis), oxidation and reduction zones from the top to the bottom of the bed. The producer gas may flow out of the gasifier from the bottom (below the grate) or the upper section of the gasifier (above the biomass bed). The former is termed downdraft gasifier, and the latter is called updraft gasifier, as shown in Figure 9 [20].

The fixed bed gasifiers are usually applied for small-scale operations where biomass is gasified by the downdraft or the updraft gasification using air as the gasification agent [21]. This type of gasifier has low oxygen consumption, but the tar content in the producer is high, especially for the updraft fixed bed gasifier [22]. The non-uniform temperature distribution inside the gasifier bed is a common technical issue affecting the performance and producer gas quality. In addition, the fixed bed gasifier is not suitable for fine particles of the biomass due to the entrainment of fine particles in the producer gas [23].

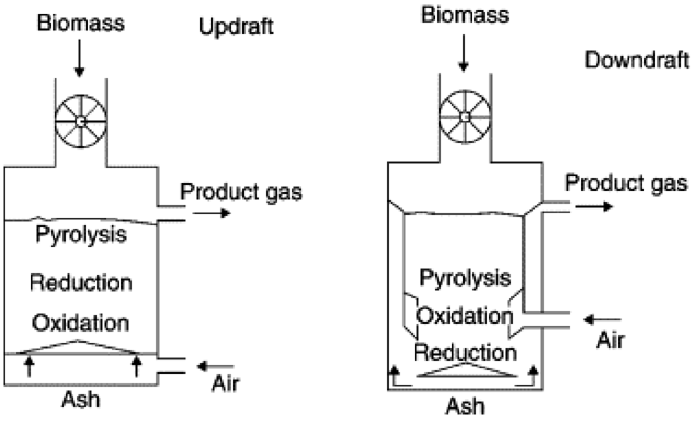


Figure 9. Sketches of updraft and downdraft fixed bed gasifier [20].

For medium to large-scale plants, fluidized bed gasifiers are commonly used in which the biomass fuel is fluidised by an upward flow of gasification agent or carrier gas [22]. The fluidized bed reactor consists of a vessel containing a bed of particles such as sand, as shown in Figure 10. The bed is supported by a distributor where the gasification agent passes through to achieve the required fluidization. The fluidization occurs when the gas velocity is faster than the minimum fluidization velocity. If the gas velocity is controlled in a specific range of values, the gas flows as bubbles, and the solid bed is suspended [24]. This regime is called bubbling fluidised bed gasification (Figure 10 left). However, if the gas velocity is further increased to above the terminal velocity, the solid particles in the bed are carried up and then out of the gasifier. To maintain stable operation, the bed material (sand) is returned back to the gasifier. This regime operation is called circulating fluidised bed gasification (Figure 10 right).

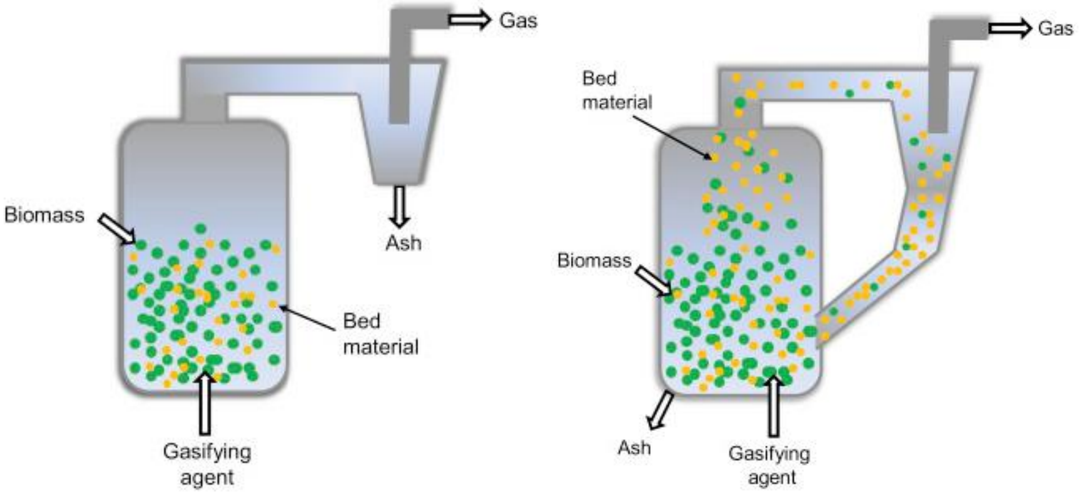


Figure 10. Sketches of a bubbling fluidized bed gasifier (left) and a circulating fluidized bed gasifier (right).

The fluidized bed gasifiers have advantages, including enhanced hat and mass transfer between gas and solid and uniform temperature profile in the bed [25]. Therefore the biomass conversion is fast and the processing capacity is high [26]. Consequently, the fluidised bed gasifiers have high carbon conversion, high efficiency and low tar formation compared to the fixed bed gasifiers [27].

The bubbling fluidization regime produces gases with medium tar content, while the circulating fluidization regime allows a much higher processing capacity at the same reactor size. However, the power consumption for gas flow in the latter is higher than in the former [28]. Therefore, the bubbling fluidised bed gasifiers are suitable for medium-scale plants (30-50

MWth or 50,000 to 80,000 tonnes per year biomass), and the circulating fluidised bed gasifiers are ideal for large-scale plants (50 – 100 MWth or 80,000 to 160,000 tonnes per year biomass).

Entrained flow gasifier has the feedstock and gasification agent flowing in a co-current arrangement and the residence time in an entrained flow gasifier is very short (a few seconds) [19]. This type of gasifier requires a high-temperature environment and rich oxygen supply, leading to high capital cost of operation and down steam units [29]. An entrained flow gasifier usually operates at 1400 °C and 20 to 70 bar pressure and powered fuel is charged [30]. To ensure efficient mixing and high carbon conversion, sold feedstock must be finely pulverized into powders [31]. Therefore, the entrained flow gasification is mainly used for coal and petroleum-based feedstock [21].

Advantages of biomass gasification:

- It is an efficient process to convert biomass to a gaseous fuel.
- There are flexibilities for gas use: direct combustion for heat and power or feedstock for further synthesis.
- The system can potentially heat self-sufficient with a dual fluidised bed system.
- Various technologies are available.

Disadvantages and challenges:

- Gasifiers for large-scale plants (fluidised bed reactors) are complicated.
- Gas cleaning technologies are available, and the current R&D is still seeking effective, low-cost solutions.
- Capital cost is relatively high.

2.4 Biomass pyrolysis

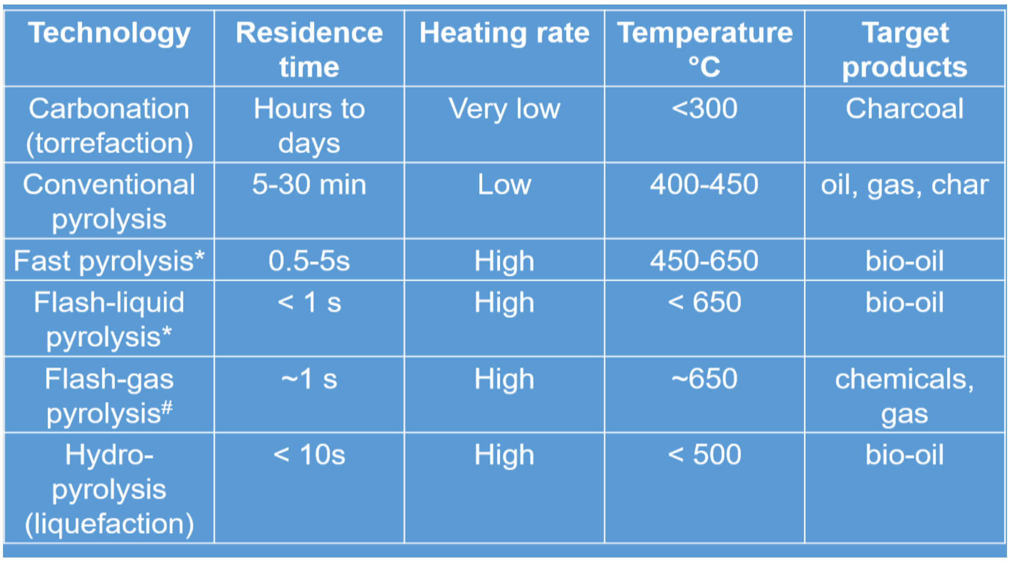
Pyrolysis process

Pyrolysis is another thermochemical process of biomass in the absence of oxygen or limited oxygen [32]. Products from the pyrolysis include a gaseous mixture (non-condensable gas), a liquid mixture (bio-oil) and a solid product (solid char or bio-char). The distribution of yields of the products and the chemical compositions of gas and liquid is affected by the composition of the feedstock, the type of pyrolysis reactor system and operation conditions (temperature, residence time and heating rate) [33]. In general, a higher liquid product yield is achieved at high pyrolysis temperature, short resident time and fast heating rate) while a higher gaseous product yield is achieved at high pyrolysis temperature and long residence time [34].

The pyrolysis process has three modes of operation based on the operation conditions (temperature, residence time and heating rate): slow pyrolysis, fast pyrolysis and flash pyrolysis. A summary of the operation modes and target product distribution is given in Table 2 below.

The flow pyrolysis is usually operated at low temperatures and a slow heating rate to produce solid bio-char [35]. Fast pyrolysis is to produce liquid product (bio-oil), while flash pyrolysis produces both bio-oil and non-condensable gas [32].

Table 2. Operation conditions and target products for biomass pyrolysis



Technology	**Residence time**	**Heating rate**	**Temperature °C**	**Target products**
Carbonation (torrefaction)	Hours to days	Very low	<300	Charcoal
Conventional pyrolysis	5-30 min	Low	400-450	oil, gas, char
Fast pyrolysis*	0.5-5s	High	450-650	bio-oil
Flash-liquid pyrolysis*	< 1 s	High	< 650	bio-oil
Flash-gas pyrolysis#	~1 s	High	~650	chemicals, gas
Hydro-pyrolysis (liquefaction)	< 10s	High	< 500	bio-oil

*. With rapid cooling of pyrolysis vapours, more bio-oil is formed.

#. More gas is formed with slow cooling of pyrolysis vapours or applying catalysts.

The bio-char can be used as solid fuel, a sorbent for water cleaning and contaminant removal from the environment, or soil nutrient retaining [36]. The bio-oil can be used as boiler fuel. However, it requires chemical upgrading if the bio-oil is used as a liquid fuel for transportation. The bio-oil derived directly from the biomass pyrolysis contains 20-30% water, has a high viscosity and is unstable, with its chemical and physical properties varying with time (Table 3). The Lower heating value of the bio-oil is around 20 MJ/kg, which is less than half of the crude-oil-derived petrol or diesel. The upgrading process is complicated and costly as it operates at high pressures (100 – 200 bars) and high temperatures (200 – 300°C). The non-condensable gas from biomass gasification can be used as a gaseous fuel for combustion. However, the quantity of the gas production is limited as, in most cases, solid bio-char or bio-oil is the target product. Nevertheless, the gas can be used internally for heat supply throughout the process.

Table 3. Characteristics of pyrolysis liquid compared with conventional liquid fuels.

		Pyrolysis liquid	Diesel	Heavy fuel oil
Density	kg/m^3 at 15°C	1220	854	963
Typical composition	%C	48.5	86.3	86.1
	%H	6.4	12.8	11.8
	%O	42.5	–	–
	%S	–	0.9	2.1
Viscosity	cSt at 50°C	13	2.5	351
Flash point	°C	66	70	100
Pour point	°C	−27	−20	21
Ash	%wt	0.13	<0.01	0.03
Sulphur	%wt	0	0.15	2.5
Water	%wt	20.5	0.1	0.1
LHV	MJ/kg	17.5	42.9	40.7
Acidity	pH	3	–	–

The pyrolysis technology has also been used for the conversion of biomass and solid wastes. However, contaminations in the pyrolysis products need to be addressed [37]. Therefore, the utilization of products from pyrolysis may not be suitable due to the high-level content of contaminants, and advanced pollution control devices are required, which will increase the investment. The homogenous waste with a small particle size and low moisture content is desirable for pyrolysis. However, this will further add costs to the pyrolysis operation [38].

Pyrolysis systems

The pyrolysis reactors can be classified based on the operation conditions: slow pyrolysis reactors, fast pyrolysis reactors and flash pyrolysis reactors [39]. The flash and the fast pyrolysis reactors are used to maximize the bio-oil yield and require small particle sizes for the feedstock (1-3 mm). On the other hand, the slow pyrolysis reactors are used for the carbonization process, which is to produce chars.

The pyrolysis reactors can also be classified as single-stage reactors and multi-stage reactors [40]. The single-stage reactors have their products being further treated downstream of the reactors, while the multi-stage reactors include the post-treatment of the pyrolysis products within the pyrolysis system.

In the following paragraphs, different configurations of the single-stage reactors are described, which have been applied in industry-scale plants [40].

A **fixed bed pyrolysis reactor** has a similar configuration as the fixed bed gasifiers, but no reactant gas agent is injected into the pyrolysis reactors. This type of reactor has a low heat transfer rate, and non-uniform temperature profile and thus has been used for carbonisation for bio-char production at a small scale.

