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Combined Heat and Power Systems for the Provision of Sustainable Energy from Biomass in Buildings

Andreas Ortwein[1,a]

[1]*Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Torgauer Straße 116, 04347 Leipzig, Germany*

Abstract. Against the background of greenhouse gases causing climate change, combined heat and power (CHP) systems fueled by biomass can efficiently supply energy with high flexibility. Such CHP systems will usually consist of one or more thermo-chemical conversion steps and at least one (the more or less separated) electric power generation unit. Depending on the main products of the previous conversion steps (e.g. combustible gases or liquids, but also flue gases with sensible heat), different technologies are available for the final power conversion step. This includes steam cycles with steam turbines or engines and different working fluids (water, organic fluids), but also combustion based systems like gas turbines or gas engines. Further promising technologies include fuel cells with high electric efficiency. When integrating such CHP systems in buildings, there are different strategies, especially concerning electric power generation. While some concepts are focusing on base load production, others are regulated either by thermal or by electric power demand. The paper will give a systematic overview on the combination of thermo-chemical conversion of biomass and combined heat and power production technologies. The mentioned building integration strategies will be discussed, leading to conclusions for further research and development in that field.

1 Introduction

Climate change caused by greenhouse gases is a major challenge for the world. At the world climate conference in Paris 2015, it was decided to keep the increase of global average temperature below 2 K. Substitution of fossil fuels like coal or natural gas by renewable energy is considered to be a key element of carbon dioxide emission reduction since energy consumption is one of the main contributors to greenhouse gas emissions.

Compared to solar and wind power, biomass has the potential to provide energy whenever it is needed. Especially for decentralized applications (e.g. in domestic and industrial buildings), combined heat and power (CHP) systems fueled by biomass are an interesting option and should be considered. Flexible operation of such systems in terms of power provision, heat-power-ratio and usage of advanced control strategies is a key issue for successful decentralized grid stabilization. This paper aims to give an overview on several CHP technologies and their application in buildings.

In section 2, a systematic overview on CHP technologies fueled by solid biomass will be given. Section 3 will present several technology examples for such systems including relevant research on their flexible operation. In section 4, several strategies on the implementation of such technologies into buildings will be discussed. Section 5 presents conclusions of the paper.

2 CHP Technologies for Solid Biomass

Combined heat and power systems for solid biomass usually consist of several process steps (see Figure 1).

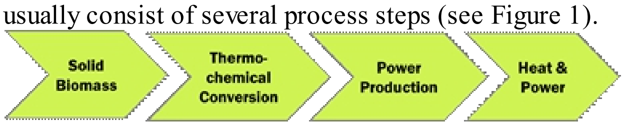

Figure 1. Process steps in combined heat and power from solid biomass.

In a first step, solid biomass is provided as a fuel for the process. Typical fuels to be considered are woody biomass, agricultural residues, and biogenic fractions of municipal solid waste (MSW).

In the next step, usually one or more thermo-chemical conversion processes (or primary conversion technologies) take place. This may include pyrolysis, gasification, combustion or more uncommon processes like hydro-thermal conversion [1]. Additionally, fuel preparation processes like chipping, pelletizing or briquetting might occur.

Pyrolysis is defined as the thermal decomposition of fuel without additional oxidation agent. The main products of pyrolysis include solid char and ash, liquid products, and gases (combustible and inert). The product composition depends on several parameters, including maximum conversion temperature, heating and cooling rate. [1]

Gasification is the process of under-stoichiometric oxidation of fuel. This is usually obtained by using

[a] Corresponding author: andreas.ortwein@dbfz.de

a gasification agent like air, steam or carbon dioxide. Depending on the process design, gasification as an endothermal process is allothermal (external heat necessary) or autothermal (heat is provided by partial oxidation of fuel). The main products of gasification include carbon monoxide, hydrogen and methane. Depending on the process and gasification agent, further product gas components include carbon dioxide, water (steam), nitrogen and several trace components. [1]

Full oxidation converts the fuel completely to carbon dioxide and water (steam). This is conducted by using an oxidation agent containing enough oxygen for complete oxidation. Depending on the process conditions, the flue gas also contains nitrogen and oxygen as well as several trace components and byproducts (e.g. carbon monoxide from incomplete oxidation). All energy content is converted to sensible heat.

