

Biomass-fired CHP Systems: Current Status and Future R&D Needs

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ABSTRACT: The dramatic increase in global energy demand and the imminent fossil fuel shortage are pushing for an increase of biomass utilization in distributed electricity generation and domestic heating. Worldwide, biomass ranks fourth as an energy resource, providing approximately 14% of the world's energy needs following coal, oil and natural gas. In developing countries, biomass accounts for approximately 35% of the energy used. Currently a variety of biomass technologies have been developed, such as combustion, gasification and biochemical methods. Combustion is the most mature conversion technology utilized for biomass. Although biomass combustion releases some combustion pollutants, biomass is renewable and produces no net CO₂ emission in combustion. Due to the low sulphur and low nitrogen contents of biomass, substituting biomass for fossil fuels (particularly coal) can reduce SO₂ and NO_x emissions.

Biomass-fired combined heat and power (CHP) system is a great improvement of traditional biomass combustion utilization. This paper briefly reviews the biomass-fired power generation. State-of-the-art of biomass-fired organic Rankine cycle (ORC) combined heat and power systems are presented. Small-scaled domestic biomass-fired CHP (1-10 kWe) has a potential huge market, but has not been available on the commercial market. The authors of this paper are currently developing such kind of a CHP unit.

Key words: Biomass, biomass-fired CHP, organic Rankine cycle(ORC), turbine

1. INTRODUCTION

The uses of fossil fuels have given rise to environmental disasters and simultaneously fossil fuels are being depleted. Oil prices recently hit record highs of above US\$139 a barrel in June of 2008 and have doubled in less than a year. Both the climate change and energy crisis will eventually accelerate the investment and development of new energy and renewable energy, as well as new energy-saving technologies. Renewable energy sources mainly include solar energy

(solar thermal & photovoltaic), hydropower, wind power, biomass and geothermal energy etc. They are continuously phasing in the energy market due to their cleanness and sustainability. On the other hand, current electricity is mainly generated by large central power stations using, e.g. steam turbines which spin alternators to produce AC electricity we use at home. The steam is produced in a large boiler fuelled by coal, oil, natural gas or a nuclear reaction. The electricity generation efficiencies of power

stations are not high, typically only 30-40% of the thermal energy from the fuel is converted to electricity. The rest is lost as waste heat typically to the atmosphere using a cooling tower, or warms up the local river, lake or sea water from which the cooling water is drawn. To make matters worse, presently, on average, around 7.5% of the electricity produced is lost in transportation to its end users. In order to utilize the enormous waste heat, some power stations are designed and operated as CHP plants which generate power and supply heating to industrial processes and/or district heating network. The overall energy efficiency of a CHP plant can be up to 80% or higher. A micro-CHP system (1-10kW) on site can not only provide electricity and heating to its user, but also reduce the loss of heat and electricity in transportation. Biomass is traditional renewable energy source and currently ranks fourth as an energy source, providing approximately 14% of the world's energy needs. In developing countries, biomass accounts for around 35% of the energy used. Therefore, biomass CHP has huge application potential in developing countries. In many developed countries, energy consumption by buildings occupies nearly half of total energy, e.g. 46% in the UK, including heating, cooling, hot water and electricity. Biomass-fuelled micro-CHP is expected to be an alternative to the gas-fired boiler in developed countries in the future.

2. BIOMASS

Biomass is C-based organic materials that stem from plants, such as wood, crops and animal wastes. It stores chemical energy from sunlight by photosynthesis in bonds of carbon, hydrogen and oxygen molecules. Biomass energy has its advantage of continuity over the intermittence of solar energy and wind energy and so on. A variety of biomass technologies have currently been developed, such as combustion, gasification and biochemical methods. Combustion is the most mature

conversion technology utilized for biomass. Biomass combustion has different environmental impacts from that of fossil fuel. Although biomass combustion also results in combustion pollutants (CO, NO_x etc.), biomass is renewable and produces no net CO₂ emission in combustion. Due to the low sulphur and low nitrogen contents of biomass, substituting biomass for fossil fuels (particularly coal) can reduce SO₂ and NO_x emissions. The thermal energy resulted from biomass combustion can be used to generate electricity via engines or turbines etc.