Rotary kiln pyrolysis reactor is shown in Figure 11 and is widely used for slow pyrolysis. The slow rotation of the inclined kiln promotes the mixing of the feedstock and makes the flexible adjustments of the residence time possible. It is easy to set up and operate at low costs. The kiln structure provides sufficient space and the inclination angle can be adjusted for the feedstock to move from one end and the other end smoothly, thus making it possible to process heterogeneous materials. Therefore, the feedstock without extensive pre-treatment, such as drying, can be processed using the rotary kiln. However, the heating rate of a rotary kiln is slow due to the low contact areas among the biomass particles and between the biomass particles and the kiln cylinder's inner wall. Therefore, the residence time is high, and the productivity is low.

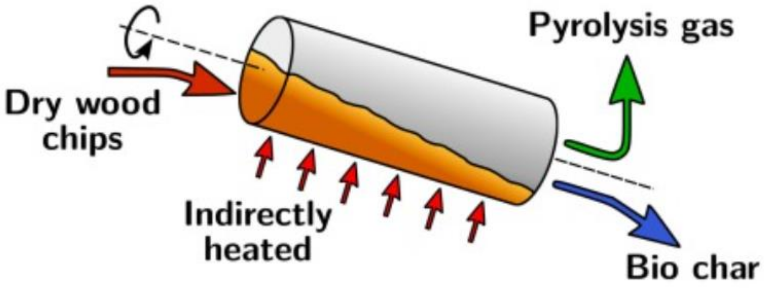
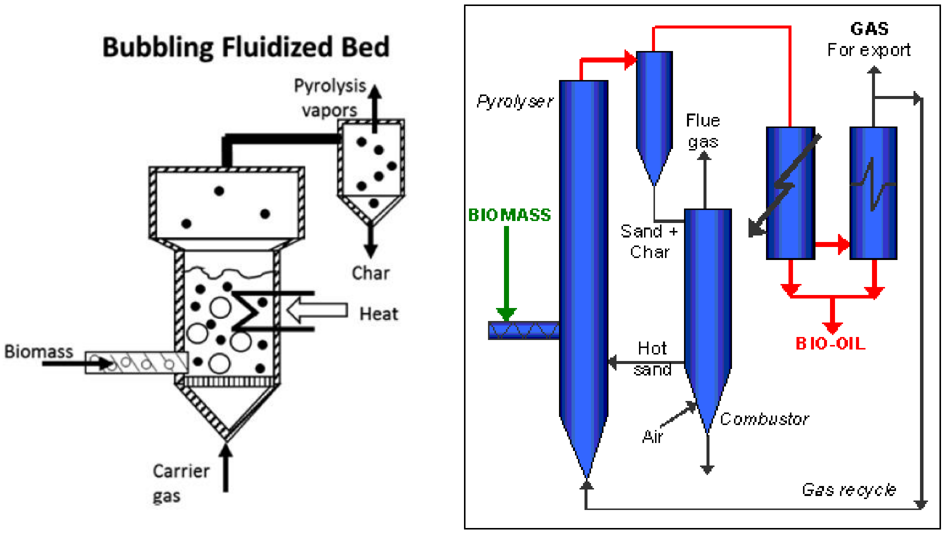


Figure 11. The schematic diagram of a rotary kiln reactor for pyrolysis.

Fluidised bed pyrolysis reactors, shown in Figure 12, work in similar principles as the fluidised bed gasifiers and are commonly used at lab scale and demonstration scales for R&D studies in fast and flash pyrolysis processes. As discussed in the gasification reactors section, the mechanism of a fluidised bed reactor can provide uniform temperature distribution inside the reactor. The fluidised bed reactor has high heat transfer rates and fast reactions, therefore, it is suitable for applications at large-scale plants for bio-oil production. However, only limited industrial applications have been reported for the fluidised bed reactors (https://www.btg-bioliquids.com/plant/empyro-hengelo/ and https://www.ensyn.com/) due to the complexity of the system and high costs.



(a) (b)

Figure 12. The schematic diagram of (a) a bubbling fluidized bed pyrolysis reactor and (b) a circulating fluidized bed reactor.

Advantages of biomass pyrolysis

- The reactors and operation are relatively simple.
- The bio-char product from the pyrolysis can potentially be used as an adsorbent for water and gas cleaning.
- The bio-oil product has potential as boiler fuel.

Disadvantages and issues

- The chemical and physical properties of the bio-oil product are complex. However, the upgrading process is complicated and costly if the bio-oil is upgraded to the transport liquid fuel grade.
- The bio-char yield is lower than that from torrefaction if the bio-char is used as a coal substitute.

2.5 Biomass torrefaction

Biomass torrefaction process

Torrefaction is another thermochemical conversion process to produce charcoal from biomass. Compared with pyrolysis, torrefaction operates at lower temperatures and slow heating rates, thus producing a higher yield of solid products. Therefore, this technology is suitable for obtaining high-quality solid fuel since torrefaction has lower heat requirements [41] [42]. The

temperature for the biomass torrefaction is 300 °C or lower, leading to more than 80% solid yield, which is much higher than solid yield in slow pyrolysis [35].
The torrefaction maims to release volatile biomass components and thus produce a more hydrophobic, homogeneous, and energy-dense solid fuel source [42]. Torrefaction shares similar operating conditions with slow pyrolysis. However, the difference is to control the operating conditions for the different target products. Torrefaction focuses on maximizing the solid product yield and energy content in the solid product by minimizing oxygen to carbon and hydrogen to carbon ratio. However, a solid product from pyrolysis contains over 90% of solid carbon with very low contents of hydrogen and oxygen; thus, the solid yield is much lower.

Torrefaction can be operated for either dry or wet biomass [41]. Dry biomass torrefaction works under atmosphere pressure at an oxygen absence environment and the operational temperature range is from 200 °C to 300°C. Nitrogen gas or CO_2 is usually used during the torrefaction process to prevent the char oxidation that has already been commercialized [42]. The biomass feedstock is required to undergo a pre-drying process which reduces the moisture content in the biomass feedstock to about 10%. The pre-drying process is highly energy intensive and thus increasing the operation cost.

Wet torrefaction has also been reported, which operates at lower temperatures between 180 to 260°C but under high pressure. The advantage of wet torrefaction is that it avoids the energy-intensive process of drying biomass and has a higher solid yield; however, the process is much more complicated and thus is not economically feasible [43].

Torrefaction reactors

Most torrefaction reactors are designed based on existing reactors for biomass pyrolysis and can be divided into two groups: direct heating and indirect heating. Typical indirect heating reactors are rotary drums and screw reactors. The direct heating reactors use an inert gas as the heating medium where biomass is directly heated up [44]. The two common direct heating reactors are the fluidized bed and multiple hearth furnaces.

The **rotary drum reactor** is shown in Figure 12, in which heat is transferred from the drum wall to the biomass inside the drum. During the operation, the torrefaction temperature, the rotational speed, and the length and angle of the drum are controlled to optimize solid production. As the drum rotates, the biomass is mixed homogeneously. Heat is first transferred from the inner wall surface to the contacting biomass particles and then transferred between the biomass particles.

In the rotary drum reactor, uniform heat transfer can be achieved from the wall, and the technology is mature. However, the heat transfer rate is low, resulting in a large heat transfer area requirement and limiting the production capability [44].

Figure 12. A commercial scale rotary drum reactor for biomass torrefaction [44].

The **screw torrefaction reactor** is also an indirect heating reactor, as shown in Figure 13. The biomass is churned and moved through the reactor by a rotating screw, improving the heat transfer between the wall and the biomass. The reactor is heated by the heating medium inside the hollow wall or by the screw. For the screw reactor, the biomass feedstock must have low moisture content, and high bulk density, meaning biomass pretreatment is necessary. A screw reactor can be vertical, horizontal, or inclined with a circular or rectangular cross-section area.

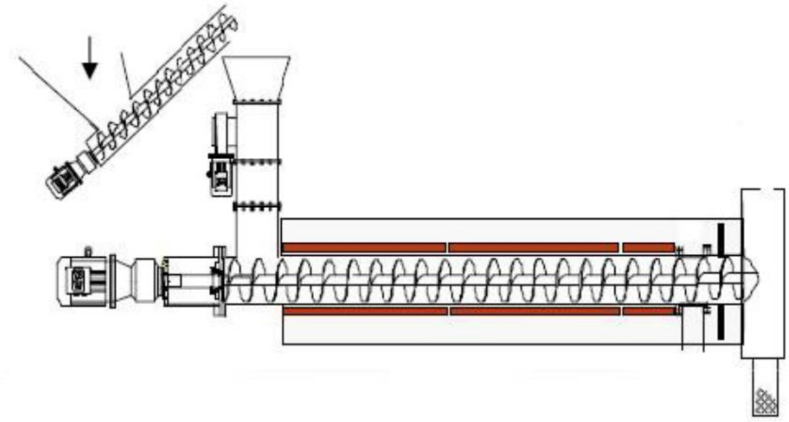


Figure 13. A schematic of a screw reactor [44].

The **fluidized bed reactor** has been introduced in the gasification and pyrolysis sections. The fluidized bed reactor for torrefaction follows the same principle. There is a special type of fluidized bed reactor in torrefaction called the rotating fluidized bed reactor. As shown in Figure 14, the biomass particles are fed from the top and then distributed along the cone surface towards the reactor wall, leading to toroidal swirls. The toroidal swirls can improve the heat and mass transfer among solids and gases, leading to lower retention time and more homogeneous products. The intense heat transfer makes the torrefaction occur within a short residence time with a high loss rate of volatiles from biomass during the torrefaction process.

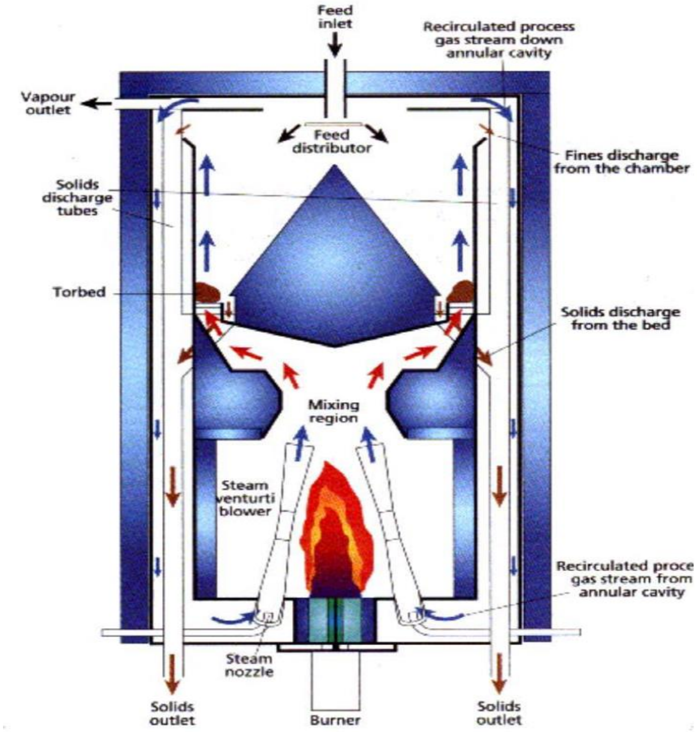


Figure 14. A rotating fluidized bed reactor [44].

The **multiple hearth furnace** has been reported in the literature, with its configuration being shown in Figure 15, in which a series of circular hearths are placed one above another, and a refractory-line steel shell covers all the hearths. Hot gas is injected through the hearth to heat the biomass on it. Biomass is fed to the top of the hearth and passed through drop holes, allowing the biomass to reach the hearth below. The vertical rotating shift with rabble blades at the centre stirs and moves the biomass in a spiral path through each hearth. The multiple hearth reactor can achieve a uniform temperature profile and fast reactions. The biomass particle size can vary in a relatively wide range, and the moisture content of the biomass is also fairly flexible.

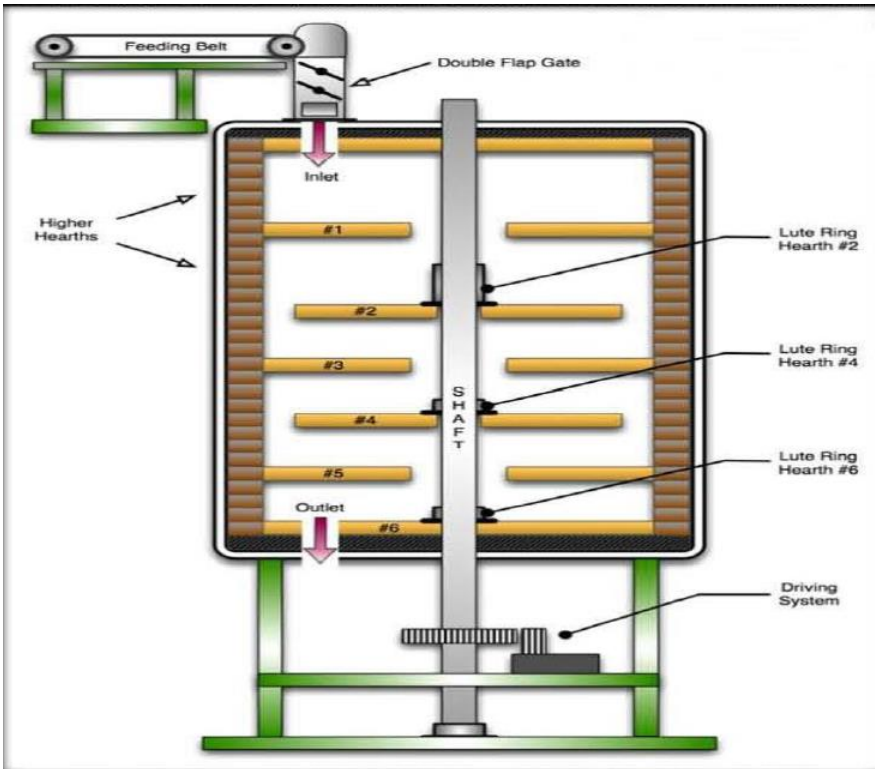


Figure 15. Sketch of a multiple hearth furnace [44].

3. Review of Technology Applications

3.1 Biomass combustion applications

Reported systems

In biomass combustion, the flame and the flue gas provide heat directly to the heating medium (hot water, steam or hot oil). The heating medium can provide heat in target applications such as industry heat or district heating. However, it is worth noting that the heat used in this way does not realise the potential for better quality energy application even if the energy efficiency is high. Using steam for power generation through a steam turbine can improve the quality use of energy with an output of combined heat and power (CHP).

A simulation of a wood-fired power plant to study the feasibility of the CHP route in England [45] in which a circulating fluidized bed combustion system (CFBC) is applied, considering that the CFBC system has the advantage of less NO_x emission [46]. The results indicate that wood combustion-based CHP plant has a low capital cost but low efficiency [45]. When the plant can process more than 500 dry tonne equivalent (DTE)/day of wood, the break-even selling prices (COES) are low enough for commercial interest [45]. It was also mentioned that the wood combustion CHP plant could be commercially competitive at a large scale even compared with fossil fuel power plants. If the CHP plant has coppiced wood at more than 1000 DTE/day, the plant is profitable in England and Wales [45].

Based on energetic and economic performance analyses of biomass combustion and gasification-based CHP plants in the Netherlands [47], it is found that the system of the gasification CHP plant is more favourable in both economic and energy aspects than the wood-fired CHP plant, and the wood-fired system is not always profitable at Dutch conditions.

In a case study of a white wood pellet combustion power plant and a coal-fired power plant in the UK [48], it is found that the wood pellet (WWP) combustion CHP plant can reduce CO_2 emissions by 3 million tonnes a year from the 650MW plant. Negative CO_2 emission can be achieved with the application of additional carbon capture and storage technologies.

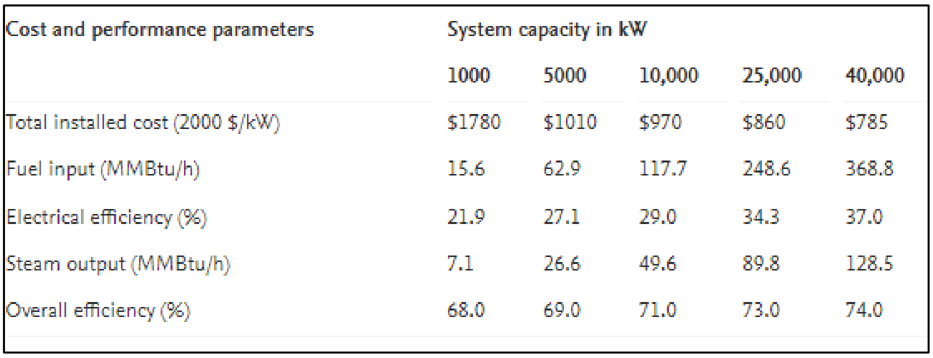
A district heating system (DHS) is a simple way to utilize heat from biomass combustion. Large scale DHSs have been built in the cities of Helsinki, Stockholm, Copenhagen, Berlin, Munich, Hamburg, Paris, Prague, Moscow, Kiev, Warsaw, and the total annual heat turnover is approximately 11 EJ in several thousand district heating systems operating throughout the world [49]. Biomass combustion can be integrated into the DHS system which the heating medium is pumped through a network of pipe lines for the heating purpose [50]. It is reported that the large-scale biomass combustion facility contributes around 50% of the heating service in Denmark and Finland, and heat generation from biomass is cost-competitive with that from fossil fuels. However, DHS requires massive infrastructure as backup, and operations are restricted to the cooler month [51]. The considerable infrastructure requirement makes this application not economically suitable in New Zealand, and the time to complete this project is long due to this infrastructure requirement. Analysis of the DHS in Denmark has found that the optimum forward temperature is around 75°C and the return temperature is around 35-40 °C [52]. The efficiency of DHS was increased by developing good insulation material pipes and twin pipes.

As mentioned before, the DHS operation is restricted to cooler months. However, seasonal heat storage is a potential solution to expand the operation period of DHS. Therefore it is suggested that DHS utilize the waste heat from electricity generation units, and in this way, its overall efficiency is increased [53].

Cost analysis

The performance and cost of various CHP plant scales have been reported; a summary is given in Table 5 below. However, it is aware that the cost may be difficult to accurately estimate due to factors including: currency exchange and inflation rates, local salaries, and the technological development stage [6].

Table 5. The performance and cost of a CHP system at different system capacities are based on the Energy Nexus Group report in 2002 [8].

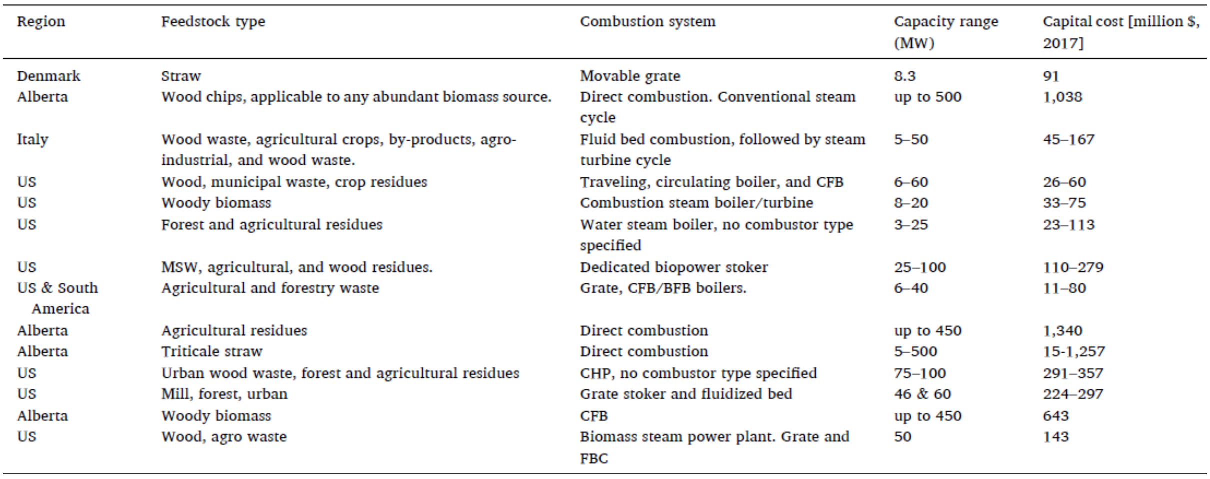


Cost and performance parameters	System capacity in kW				
	1000	5000	10,000	25,000	40,000
Total installed cost (2000 $/kW)	$1780	$1010	$970	$860	$785
Fuel input (MMBtu/h)	15.6	62.9	117.7	248.6	368.8
Electrical efficiency (%)	21.9	27.1	29.0	34.3	37.0
Steam output (MMBtu/h)	7.1	26.6	49.6	89.8	128.5
Overall efficiency (%)	68.0	69.0	71.0	73.0	74.0

In a separate study, Broek at al. summarized several investment costs of commercial biomass combustion plants back in 1992 [6]. The moving grate furnace-based CHP plant at a scale of 25 MW and electrical efficiency of 24% required capital investment between 1710 and 2140 US$/kW. When circulating fluidized bed furnace technology is used, the CHP plant at the same scale (25 MW) and electrical efficiency (24%) requires capital investment between 1820 and 2270 US$/kW. However, the stoker-fired combustion-based CHP plant at a scale of 50 MW and electrical efficiency of 29% requires a capital investment of around 1780 US$/kW.

Morató et al. conducted a study of the cost analysis of different biomass combustion systems, and the results are summarised in Table 6.

Table 6. Summary of capital costs for biomass combustion-based plants using various technologies [54].



Region	Feedstock type	Combustion system	Capacity range (MW)	Capital cost [million $, 2017]
Denmark	Straw	Movable grate	8.3	91
Alberta	Wood chips, applicable to any abundant biomass source.	Direct combustion. Conventional steam cycle	up to 500	1,038
Italy	Wood waste, agricultural crops, by-products, agro-industrial, and wood waste.	Fluid bed combustion, followed by steam turbine cycle	5–50	45–167
US	Wood, municipal waste, crop residues	Traveling, circulating boiler, and CFB	6–60	26–60
US	Woody biomass	Combustion steam boiler/turbine	8–20	33–75
US	Forest and agricultural residues	Water steam boiler, no combustor type specified	3–25	23–113
US	MSW, agricultural, and wood residues.	Dedicated biopower stoker	25–100	110–279
US & South America	Agricultural and forestry waste	Grate, CFB/BFB boilers.	6–40	11–80
Alberta	Agricultural residues	Direct combustion	up to 450	1,340
Alberta	Triticale straw	Direct combustion	5–500	15-1,257
US	Urban wood waste, forest and agricultural residues	CHP, no combustor type specified	75–100	291–357
US	Mill, forest, urban	Grate stoker and fluidized bed	46 & 60	224–297
Alberta	Woody biomass	CFB	up to 450	643
US	Wood, agro waste	Biomass steam power plant. Grate and FBC	50	143

Concluding remarks

- Biomass combustion is the most straightforward technology to convert wood to heat or heat and power.
- District heat supply is not suitable in New Zealand due to the short cold winter season.
- Heat supply to industry needs customers in adjacent locations. Otherwise, heat loss for long-distance supply is significant.
- CHP is potentially viable under the high demand for electricity. However, this required a large-scale plant (100 MW, or 160,000 tonnes of biomass per year). Heat supply is still needed to maximise investment returns even in this case.
- Emission from biomass combustion is still an issue for further consideration.

3.2 Biomass gasification applications

The producer gas from biomass gasification can be used directly as fuel gas or be further processed for synthetic natural gas (SNG), hydrogen, and liquid fuel. A more comprehensive summary of the producer gas applications after cleaning (Syngas) is shown in Figure 16 below. If the producer gas is used for CHP, a gas engine or gas turbine is used, and the exhaust gas passes through a heat recovery for heat supply. When more power is desired, the heat exchanger can be replaced by a heat recovery boiler to generate steam and the steam is fed to a steam turbine [55].

Recently, synthetic natural gas and hydrogen are attracting significant interest in biomass gasification, which will provide future opportunities for biomass gasification technologies. However, these pathways need further research and development before full commercialisation. The following discussion is focused on heat and power generation, including current commercial projects and cost analysis.

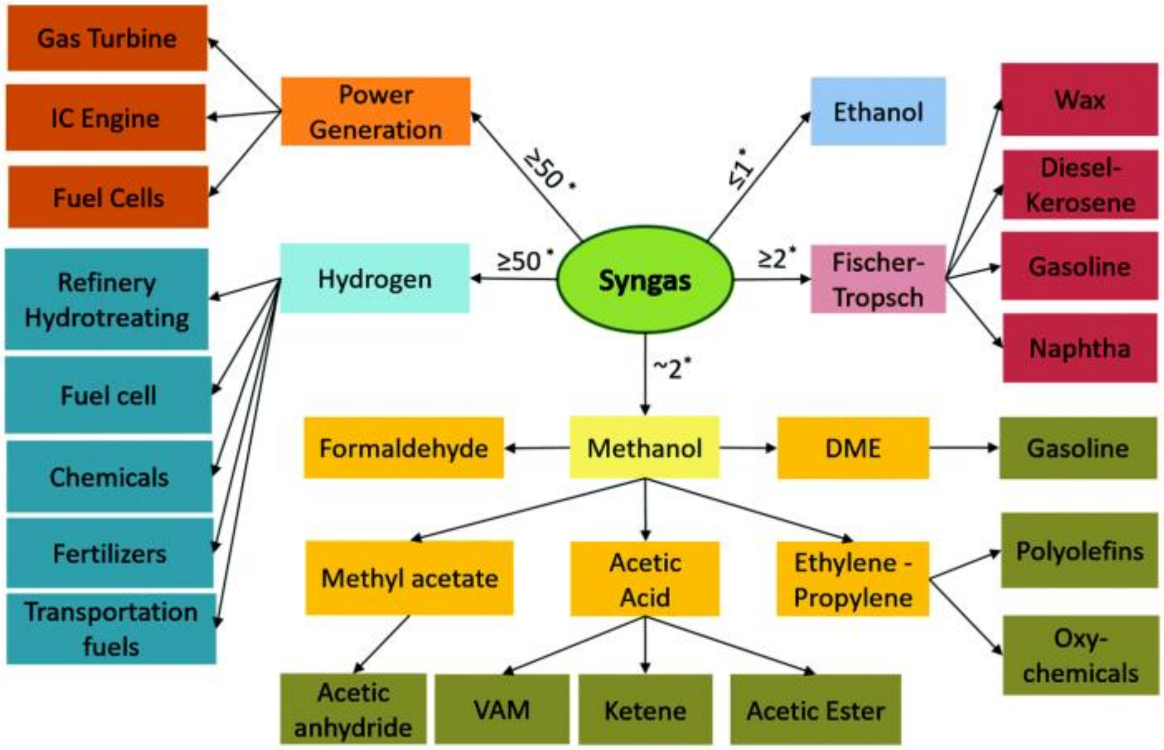


Figure 16. Potential applications of the cleaned producer gas (Syngas) from biomass gasification [56].