Biomass feedstocks come from both primary and secondary sources. Primary sources are energy crops that have the sole purpose of energy production. Willow, miscanthus, reed canary grass and sorghum are a few examples of this category. Secondary sources of biomass feedstocks are mainly from agriculture activities and wastes, including straw, forest residues, sugar cane fibre, rice husks, waste vegetables, cardboard and paper, etc. Wood pellets and chips become very common biomass fuels in many parts of the world. They can be made from both primary sources and secondary sources of biomass feedstocks. There are a wide range of biomass boilers in the commercial market, designed to burn wood pellets and/or chips with automatic fuel feeding devices. The main components of wood are cellulose, hemicellulose and lignin, as shown in Fig. 1 [1], forming around 99% of the weight of the wood material [2]. Lignin has complex

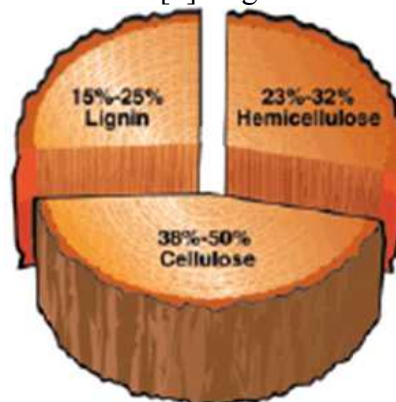


Figure 1: Wood constituents [1]

aromatic structures rich in carbon and hydrogen, and binds to cellulose fibres to harden and strengthen cell walls. Lignin is the main heat producing element from combustion. Compared with conventional fossil fuels, biomass has some advantages including:

- Biomass is far more widely available than fossil fuels, especially in developing countries.
- Biomass can be produced renewably and its production and use leads to nearly zero buildup of CO₂ in the atmosphere, because the CO₂ released in combustion is offset by the CO₂ extracted from the atmosphere during photosynthesis.
- Solid waste from biomass combustion is less a problem compared with coal combustion. Unlike coal ash, which may contain toxic metals and other trace contaminants, biomass ash may be used as a soil amendment to help replenish nutrients removed by harvest.
- Modernized biomass energy utilization can provide a basis for rural development and employment to help curb urban migration.
- Growing biomass for energy on deforested and degraded lands may restore these lands.

3. BIOMASS-FUELLED COMBINED HEAT AND POWER

Biomass-fuelled power generation and combined heat and power generation represent significant technology advances over traditional biomass combustion. There are four primary classes of biomass power generation systems: direct-fired, co-fired,

gasification-based, and pyrolysis-based [3, 4]. The direct-fired system using a biomass boiler is the simplest and the most mature technology that has been developed.

3.1 BIOMASS COMBUSTION

When biomass is combusted, the amount of heat released from a given mass of fuel can be determined by the following equation:

$$\text{Thermal Energy}(Q) = \text{Mass}(M) \times \text{Calorific Value of the Fuel}(CV) \quad (1)$$

Biomass feedstocks can contain significant amount of water. The amount of water in a feedstock is known as moisture content. The moisture content of a biomass feedstock, e.g. freshly cut grass, can be as high as 80%. However, many biomass boilers can only handle fuels with 20-30% moisture content. Water in the fuel lowers the calorific value of the fuel as the water must be evaporated first. The evaporation of water requires energy and causes an increase in fuel consumption for a given energy output. The combustion process of a solid biomass fuel involves several phases, as shown in Fig. 2: water evaporation, volatile release, combustion of char and combustion of volatiles. These phases may be overlapping. Physically, solid biomass fuels may be in various forms: pellets, chips, briquettes, etc. Fig. 3 shows some samples of solid biomass fuels. Table I shows the calorific values(CV) of biomass and other fuels [5]. From Table I, it can be seen that biomass has a significantly lower heating value than fossil fuels due to the generally higher moisture