Heat and power generation based on biomass gasification

The worldwide power production from biomass reached over 51 GW in 2016 [57]. Many commercial gasification plants have been built for power generation or for CHP, and these are listed in Table 7 below [58]. These plants are based on either a simple CHP process or a biomass integrated gasification combined cycle (BIGCC), shown in Figure 17.

Table 7. Summary of biomass gasification-based commercial power generation plants [58].

Name	Country	Raw material	Thermal output (MW)	Electricity output (MW)	Technology
Andritz-Carbona	Denmark	Lignocelluloses, wood pellets	11	5.5	Fluidized bed reactor
Bubcock and Wilcox Volund	Denmark	Lignocelluloses, wood chips	3.5	1	Reactor updraft gasifier
Bubcock and Wilcox Volund	Japan	Lignocelluloses, wood chips	12	-	Updraft gasifier
Bubcock and Wilcox Volund	Japan	Lignocelluloses, wood chips	8	2	Updraft gasifier
Biomass Engineering Ltd	UK	Lignocelluloses, wood chips	-	1	Downdraft gasifier
Biomass Engineering Ltd	UK	Lignocelluloses, wood chips	-	0.25	Downdraft gasifier
FICFB	Austria	Lignocelluloses, wood chips	4.5	2	FICFB gasification
FICFB Oberwart	Austria	Lignocelluloses, wood chips	1–6	2.7	FICFB gasification
CHP Urban Neumarkt	Austria	Clean wood, biomass	0.58	0.240	Downdraft gasifier
CHP Urban Sulzbach-Laufen	Germany	Waste wood, biomass	0.28	0.13	Downdraft gasifier
CHP Heatpipie Reformer	Germany	Lignocelluloses, waste wood, clean wood	0.25	0.11	FB
CHP Urban Neunkirchen	Austria	Lignocelluloses, waste wood, clean wood	0.62	0.3	Downdraft gasifier
CHP Pyroforce Nidwalden	Switzerland	Lignocelluloses, dried chips	1.2	2 × 0.69	Downdraft pyroforce gasifier
CHP Wila	Switzerland	Lignocelluloses, dried chips	0.45	0.35	Downdraft woodpower gasifier

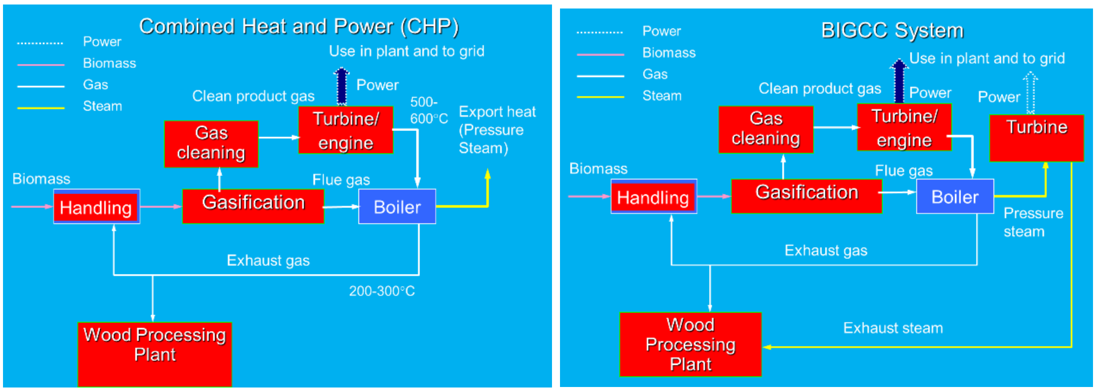


Figure 17. Illustration of biomass gasification-based CHP and BIGCC systems.

Compared with biomass combustion-based CHP plants, the biomass gasification-based CHP plants have more power generation and heat supply flexibility. For heat generation, the pressure steam from the heat recovery boiler can supply heat at high temperatures for industry use, such as plywood manufacturing. Simultaneously the low-temperature heat from the exhaust gas can be used for timber drying or district heating [59]. If the power supply is the target, high power efficiency can be achieved with a second stream of power generation using heat recovery boiler steam, e.g., through the BIGCC system. In both the CHP and BIGCC systems, the exhaust gas from the heat recovery is clean. Thus, the heat efficiency can be improved, and gas emission is a minor concern [60], [61], [62].

However, the internal combustion gas turbine has some technical issues for power generation due to the impurities of the producer gas, which causes unpredictable failure and a shorter lifetime of the turbine [63]. It has been found that the external combustion gas turbine and the gas engine can overcome these issues [64]. The gas engine is widely used in distributed power generation because of its small capacity, compact structure, low investment cost, and maintenance cost [65]. A gas engine requires less purity and high heating value combustion gaseous fuel to achieve high electricity generation efficiency. However, most of the gas engines in the market are designed for fossil gaseous, so modification of the injection system is necessary [14].

Cost analysis has been reported for power generation and CHP plants. In general, a biomass gasification-based power generation plant, as shown in Figure 18, consists of pre-treatment of biomass, biomass gasification unit, gas cleaning, and feeding of the syngas into the gas-turbine or gas engine to generate electricity [66].

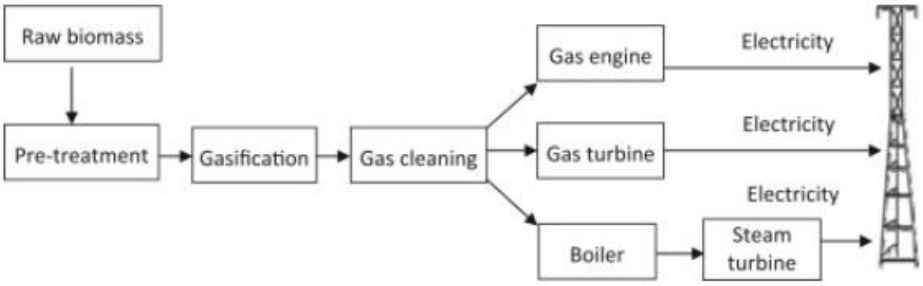


Figure 18. Illustration of a biomass gasification-based power plant [66].

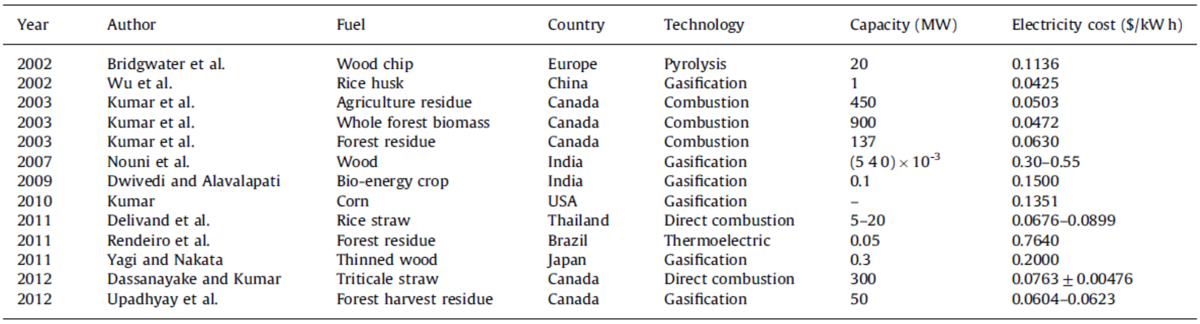
In biomass gasification-based systems, effective and low-cost gas cleaning technology is one of the key operation units to remove tar, particulates and other gaseous contaminants. Tars are the most critical impurity that will cause blockage and corrosion in gas pipelines and machine stationary parts, thus affecting plant performance and operation time [55]. For most gas turbines and engines, the stringent requirement of tar should be lower than 100 mg/Nm^3 [66]. It is reported that some demonstration and commercial scale gasification power plants were closed down due to technical issues of gas cleaning and ash problems [67]. Most of these plants used scrubber gas cleaning technologies.

Studies have shown that hot catalytic gas cleaning is potentially the most promising and cost-effective technology [57]. For large plant operations, a stable biomass supply with consistent quality is another crucial factor of a feasible biomass gasification plant [59]. The sufficient biomass supply ensures the designed efficiency of the operation is achieved, while dry biomass with consistent particle size causes fewer issues in the gasification plant operation.

A feasibility study of a pilot scale power generation from biomass gasification with co-feeding of diesel has been reported in Nigeria [60]. The plant capacity was 100 kW and had the potential to produce electricity at 0.557 US$/kWh. However, the plant was not expected to have a positive net present value due to the high diesel cost in Nigeria and the high capital cost of investment in the rural area.

Another research was also reported on the biomass gasification CHP plant in the Humber region, UK [68]. The plant was designed to supply enough heat for the local district heating and hot water applications. The power efficiency of the plant was 29% and the system's total energy efficiency was 36.8%, with the production cost of electricity being 0.19£ per kWh. The authors highlighted that the net present value is susceptible to total investment cost, O&M (operation and maintenance) cost and electricity tariff. The system is profitable if a subsidy supports 70% of the total investment cost. The electricity production costs from various biomass-based plants, including combustion, gasification and pyrolysis routes, are shown in Table 8 for comparison [58].

Table 8. Electricity costs from various biomass-based power plants [58].

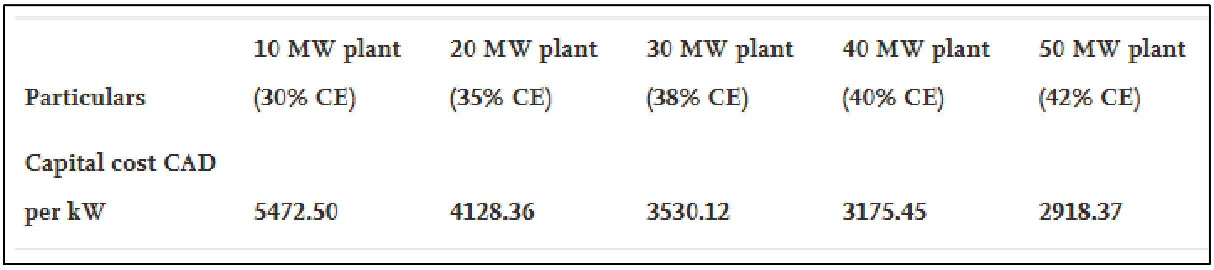


Year	Author	Fuel	Country	Technology	Capacity (MW)	Electricity cost ($/kW h)
2002	Bridgwater et al.	Wood chip	Europe	Pyrolysis	20	0.1136
2002	Wu et al.	Rice husk	China	Gasification	1	0.0425
2003	Kumar et al.	Agriculture residue	Canada	Combustion	450	0.0503
2003	Kumar et al.	Whole forest biomass	Canada	Combustion	900	0.0472
2003	Kumar et al.	Forest residue	Canada	Combustion	137	0.0630
2007	Nouni et al.	Wood	India	Gasification	$(5\ 4\ 0) \times 10^{-3}$	0.30–0.55
2009	Dwivedi and Alavalapati	Bio-energy crop	India	Gasification	0.1	0.1500
2010	Kumar	Corn	USA	Gasification	–	0.1351
2011	Delivand et al.	Rice straw	Thailand	Direct combustion	5–20	0.0676–0.0899
2011	Rendeiro et al.	Forest residue	Brazil	Thermoelectric	0.05	0.7640
2011	Yagi and Nakata	Thinned wood	Japan	Gasification	0.3	0.2000
2012	Dassanayake and Kumar	Triticale straw	Canada	Direct combustion	300	0.0763 ± 0.00476
2012	Upadhyay et al.	Forest harvest residue	Canada	Gasification	50	0.0604–0.0623

More details on the cost analysis for biomass gasification plants in Malaysia have been reported in the literature [58], with plant scales from 0.5 MW to 79.2 MW using various local biomass resources. The cost estimation is highly related to the local economic conditions, gasification technology, overall efficiency and government policy. The capital costs of a commercialized biomass gasification CHP plant will follow the distribution of 30% for the gasifier, 15% for the producer gas clean up, 40% for the power generation and 15% for the air separation when oxygen biomass gasification technology is applied [69].

Other studies suggest that the distribution of total cost is 6% for engineering consultancy, 13% for civil works, 6% for biomass handling, 4% for electrical consumption of the plant, 62% for the gasifier and 9% for the gas engine [60]. The cost estimation was conducted using a biomass gasification plant in Ontario, Canada. More detailed data are given in Table 9, where the costs are in Canadian dollars (CAD) [70]. The capital cost per unit of power output decreases as plant capacity creases.

Table 9. The capital cost of biomass gasification plants at different capacities (CE: conversion efficiency) [70] [71].



Particulars	10 MW plant (30% CE)	20 MW plant (35% CE)	30 MW plant (38% CE)	40 MW plant (40% CE)	50 MW plant (42% CE)
Capital cost CAD per kW	5472.50	4128.36	3530.12	3175.45	2918.37

The capital cost in Table 9 was estimated for air-blown biomass gasification with hot gas cleaning model [71]. The plant was located in an area with abundant biomass resources, and the maintenance cost was also included, which was 2.5% of the total capital requirement. The overhead cost was 2% of the total capital requirement and the project was assumed to have a full capital loan with an interest rate of 10%.

3.3 Biomass pyrolysis applications

It is well known that the pyrolysis product distribution and composition are related to the wood chemical composition, namely cellulose, hemicelluloses and lignin [72]. Major species in the non-condensable gas product from wood pyrolysis are H_2, CO, CO_2, CH_4, C_2H_4, C_2H_6 and C_3H_8 [73]. In contrast, the liquid product contains a complex mixture of oxygenated aliphatic and aromatic compounds as well as water, and the solid product from wood pyrolysis is essentially char [74]. From the previous discussion, it is known that fast pyrolysis and flash pyrolysis aim to produce bio-oil while slow pyrolysis is to produce char.

Several demonstration and commercial plants have been reported in the literature [75]. In Canada, pyrolysis plants with capacities varying from 20 kg/h to 8,000 kg biomass/h have been built by Agritherm, RTIm Ensyem and Pyrovac. There are also pyrolysis plants in the UK with a capacity of 250kg/h and plants in Finland with a capacity of 500 kg/h. Biochar and bio-oil production were conducted in China and Germany as well. In this section, the bio-oil and the bio-char production from wood pyrolysis will be discussed, respectively.

Bio-oil production from biomass pyrolysis

Fast pyrolysis of biomass can be optimised for bio-oil production at a yield of up to 75% [35]. During the fast pyrolysis process, biomass decomposition produces volatile vapours (organic compounds), aerosols, gases and charcoal. When the mixture of vapours and gases is cooled down, the vapours condense to form a liquid called the bio-oil or pyrolysis oil which usually has about half the heating value of conventional fuel oil. The key factor in the bio-oil production process is to control the process temperature (450-600°C), the residence time (less than 2 seconds) and the fast heating rate. A rapid removal of solid char and fast quenching of the vapour/gas mixture is important to enhance the liquid yield and prevent secondary reactions. Low ash biomass, such as radiata pine wood, has a high yield of liquid product in pyrolysis [35]. The bio-char can be separated as a by-product and the non-condensable gas can be combusted for heat supply to the pyrolysis process.

In general, the overall bio-oil production from pyrolysis can be summarized as (1) drying of the biomass feedstock, which minimizes the water in the product oil; (2) grinding the biomass into small particles, which allows for fast reaction; and (3) rapid separation of char since char has a catalytic effect on the vapour cracking and collection of the liquid product (bio-oil) for future refining, or clean-up to other products such as electricity, heat and chemicals. The full potential applications of the products from fast biomass pyrolysis are shown in Figure 19.

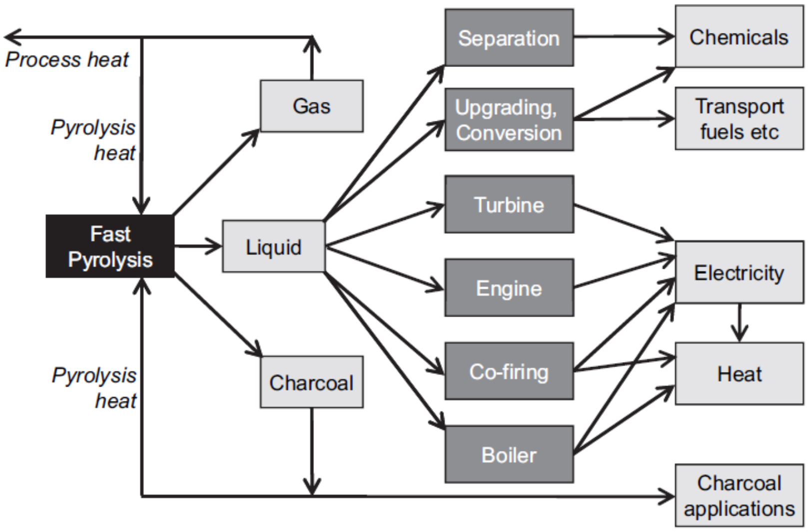


Figure 19. Potential applications of biomass fast pyrolysis products [75].

Considering the properties of the biomass pyrolysis bio-oil (Table 3), the bio-oil can be used directly as fuel for turbines, engines and boilers to generate electricity. However, due to the undesirable high oxygen content, high water content and high viscosity, this equipment needs modification in design [75]. The bio-oil storage is another tricky problem since the ageing phenomenon can change the characteristic of the bio-oil [76]. Removing fine particles from the bio-oil can deaccelerate the ageing process, and adding alcohols can reduce or control the ageing phenomenon [75]. Trials have been reported to compare bio-oil (wood pyrolysis oil) engines and diesel engine power plants [76]. The results confirmed that the bio-oil is feasible for replacing diesel in a small-scale power plant.

For large-scale production, the pyrolysis-based biorefinery concept, as shown in Figure 20, has been proposed to produce a cluster of products to make the process economically feasible. However, this concept is very complex and has low energy efficiency. In addition, it requires high capital investment.

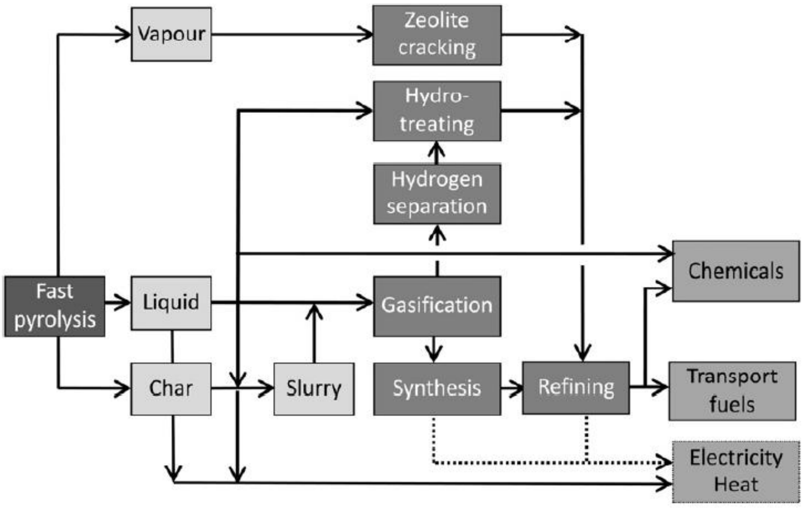


Figure 20. Biorefinery concept based on biomass pyrolysis.

The biomass pyrolysis bio-oil has been processed for hydrogen production [77]. In this process, the bio-oil first undergoes steam reforming to produce hydrogen and carbon monoxide. The carbon monoxide further reacts with water vapour through a water-gas shift reaction to produce more hydrogen and CO_2. Pure hydrogen is finally generated by H_2 and CO_2 separation. Nickel-based catalysts are required in this process for higher hydrogen yield. However, this is still in the R&D stage, and some technical issues are still to be resolved.

Costs analysis for bio-oil production

The costs of a fast pyrolysis plant for crude bio-oil production have been estimated, and the results are shown in Figure 21 as a function of plant scale and biomass costs [75]. In the figure, the figures are in euros per tonne at the 2011 value.

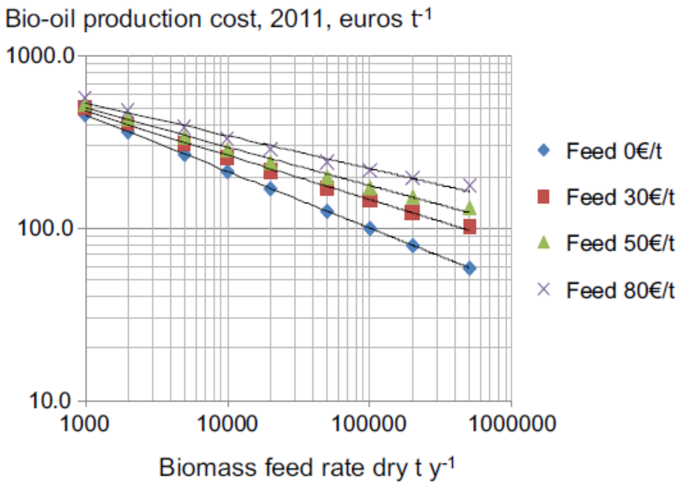


Figure 21. Crude bio-oil production costs.

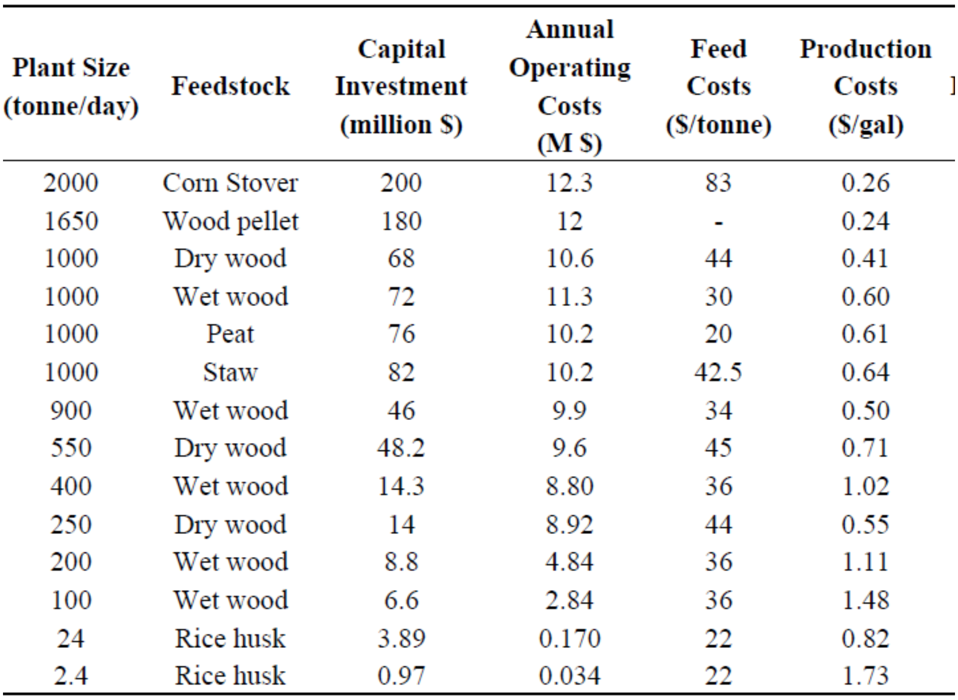
As shown in Figure 21, the production cost of bio-oil increases with the cost of biomass and decreases with plant capacity. The same trend was reported for the bio-oil production in the US [76], with the oil price increasing from 6.1US$/GJ (122 US$/t bio-oil) to 9.9 US$/GJ (198 US$/t bio-oil) when the price of wood increased from 1.1US$/GJ (20US$/t biomass) to 3.3 US$/GJ (60 US$/t biomass). On the other hand, the oil price decreased from 7.8US$/GJ (156 US$/t bio-oil) to 6.4US$/GJ (128 US$/t bio-oil) when the plant capacity increased from 2.6 t/h to 6.7t/h in the oil production rate. The operation cost distribution in bio-oil production from biomass pyrolysis is listed in Table 10 [78]. However, these costs can only be used as a guide as these costs are highly related to local situations.

Table 10. Operation cost distribution for production of bio-oil from biomass pyrolysis [78].

Items	**Percentages**
Biomass harvesting or feedstock	23%–30%
Maintenance	17%–24%
Utilites	22%–25%
Labor	12%–19%
Grinding	7%–9%
Transportation	5%–7%

A more comprehensive summary of the biomass pyrolysis costs is given in Table 11 below [78].

Table 11. Summary of bio-oil production costs and capital investment [78].



Plant Size (tonne/day)	Feedstock	Capital Investment (million $)	Annual Operating Costs (M $)	Feed Costs ($/tonne)	Production Costs ($/gal)
2000	Corn Stover	200	12.3	83	0.26
1650	Wood pellet	180	12	-	0.24
1000	Dry wood	68	10.6	44	0.41
1000	Wet wood	72	11.3	30	0.60
1000	Peat	76	10.2	20	0.61
1000	Staw	82	10.2	42.5	0.64
900	Wet wood	46	9.9	34	0.50
550	Dry wood	48.2	9.6	45	0.71
400	Wet wood	14.3	8.80	36	1.02
250	Dry wood	14	8.92	44	0.55
200	Wet wood	8.8	4.84	36	1.11
100	Wet wood	6.6	2.84	36	1.48
24	Rice husk	3.89	0.170	22	0.82
2.4	Rice husk	0.97	0.034	22	1.73

Costs analysis for bio-char production

Biochar is produced from slow biomass pyrolysis. However, the biochar yield is low at around 30% [79]. To improve the biochar yield, operation conditions such as temperature, particle size and heating rate should be carefully controlled to balance the operation time and the pyrolysis temperature and heating rate. Low temperature and slow heating rate enhance the biochar yield but increase the operation time. Large particle size also tends to promote the biochar yield [80].

The produced biochar can be used to substitute charcoal in thermal power plants and boiler or used for soil amendment. Most biochars produced from the biomass pyrolysis process are combusted [81]. However, some co-production plants are reported, and the char production by kilns or retort systems for energy application is approved to be profitable [79].

Biochar application in the soil can be regarded as a way for carbon sequestration, but it is also found that biochar can retain or control the nutrients in the soil, therefore, the biochar is also regarded as a fertilizer in the soil.