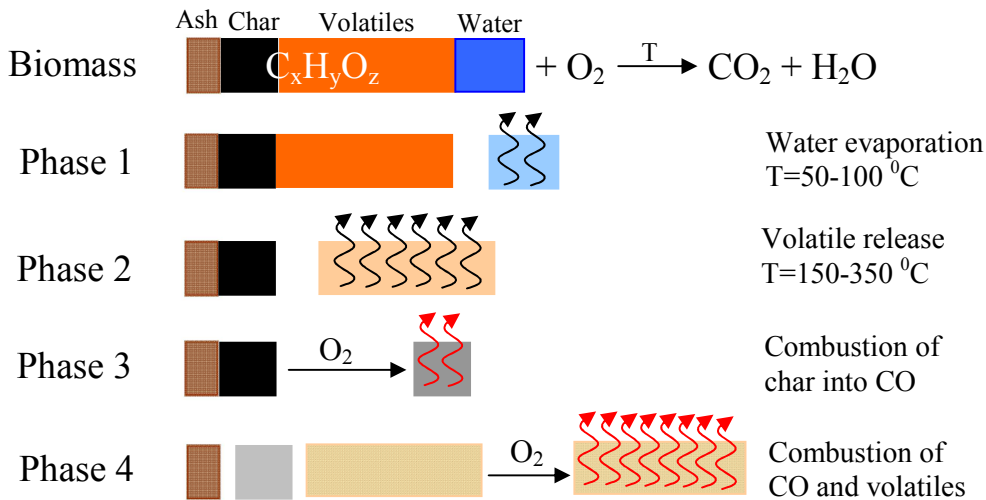


Figure 2: The wood combustion route [2]



Figure 3: Biomass fuel samples

Table I: Calorific values of biomass and other fuels [5]

Fuel	CV (MJ/kg)	Fuel	CV (MJ/kg)
Wood (green, 60% moisture)	6	Straw (as harvested, baled)	15
Wood (air-dried, 20% moisture)	15	Sugar cane residues	17
Wood (oven-dried, 0% moisture)	18	Domestic refuse (as collected)	9
Charcoal	30	Commercial wastes (UK average)	16
Paper (stacked newspapers)	17	Oil (petroleum)	42
Dung (dried)	16	Coal (UK average)	28
Grass (fresh-cut)	4	Natural gas (at supply pressure)	55

content and the high oxygen content as well. The relatively low biomass energy density can lead to significant fuel transportation cost, particularly for large-scale biomass power plants. Although small-scale biomass power generation units have lower electricity generation efficiencies than large-

scale power plants, they can be built near the biomass resources and the energy users. The market demand for micro-scale biomass-fuelled CHP system is widely predicted to increase over the coming years. The authors recently started to develop a first-of-its-kind 2 kW_e biomass-fired CHP

system which is suitable for applications in domestic buildings.

Efficient combustion of biomass can be achieved by a well-designed biomass stove or boiler. Fig. 4 shows an example of A micro-scale biomass boiler.



Figure 4: 25kW biomass boiler designed by Ashwell Engineering Services Ltd (UK) in the University of Nottingham

Biomass combustion does produce combustion pollutants, but it is less detrimental to the environment than fossil fuels because of its net zero CO₂ emissions. Biomass feedstocks may have a high content of alkali metals and chlorine, but they contain very little sulphur. Biomass combustion systems emit very little SO₂ which is a precursor of acid rain. Modern biomass combustion systems usually have equipped with some forms of flue gas cleaning to minimize the fouling and corrosion from particulate matter and alkali vapour.

3.2 ORGANIC RANKINE CYCLE (ORC)

One of the latest power generation technologies applied to small scale biomass-fired CHP systems is organic Rankine cycle (ORC). Unlike the traditional steam Rankine cycle, ORC uses an organic fluid with suitable thermodynamic properties, such as HFE7100, toluene etc., instead of water, as a working fluid. The suitable organic

working fluids are capable of efficiently exploiting low and medium temperature heat sources such as industrial waste heat, geothermal heat, solar thermal energy etc., to produce electricity in a wide range of power outputs (from a fraction of kW_e up to several MW_e). Choosing a good organic working fluid is a challenging task with the design of the cycle [6]. The selected organic working fluid must not only have suitable thermodynamic properties, but also provide the best match between the heat source and heat sink temperatures.

The working principle of the ORC is the same as that of conventional steam Rankine cycle. However, the ORC fluids are generally used at lower pressures and temperatures. Operations at lower pressures and temperatures increase safety, and also reduce the complexity and cost of ORC systems. In a biomass-fired CHP plant based on the ORC, thermo-oil or other suitable heat transfer fluids can be used as heat transfer medium in the biomass boiler to transfer the heat to the ORC cycle. The organic working fluid is heated in a heat exchanger (evaporator) rather than in the boiler because the organic working fluid can pose an explosive hazard. There is no need for high pressures in the boiler due to the liquid state of the heat transfer fluid. If the evaporative temperature of an organic working fluid, such as HFE7100 or HFE7000, is relatively low, water may be used as a heat transfer fluid in a biomass boiler, as the authors have done in their research project.