Cost for biochar production from biomass pyrolysis

Due to the low yield and long operation time, biochar production is commonly from pyrolysis plants that produce bio-oil. Therefore, the capital cost and operation cost for biochar production are not available, but the cost analysis for pyrolysis bio-oil production can be used as a reference. Nevertheless, a review of the costs of slow biomass pyrolysis for biochar production is available in the literature [79]. For example, the slow pyrolysis process using an earthen kiln was reported to produce char at the cost of 1860 US$/t char in 2010, when the co-produced wood vinegar was sold as revenue. Another slow pyrolysis plant of wood using Lambiotte continuous retort showed a production cost of 373 US$ per ton of char in 2010 value. The capacity of the pyrolysis plant was 262,000 tonnes of biochar per year, and the capital cost was around 71 million US$ (2010).

3.4 Biomass torrefaction applications

As discussed above, bio-char is commonly used for combustion or co-firing as a charcoal substitute in power generation plants or ironmaking processes. If only for this purpose, the char can be produced from the torrefaction process at a much higher solid yield than the pyrolysis. We can term the char from torrefaction as solid char to differentiate from that from biomass pyrolysis. Torrefaction is also used for biomass pretreatment for volatile release and the solid char is then used from pyrolysis or gasification.

In the following section, the production of solid char by torrefaction, its applications and production costs will be described and discussed.

Solid char production from biomass torrefaction

Torrefaction is a thermal process in the absence of oxygen and commonly operates at temperatures lower than 300°C, in which the solid char yield can be 85% or higher. When it is used for combustion or co-firing, the solid char will go through palletization or other densification processes to increase its energy content per volume [82]. The densification process also makes it easy for storage and transportation. As a result, the solid char is a high-quality fuel for combustion and combustion heat-related applications due to its low volatile content, high energy density and increased porosity[83].

Back in the 1980s, a French company, Pechiney, developed a torrefaction process to manufacture solid char as the reduction agent for aluminum production [84], although it was shut down after a period of operation due to low energy efficiency. Based on the assessment of this project, an improved concept with energy recovery was proposed, as shown in Figure 22 [84].

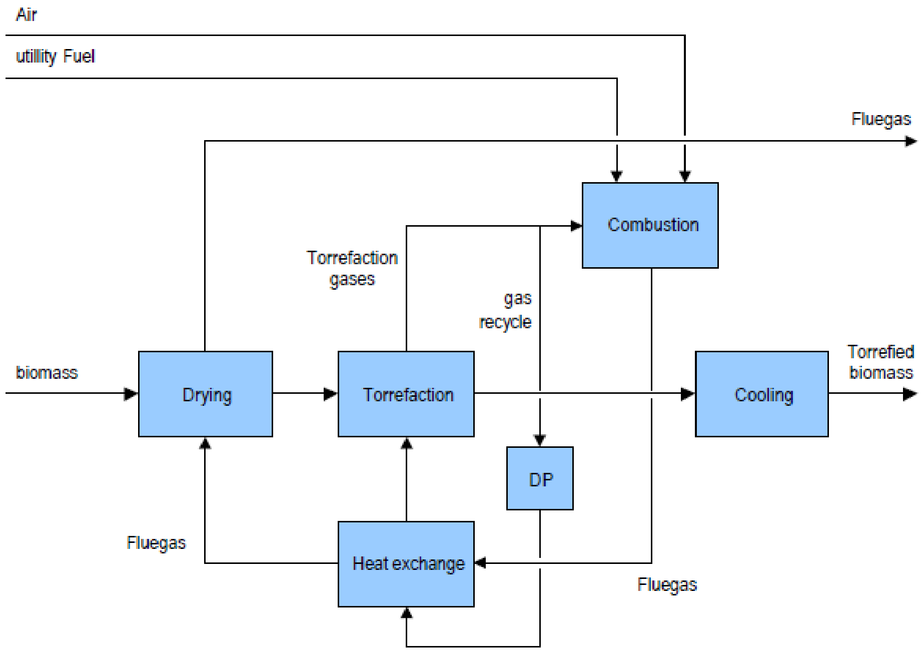


Figure 22 Schematic diagram of an improved torrefaction plant [84].

As shown in Figure 22, the plant uses volatile gas to heat the torrefaction process; thus, no external heat is required. The volatile gas is combusted, and the flue gas provides heat in a heat exchanger for heating the circulating gas through the torrefaction reactor. This circulating gas is part of the volatile gas from the biomass torrefaction process. By controlling the torrefaction operation conditions, the volatile gas yield can be managed to provide sufficient heat to the torrefaction process. Alternatively, if the solid char production is maximized, supplementary fuel will be needed when the heat from volatile combustion is insufficient. This new concept is recognized as promising for commercially producing solid char from biomass torrefaction [84].

A similar design was proposed by Kiel et al. [44], which uses a separate gas stream for providing heat from the heat exchanger to the torrefaction reactor. Several pilot and commercial scale torrefaction plants are operating in the Netherlands, Belgium, France, Sweden, Austria, Canada, America and the UK [85]. Most plants in America are at the pilot scale while fully commercialized plants are developed in Europe. For example, two commercial plants have been reported in the Netherlands with solid char production capacities of 60,000 and 70,000 tonnes per year, respectively. Two commercial plants were also built in France with a solid char production capacity of 20,000 tonnes per year. A commercial plant was also reported in the UK with a solid char production capacity of 110,000 tonnes per year. Among all reported plants, moving bed, rotary drum and screw torrefaction reactors are most common types at fully commercialized scale while the fluidized bed and multiple hearth furnace torrefaction reactors are used the pilot scale.

Recently, a mobile torrefaction system has been developed that can be moved from one site to another and thus can reduce costs for biomass transportation and logistics [86]. The torrefaction reactor, biomass dryer, heat supply system, and other auxiliaries are installed on the mobile platform. However, if significant drying duty is required, the dryer can be of a large size and requires substantial heat demand. In this case, the dryer can be set up separately from the torrefaction unit, which may be non-ideal for a mobile unit [87]. Therefore, an effective mobile torrefaction unit requires careful system unit integration and heat management.

Nevertheless, mobile torrefaction case studies for wood residues were carried out in California, the US, and South Europe [86, 87]. Both studies suggested that the feasibility of a mobile torrefaction system is related to the biomass properties (density, moisture content), biomass costs, solid char market demand, and environmental impacts.

Based on the IEA Bioenergy report in 2015 [88], *Earth Care Products Inc* has developed a mobile torrefaction system, as shown in Figures 23 - 25. This system has a solid char production capacity of 20,000 tonnes per year, equivalent to a solid char production capacity of 60 tonnes per day. The biomass with particle sizes smaller than 3.5 cm × 3.8 cm × 3.8 cm and moisture content less than 40% can be fed into the rotary dryer. The heat for the dryer is from a biomass burner. Then, the dried biomass is torrefied in a rotary drum torrefaction reactor. In the end, the solid char is transferred to the airtight cooling unit, which consists of a screw conveyor with a water jacket. The cooled biochar is then densified and ready for dispatch to market.

Figure 23. The mobile torrefaction system [89].

Figure 24. The mobile torrefaction system in operation [89].

Figure 25. The mobile torrefaction system is in a package and ready to move [89].

Solid char application in ironmaking

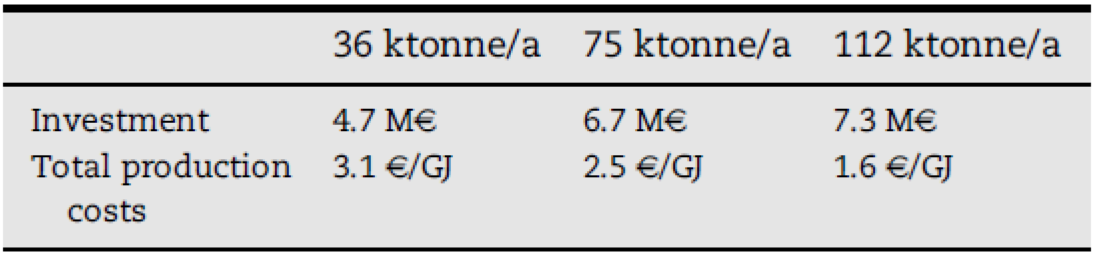
In addition to combustion and co-firing, the solid char can also be used in the ironmaking industry to replace coke and coal in the blast furnace [90]. Modern blast furnace in ironmaking consumes around 325 kg of coke and 175 kg of coal to produce one tonne of iron. Thus, the replacement or substitute of the coke and coal by the solid char from biomass torrefaction has excellent potential to reduce greenhouse gas emissions in the ironmaking industry [91]. Currently, the steel industry contributes 5 – 7% of the total anthropogenic CO_2 emission [91]. Studies have shown that the solid char from biomass torrefaction is more suitable for replacing high volatile bituminous coal than the low-volatile coals. However, further R&D is needed to investigate the impacts of alkali and volatile contents in the torrefied solid char on the performance of the blast furnace in ironmaking [44].

Costs of solid char production from biomass torrefaction

The solid char from biomass torrefaction has advantages over the raw biomass [91]. Higher energy density and hydrophobic behaviour of the solid char can reduce transportation and storage costs. The Torrefaction process, in combination with palletization, is economically attractive. The production cost of solid char from biomass torrefaction is related to the scale of the plant, operating conditions and biomass properties (moisture content, size and type).

A torrefaction system in combination with palletization was reported in France at a solid char production of 60,000 tonnes per year with the plant's total investment of 5.5 to 7.5 million € (in 2005 value) [84]. Similar results are also reported in a separate study on the impact of the plant scale on the costs, which are given in Table 12 [92]. However, the reported costs analysis is likely to have high uncertainty due to unexpected implementation challenges and a lack of previous scaling experience [44] [91] [92]. The moisture content is an essential parameter of the cost of the torrefaction process as it defines the energy input of the process [91]. As shown in other sectors, larger-scale torrefaction plants can reduce production costs per tonne of solid char. However, the total capital investment is increased [92].

Table 12. Capital and production costs from solid char production from biomass torrefaction [92].



	36 ktonne/a	75 ktonne/a	112 ktonne/a
Investment	4.7 M€	6.7 M€	7.3 M€
Total production costs	3.1 €/GJ	2.5 €/GJ	1.6 €/GJ

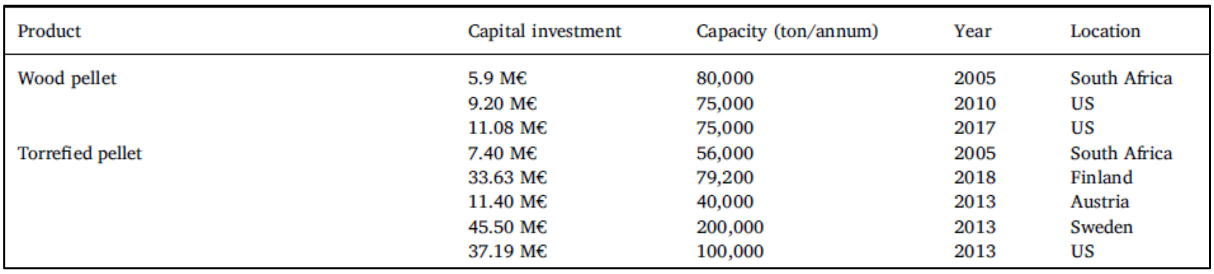
In the study discussed above [92], a torrefaction plant with a solid char production capacity of 75,000 tonnes per year requires capital investment in the range of 6.1 to 7.3 M€ (2007 value) and the production cost of torrefied biochar was 37€ per tonne of solid char when the feedstock biomass had a moisture content of 35%. The production cost was increased to 50 € per tonne of solid char when the biomass moisture content was 50%, while it was reduced to 34 € if the biomass content was 25%.

Margareta et al. reported a detailed review on the economic analysis of the biomass torrefaction process [93]. They found that the major part of the capital cost was from the torrefaction reactor (approximately 50%). For a plant with solid char production of 227,000 tonnes per year, the highest total capital cost was 49 million € (in 2005 value), in which the screw reactor was used. However, the total capital cost was reduced to 36 million € when the rotating drum reactor was used and 25 million € when the moving bed reactor was used.

The total capital costs for integrated torrefaction and pelletizing plants with different capacities and locations are given in Table 13, which also includes wood pellet production plans for comparison. It is noted that the wood pellet production only requires drying and pelletizing, while torrefied solid char pellet production needs an additional torrefaction reactor.

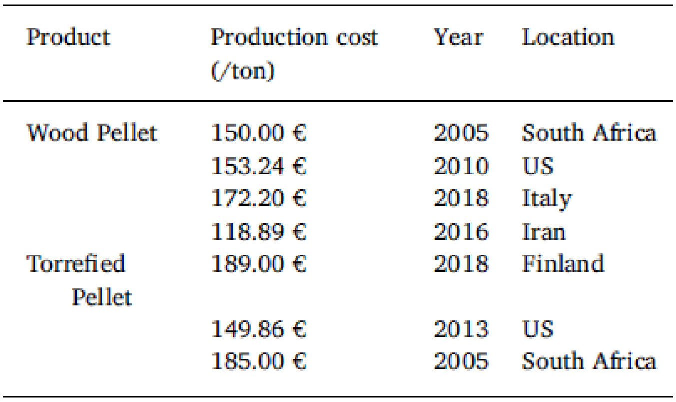
Table 14 presents the production costs of torrefied solid char pellets, which are again higher than wood pellets' production cost due to the high energy demand and more complicated operation. The other factors contributing to the higher production costs include the manpower and the depreciation of the torrefaction reactor.

Table 13. Capital investment of wood pellets and torrefied solid char pellets production [93].



Product	Capital investment	Capacity (ton/annum)	Year	Location
Wood pellet	5.9 M€	80,000	2005	South Africa
	9.20 M€	75,000	2010	US
	11.08 M€	75,000	2017	US
Torrefied pellet	7.40 M€	56,000	2005	South Africa
	33.63 M€	79,200	2018	Finland
	11.40 M€	40,000	2013	Austria
	45.50 M€	200,000	2013	Sweden
	37.19 M€	100,000	2013	US

Table 14. Production costs of wood pellets and torrefied solid char pellets [93].



Product	Production cost (/ton)	Year	Location
Wood Pellet	150.00 €	2005	South Africa
	153.24 €	2010	US
	172.20 €	2018	Italy
	118.89 €	2016	Iran
Torrefied Pellet	189.00 €	2018	Finland
	149.86 €	2013	US
	185.00 €	2005	South Africa

4. Environmental Impacts

4.1 Biomass combustion environmental impacts

It is known that at the elemental level, the major component of woody biomass consists of carbon (45-51%), oxygen (41-43%) and hydrogen (5.8-6.1%), ash elements, as well as sulphur and nitrogen. Regarding the environmental concerns, the emissions from the combustion of the woody biomass include CO_2 from the combustion of carbon and N-based species and S-based species originating from the sulphur and nitrogen in the wood. However, the N-based and S-based emissions are generally less than those from coal combustion, other types of biomass and organic solid wastes [45]. Therefore, the environmental assessment usually focuses on three aspects: S-based emissions, N-based emissions, and ashes [45, 94, 95].

Figure 26 shows the nitrogen content (Figure 26a) and sulfur content (Figure 26b) in various biomass feedstocks. From Figure 26(a), the nitrogen content in pine wood varies from 0.1% to 0.5%. The nitrogen released during biomass combustion is mainly from volatile combustion, while the rest of the nitrogen is removed during char oxidation [94]. The nitrogen is released firstly as NH_3, HCN, and a small amount of HNCO [96]. This released NH_3, HCN and HNCO further react with reactive nitrogen in nitrogen oxides (NO, NO_2) or molecular nitrogen (N_2), and eventually results in NO_x emission [94].

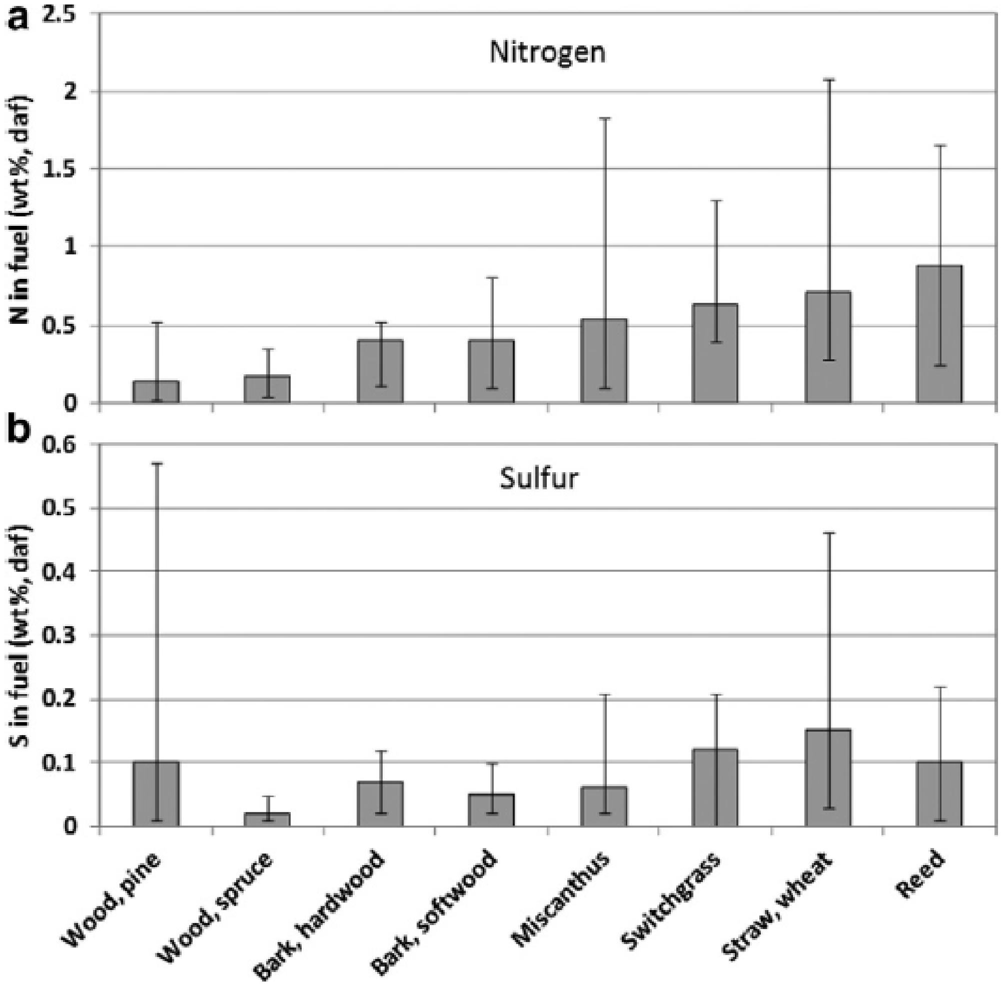


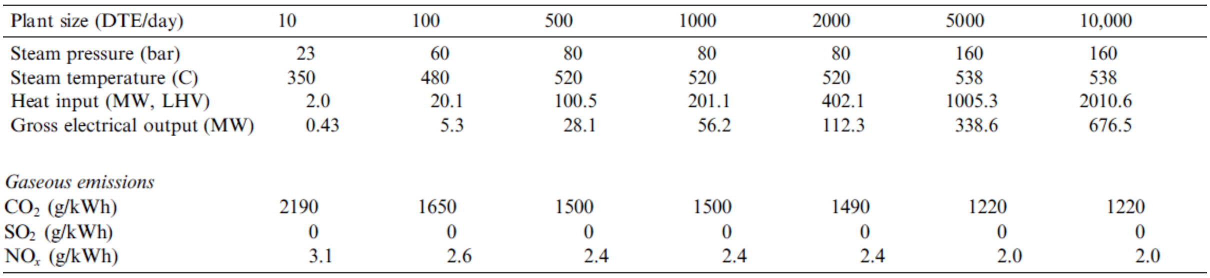
Figure 26. Nitrogen and sulfur contents in various biomass resources (daf: dried ash-free basis) [94].

The NO_x emission can be minimized by maximizing the conversion of NH_3 and HCN to N_2 based on the combustion technology applied. For example, the released nitrogen compound can be converted to N_2 up to 90% by optimizing air-staging in a bubbling fluidized bed combustor [97].

As shown in Figure 26(b), the sulfur content in wood is typically below 0.1% as organically-bound sulfur and sulfates [98]. Although the sulphur forms SO_2 after combustion, most of the SO_2 exists in the ash [94]. The ash constituents are majorly alkali, and alkaline earth metals such as Ca, K and Na, and they can effectively boost the conversion of SO_x to sulfates. It is reported that 80% of sulfur in the wood can be converted to sulfates using the bubbling fluidized combustion reactor [99].

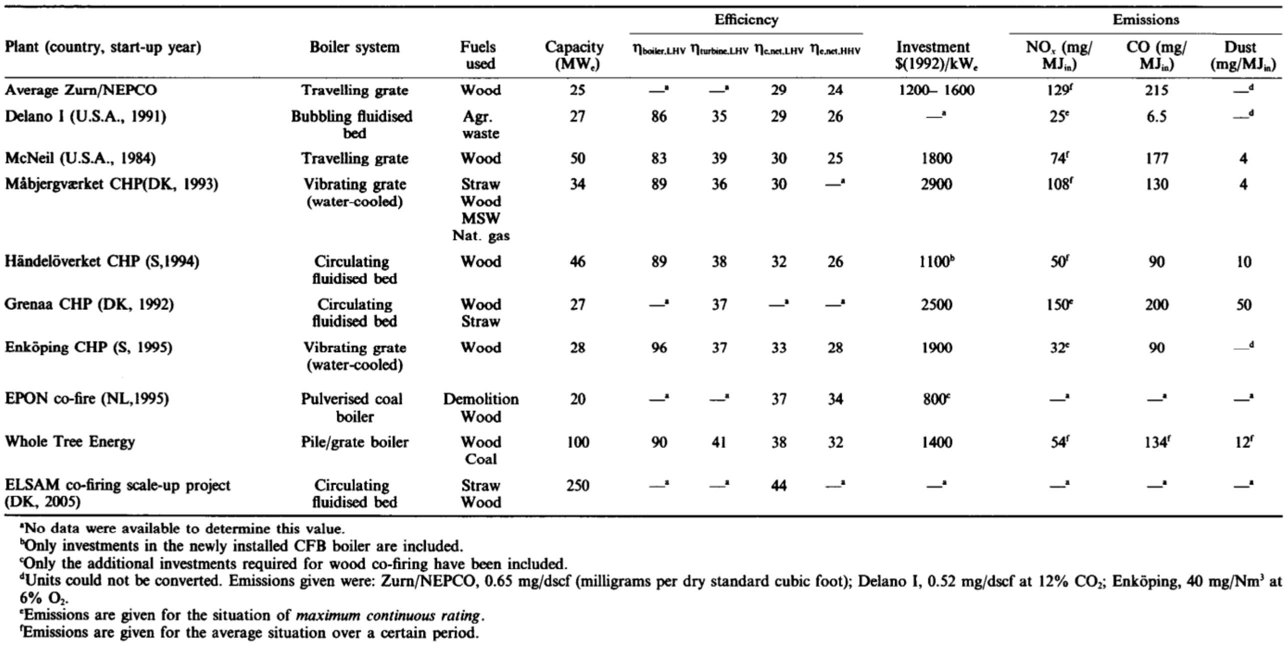
Table 15 gives the model simulation data for wood combustion CHP plants and the emissions at different plant scales [45]. However, Table 16 presents the emission data from commercial biomass combustion plants [6].

Table 15. Emission data of different wood combustion CHP plants [45]



Plant size (DTE/day)	10	100	500	1000	2000	5000	10,000
Steam pressure (bar)	23	60	80	80	80	160	160
Steam temperature (C)	350	480	520	520	520	538	538
Heat input (MW, LHV)	2.0	20.1	100.5	201.1	402.1	1005.3	2010.6
Gross electrical output (MW)	0.43	5.3	28.1	56.2	112.3	338.6	676.5
Gaseous emissions							
CO_2 (g/kWh)	2190	1650	1500	1500	1490	1220	1220
SO_2 (g/kWh)	0	0	0	0	0	0	0
NO_x (g/kWh)	3.1	2.6	2.4	2.4	2.4	2.0	2.0

Table 16. Emission data from commercial biomass combustion plants [6].



Plant (country, start-up year)	Boiler system	Fuels used	Capacity (MW_e)	Efficiency $\eta_{boiler,LHV}$	$\eta_{turbine,LHV}$	$\eta_{e,net,LHV}$	$\eta_{e,net,HHV}$	Investment \$(1992)/kW_e	Emissions NO_x (mg/MJ_{in})	CO (mg/MJ_{in})	Dust (mg/MJ_{in})
Average Zurn/NEPCO	Travelling grate	Wood	25	—[a]	—[a]	29	24	1200– 1600	129[f]	215	—[d]
Delano I (U.S.A., 1991)	Bubbling fluidised bed	Agr. waste	27	86	35	29	26	—[a]	25[e]	6.5	—[d]
McNeil (U.S.A., 1984)	Travelling grate	Wood	50	83	39	30	25	1800	74[f]	177	4
Måbjergværket CHP(DK, 1993)	Vibrating grate (water-cooled)	Straw Wood MSW Nat. gas	34	89	36	30	—[a]	2900	108[f]	130	4
Händelöverket CHP (S,1994)	Circulating fluidised bed	Wood	46	89	38	32	26	1100[b]	50[f]	90	10
Grenaa CHP (DK, 1992)	Circulating fluidised bed	Wood Straw	27	—[a]	37	—[a]	—[a]	2500	150[e]	200	50
Enköping CHP (S, 1995)	Vibrating grate (water-cooled)	Wood	28	96	37	33	28	1900	32[e]	90	—[d]
EPON co-fire (NL,1995)	Pulverised coal boiler	Demolition Wood	20	—[a]	—[a]	37	34	800[c]	—[a]	—[a]	—[a]
Whole Tree Energy	Pile/grate boiler	Wood Coal	100	90	41	38	32	1400	54[f]	134[f]	12[f]
ELSAM co-firing scale-up project (DK, 2005)	Circulating fluidised bed	Straw Wood	250	—[a]	—[a]	44	—[a]	—[a]	—[a]	—[a]	—[a]

[a] No data were available to determine this value.

[b] Only investments in the newly installed CFB boiler are included.

[c] Only the additional investments required for wood co-firing have been included.

[d] Units could not be converted. Emissions given were: Zurn/NEPCO, 0.65 mg/dscf (milligrams per dry standard cubic foot); Delano I, 0.52 mg/dscf at 12% CO_2; Enköping, 40 mg/Nm^3 at 6% O_2.