Fig. 5 shows a biomass-fired ORC-based CHP system developed by the authors in their ongoing research project. The organic working fluid is vaporised in the evaporator by the heating source (hot water) from the biomass boiler. The organic fluid vapour expands in the turbine and is then condensed using a flow of water in a shell-and-tube heat exchanger (alternatively, ambient air can be used for cooling). The condensed organic working fluid is pumped back to the evaporator thus closing the

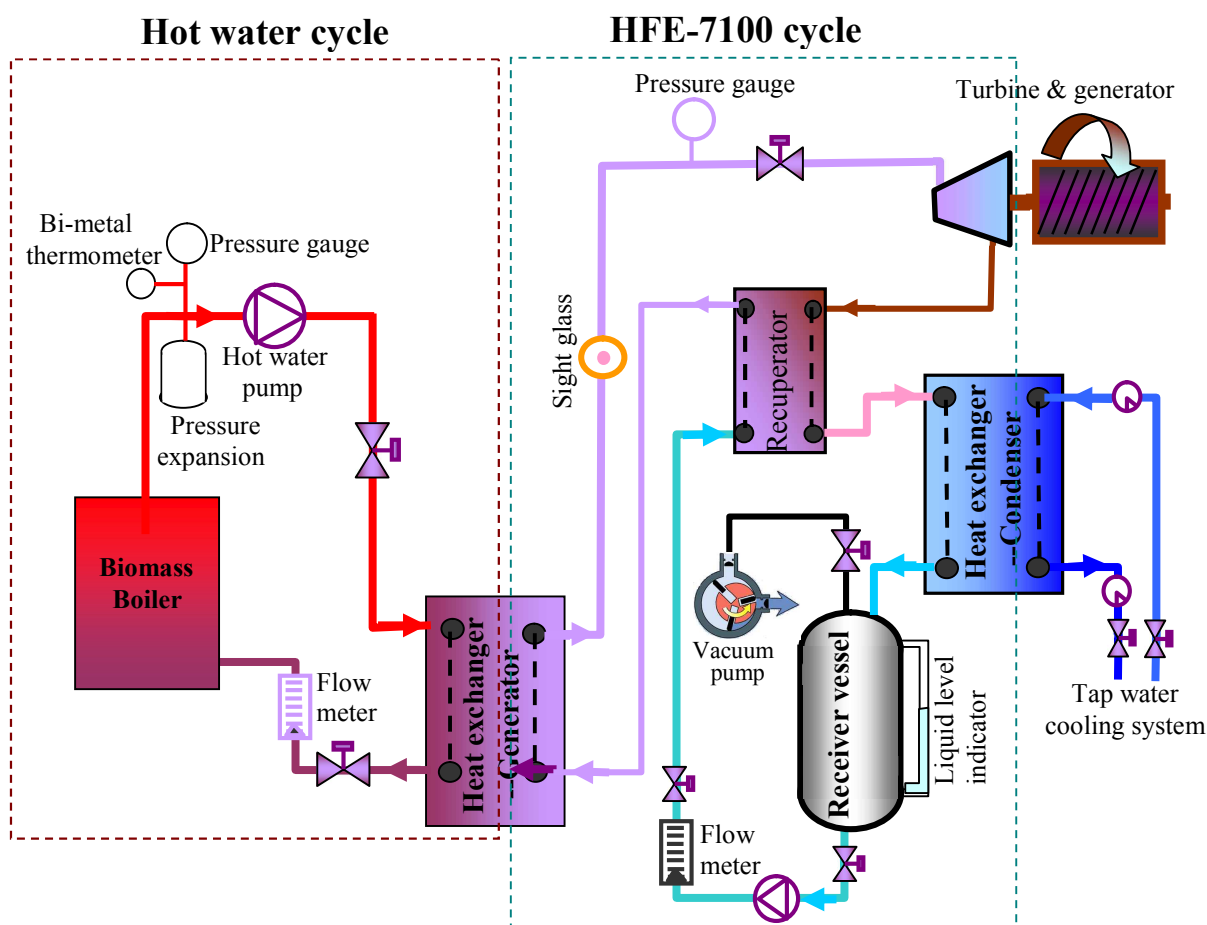


Figure 5: A biomass-fired ORC-based CHP system developed by the authors with their on-going research project

thermodynamic cycle. A recuperator is inserted into the loop to recover the heat from the turbine. Heating and cooling sources, as shown in Fig. 5, are neither directly in contact with the working fluid nor with the turbine. The warm water from the condenser may be used for underfloor heating and washing etc.

The main benefits of ORC-based power generation can be summarized as follows:

- High cycle efficiency;
- Low operational temperatures and pressures which lead to better safety and simpler systems;
- Low mechanical stress of the turbine due to low operational pressure, temperature and rotation speed which lead to long life and low cost for the turbine;
- No erosion of blades due to the absence of moisture in the vapour nozzles;

- Low rotation speed of the turbine allowing the direct drive of the electric generator without reducing gear;
- Good part load performance;
- Closed cycle operations for both the heating source and the working fluid.

The main disadvantage of an ORC-based CHP system is relatively low electrical conversion efficiency. However, as micro-CHP technologies are mostly designed to follow the thermal load, this low electrical efficiency becomes less of a drawback because significant thermal energy that can be recovered from the ORC-based CHP system [7].

3.3. BIOMASS-FIRED COMBINED HEAT AND POWER

In the four primary classes of biomass power generation systems, direct-fired

system is the simplest and the most mature, thus it is the least costly. Gasification-based biomass power generation is considerably more complex than biomass direct-fired power generation [8]. State of the art of biomass-CHP processes were reviewed by Pittermann [9]. Large and medium-scale CHP plant technologies based on biomass combustion have reached a high level of maturity. The steam turbine process is widely used in commercial large-scale biomass CHP plants ($>2000 \text{ kW}_e$). In the medium-scale power range (200-2000 kW_e) the Organic Rankine Cycle (ORC) process has proven its technological suitability and economic sustainability. For small-scale CHP plants ($<200\text{kW}_e$), the Stirling engine process has been successfully demonstrated [10, 11] and the hot air driven turbine system has been commercialized in recent years [12]. Micro-scale biomass-fuelled CHP units ($<10\text{kW}_e$) suitable for domestic applications have not been demonstrated or commercialized. The authors are currently developing a 2kW_e micro-scale biomass-fired ORC-based CHP system in the University of Nottingham.

Small and medium-scale biomass-fired ORC-based CHP plants have been in demonstration for a number of years. European countries have accumulated a lot of experiences in biomass-fired CHP systems and recent biomass-fired ORC-based CHP projects in Europe may be found in <http://www.turboden.com>. Two typical examples are presented as follows:

- (1) The first biomass CHP plant based on an ORC process in the European Union was run in 1999 in Admont, Austria. Its net electric power output is 400kW and electricity efficiency is 17.7% [13]. The heating medium is thermo-oil and working medium is silicon oil.
- (2) 1000 kW_{el} biomass-fired ORC CHP system in Leinz, Austria began its operation in 2003 [14]. Its net electric power output is 1 MW_e and electricity efficiency is 18.0% and thermal efficiency 80%. The heating

medium is thermo-oil and working medium is silicon oil.

Although a micro-scale biomass-fired CHP plant ($<10 \text{ kW}_e$) has relatively low electric efficiency (15%~20%), its overall CHP efficiency can reach 80% or higher. The novel ongoing research project by the authors aims to develop a first-of-its-kind 2kW_e biomass-fired ORC CHP system.

4. CONCLUSIONS

Biomass energy has been continuously phased in the energy market due to the ever-increasing global energy demand and the imminent fossil fuel shortage. Biomass is a wide range of available and affordable energy resources. Biomass resources are renewable and biomass combustion produces no net CO_2 emission. Although a variety of biomass conversion technologies have currently been developed, biomass direct combustion technology is the simplest and the most widely applied technology.

Biomass-fuelled combined heat and power system can efficiently convert biomass chemical energy into electricity and heat. Large-scale biomass CHP plants based on biomass combustion, mostly using steam turbines to produce electricity, have been in commercial applications for over a decade.

Organic fluids may be selected as a working fluid in a Rankine cycle due to its lower working pressure and temperature. Operations at lower pressures and temperatures increase safety, and also reduce the complexity and cost of ORC systems. Medium-scale biomass combustion ORC-based CHP plants (200-2000 kW_e) have recently been successfully demonstrated [13, 14]. However, micro-scale biomass-fuelled ORC-based CHP units ($<10\text{kW}_e$) for domestic applications have not been demonstrated or commercialized. Electricity generation efficiency for biomass-fired CHP system, especially micro-scale, is currently very low, so further investigations and demonstrations are imperative. The authors of this paper are currently developing a 2kW_e micro-scale

biomass-fired ORC-based CHP system in the University of Nottingham.

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