[e] Emissions are given for the situation of *maximum continuous rating*.

[f] Emissions are given for the average situation over a certain period.

More comprehensive life cycle assessment studies were conducted on biomass combustion plants [95] for four biomass combustion technologies at three different locations. The environmental impacts included acidification, eutrophication, fossil fuel depletion and global warming. The results concluded that biomass combustion power plants could significantly reduce the impacts of acidification, eutrophication, fossil resource depletion, and respiratory and photochemical ozone formation. However, the ecotoxicity values increased primarily because of wood ash disposal. It was also pointed out that the heavy metal contents in the wood combustion ash need to be carefully considered on the potential impact on the local eco-environment if the ash is disposed to the soil.

A study was reported on the environmental impact of a coal-biomass co-fired power plant in Finland [100]. The study confirmed that wood-pellet co-combustion in CHP plants could reduce the net environmental impacts and not cause significant concerns about air pollution in the urban environment.

4.2 Biomass gasification environmental impacts

Environmental aspects of biomass gasification operation include dust, exhaust gas, wastewater and condensates [101]. Among these, the two main environmental hazards are dust and waste water or solutions (from gas cleaning). The gasification of agricultural residuals such as rich husks usually produces a large quantity of ash. The ash may not cause environmental problems if they are disposed of in the proper ways. However, disposing of a large amount of tar-containing waste water or other solutions can lead to environmental concerns [66].

Dust is a common environmental concern rising from dried and friable solids. Thus, preparation of the biomass feedstock in drying and pelleting generate dust which can cause inhalation problem, formation of explosive fines, increased wear of the mechanical equipment and increased maintenance cost. In addition, flying ash generated during biomass gasification is also removed in the gas cleaning and thus would be contained in the waste water or waste solution.

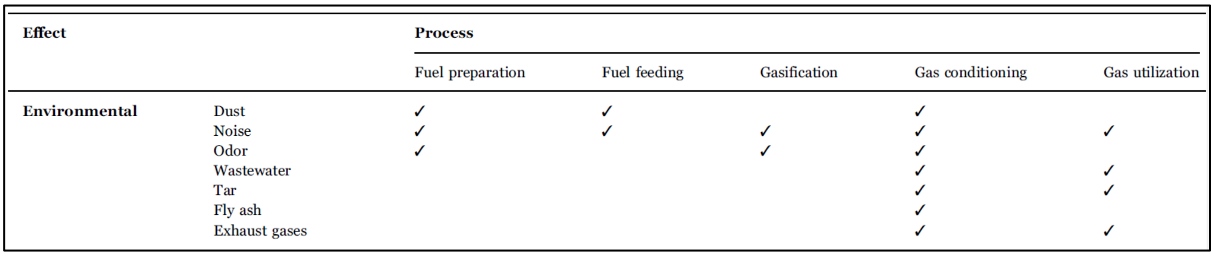
Tar species in the biomass gasification producer gas consist of acetic acid, phenols, and many other oxygenated organic compounds which need post-gasification cleaning. The tars can be removed by hot cracking at high temperatures or wet scrubbing using water or other suitable solvents (vegetable oil and bio-diesel have been used).

Wastewater or waste solution is produced during wet-scrubber gas cleaning. The presence of various contaminants in the wastewater or the waste solution is affected by the type and design of the gasifier system, the method of gas treatment, and the operating parameters of the process [102].

Dust, fine ash, and other contaminant gaseous species are emitted through the exhaust gas in the gasification system [102]. The limit of particulate emission from gasifiers is not more than two to six grams per cubic meter for different gasifiers. The gaseous emissions from the gasification can also be through the exhaust gas.

The environmental concerns of the biomass gasification process are summarized in Table 17. The overall biomass gasification plant is divided into five sections: fuel preparation, fuel feeding, gasification, gas conditioning and gas utilization. The environmental concerns are listed with corresponding sections. The environmental impacts and treatments can be carried out after the source of the problem are identified. Overall the environmental concerns for the biomass gasification-based CHP system are not severe as the gas is cleaned and the exhaust gas from the gas engine is relatively clean.

Table 17. The environmental concerns of the biomass gasification process [102].



Effect		**Process**				
		Fuel preparation	Fuel feeding	Gasification	Gas conditioning	Gas utilization
Environmental	Dust	✓	✓		✓	
	Noise	✓	✓	✓	✓	✓
	Odor	✓		✓	✓	
	Wastewater				✓	✓
	Tar				✓	✓
	Fly ash				✓	
	Exhaust gases				✓	✓

4.3 Biomass pyrolysis environmental impacts

The biomass pyrolysis process involves several sections: biomass pretreatment, pyrolysis process, vapour/gas quenching, and product handling. The environmental impacts may be from the whole biomass pyrolysis or the applications of the products, namely bio-oil, biochar and non-condensable gases.

Various studies have been reported on the environmental impact of biomass pyrolysis. LCA appears to be the most common method by considering the impacts of global warming, acidification and eutrophication. On the other hand, a study about ecotoxicity and toxicity concluded that the bio-oil production from biomass pyrolysis and the bio-oil application did not cause remarkable environmental risk [75]. Results from two LCA reports will be described and discussed in more detail here to illustrate the common environmental impacts of the biomass pyrolysis process.

The first LCA study was on a wood pyrolysis plant for bio-oil production [103] with a bio-oil annual output of 10,000 tonnes in which the system boundary included biomass collection, pyrolysis process for the bio-oil production, product (bio-oil) transportation, and pyrolysis oil combustion. In this study, the environmental impact evaluation of bio-oil transportation was highly sensitive to the transportation distance, and 500 km was assumed. In the pyrolysis oil production section, the plant was considered to operate 8000 hours per year, and the wood-feeding rate was 2,990 kg/h, which produces pyrolysis oil at the rate of 1,250 kg per hour. The greenhouse gas emission was calculated to be 177kg CO_2-e /t bio-oil, whose significant contribution was from plant electricity consumption. The acidification impact from the biomass pyrolysis process is mainly related to sulfur oxide and nitrogen oxide emissions from diesel consumption in the biomass collection process. The equivalent emission in the acidification aspect was 0.81kg SO_2/t bio-oil. The most significant influence factors for eutrophication were nitrogen oxides, nitrates and ammonium ion emission. The eutrophication was quantified by equivalent PO_4^{3-} emission, which was calculated to be 0.095 kg PO_4^{3-}/t bio-oil. The overall environmental impact of pyrolysis bio-oil is about 15% -18% of the fossil fuel. Therefore, the CO_2 emission can be reduced by 2,835kg for each tonne of bio-oil used to replace fossil fuel for providing the same energy.

Another LCA study was reported for wood pyrolysis plants for biodiesel and gasoline production, which includes bio-oil upgrading and refining [104]. The plant was assumed to process 500 tonnes of wood per day and the system boundary included biomass collection and transportation, pyrolysis process, bio-oil upgrading and end production transportation. The end products in this study were gasoline and diesel from the bio-oil upgrading by hydrogenating. However, fuel use was not included in this study. The annual operation time of the plant was 350 days per year.

The results show that the global warming impact was estimated at -2197kg CO2 per tonne of liquid fuel production, indicating CO_2 removal from the atmosphere by the growing trees. The primary reason for this negative estimation value was the cultivation stage of biomass. If the fuel use were included in the boundary system of this LCA study, the global warming impact would be positive as 1.03 tonnes of CO_2 per tonnes of liquid fuel, which was only 28% of the emissions of the combustion of crude oil-derived liquid fuel. The acidification impact was calculated to be 5.33kg SO_2 per tonne of liquid fuel and the eutrophication impact was 1.19kg PO_4^{3-} per tonne of liquid fuel.

Both of the above LCA studies indicated that bio-oil production from biomass pyrolysis could significantly reduce GHG emissions compared to fossil fuel. This reduction is due to the resource (biomass). The GHG emissions may vary with the biomass type, processing technologies, site locations, boundary conditions and end-product applications. Nevertheless, the LCA results can be used as general guidance to demonstrate the environmental benefits of using biomass for liquid fuels.

4.4 Biomass torrefaction environmental impacts

As discussed in Section 2.5 and Section 3.4, the target product from biomass torrefaction is the solid char, although volatiles and gases are also released from the torrefaction [91]. The gases include CO_2, H_2O (vapour), SO_x and NO_x and the volatiles consist of various organic compounds. NO_x and SO_x contents are low in the gas phase. There are also minor quantities of tars, but these need attention as they can condensate once the gas is cooled down [105]. Moreover, the NO_x and SO_x remain the flue gas if the gas phase is combusted to recover the energy. Therefore, the flue gas needs to be cleaned. A bag filter and ceramic filler with an absorbent are handy tools in the emission control for the torrefaction process [105].

LCA studies have also been reported on the biomass torrefaction plant to demonstrate the environmental benefits and impacts of biomass torrefaction [93]. Similarly to biomass pyrolysis, most LCA studies evaluated the environmental impacts of global warming, acidification, and eutrophication. In addition, factors that affect the GHG emissions were identified as the biomass transportation distance and types of energy input to the biomass torrefaction plant.

Interestingly, integrating biomass torrefaction with solid char palletization generates GHG emissions 30% less than direct wood pellet production [106]. This is because the combustion of torrefaction volatiles can replace 85% of utility fuels, indicating the energy benefits from the heat integration concept in the torrefaction process. The energy released from volatile combustion is highly related to the heating value of that volatiles which is, in turn, related to the operation temperature and solid char yield. The heating value of the volatiles is high at high torrefaction temperatures, whereas the solid char yield is reduced. Therefore, the GHG emissions from the torrefaction process are sensitive to energy requirements in the drying and other energy consumption units [107].

In a separate study, the environmental impacts of biomass torrefaction were assessed for the CHP plant, which used solid char to substitute 20% coal for co-firing [108]. It is reported that compared to 100% coal combustion, the GHG emission from the co-firing plant was decreased by 6%, the acidification was decreased by 26%, and the eutrophication was reduced by 11%.

5 Conclusion and recommendation

This report reviewed thermochemical technologies that potentially convert the forest slash waste wood in the Gisborne area to energy and fuels. These technologies include combustion, gasification, pyrolysis, and torrefaction. Each of the technologies and related products are described, and the equipment involved is introduced. Technology availability and current applications are also assessed. Capital costs, production costs, and environmental impacts are reviewed. In addition, the waste wood in the forests and on the beach in the Gisborne area is likely to have high moisture content and large sizes of small logs and large branches. Therefore, sizing and drying pre-treatment of the biomass are required for most of the technologies. However, with careful management, the heat for wood drying can be provided from the conversion processes.

All four conversion technologies are technically available to process the waste wood. Biomass combustion is the most mature heat or power generation technology. However, the heat generation requires local customers, who are most likely wood processors. Power generation is not very competitive in New Zealand with other renewable power generation such as hydro and geothermal power plants. Flue gas emissions and ash disposal need careful management. The fluidized bed combustion technology can handle relatively variable feedstock, including particle sizes and moisture content (up to 30%) compared to other conversion technologies.

Biomass gasification produces a clean gas (syngas) which can be further used for electricity generation and synthesis of gaseous and liquid fuels. Various gasification technologies are available, and some have been commercialised worldwide. The technology has high efficiency and low impacts on the environment due to the gas cleaning procedure. However, the capital and operation costs are relatively higher and the operation is more complicated than other conversion technologies. In addition, synthesizing gaseous and liquid fuels requires more capital investment and complex technologies.

The products (liquid, gases and bio-char) from biomass pyrolysis are complicated, although liquid (bio-oil) is the target product in most cases. The key challenge for biomass pyrolysis is the high cost that arises from wood pretreatment, heat supply, product separation and handling, and vapour quenching. The bio-oil can be directly used for boiler fuel or as engine fuel but needs upgrading if it is used for transport liquid fuel. The upgrading is again a complicated and expensive process. The environmental impacts are also an issue in dealing with the various products from pyrolysis.

The main product from biomass torrefaction is solid char which can be used as a substitute for coal in combustion or co-firing. Recently, solid char has been used in ironmaking to replace coke and coal. The energy requirement for the torrefaction is lower than pyrolysis and gasification due to the low operating temperatures. Since the torrefaction process is simple and low costs, it is the most promising technology if the solid char market is available.

The detailed assessment scores are presented in the following table in which each category is ranked from 1 to 5 (5 is the most favourable and 1 is the least favourable).

Technology	Products	Technology maturity	Product market demand	Costs	Environmental impacts	Total score
Combustion	Heat and power	5	3	3	3	**14**
Gasification	Syngas	4	3	2	5	**14**
Pyrolysis	Bio-oil and biochar	4	2	3	4	**13**
Torrefaction	Solid char	4	4	5	5	**18**

From the above analysis, torrefaction stands out as the most favourable technology for conversion of the waste wood in the Gisborne area.

Future work

If this recommendation is accepted, further work is suggested to conduct detailed feasibility analyses, including:

- Wood resource analysis provides data on the wood availability, distribution and characteristics.
- Market analysis for solid char use.
- Sizing the major processing units, and calculating energy/mass balances.
- Capital cost and operation cost calculations.
- Detailed analysis of the environmental impacts.

Acknowledgement

This project is funded by MBIE through Envionlink (UOCX2115). Authors thank Dr Murry Cave, Gisborne District Council, for his support and contribution.

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