Hydrothermal conversion of fuel takes place in hot, pressurized water. The specific conditions of the reaction medium allows for the processing of wet biomass (e.g. from municipal waste). Depending on the process conditions, different products can be provided, including biochar or synthesis gas. [1]

Depending on the product of the previous conversion step(s), especially hot flue gas and combustible syngas, the following process step consists of one or more power production technologies (or secondary conversion technologies) [2]. Typical examples for these are steam turbines or engines, Organic Rankine cycles (ORC), gas turbine or engines or fuel cells. More uncommon technologies include externally fired gas turbines (EFGT) and thermo-electric generators (TEG).

Finally, heat and power is provided and has to be integrated into the system. For electric power, this is usually done by injecting the electricity into the grid. Heat is transported to the users by hot water or steam (for higher temperatures), or is stored in hot water storages.

3 Technology and research examples

One of the most common technologies to provide heat and power from solid fuels is based on the usage of a water-steam-cycle. The basic (simplified) principle is given in Figure 2. In this process, water is evaporated under pressure within a boiler, heated by a furnace. The pressurized steam is fed to a steam turbine or steam engine, where power is generated from its relaxation. Further heat is extracted from the steam in heat exchangers for heating purposes, or in condensers.

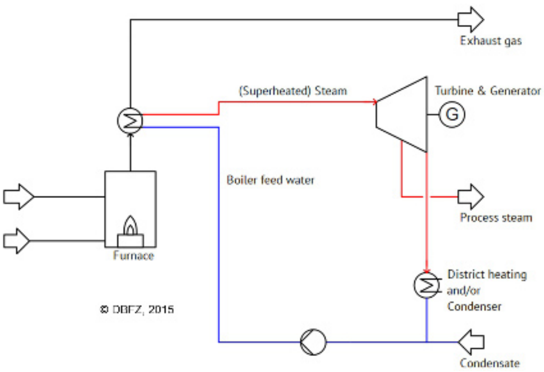

Figure 2. Basic principle of water-steam-cycle with steam turbine.

Decentralized applications of the steam-water-cycle have been developed within the last years, including a linear-piston based steam engine [3].

The basic principle for a combination of combustion and Organic Rankine Cycle (ORC) is given in Figure 3. Here, instead of water, an organic fluid is used for the thermal cycle. Thus, it is possible to optimize the process for specific conditions, e.g. combustion temperatures.

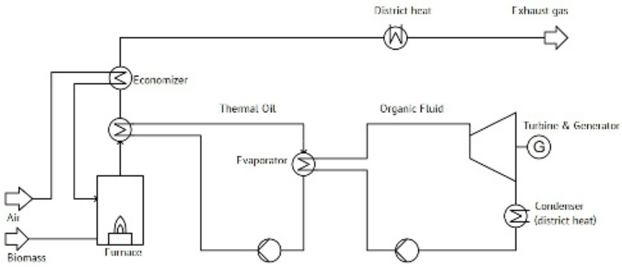

Figure 3. Basic principle of Organic Rankine Cycle.

Research on decentralized application of ORC on biomass combustion has been conducted during the last years, e.g. in [4]. In this specific case, instead of a turbine a modified compressor was used as a piston engine to overcome the technological and economic disadvantages of very small turbines.

Another example for CHP from solid biomass is the combination of gasification and gas engine. As one example, the flow scheme of a newly developed system for flexible power generation from solid biomass is given in Figure 4 [5]. Solid biomass is converted to a combustible gas within the gasifier. After a steam trap and filter, the product gas is mixed with air and fed to an adapted gas engine that can handle gases with relatively low heating values. Due to the changing gas composition, specific attention has been given to the management of ignition point [6]. Exhaust gas from the gas engine is cooled in a heat exchanger for further heat usage.

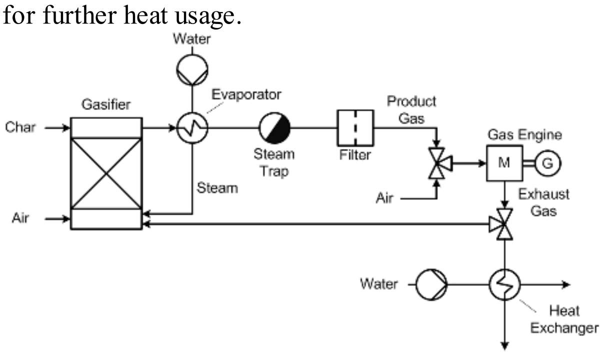

Figure 4. Micro-CHP system for solid biomass gasification in combination with gas engine.

The system shows high flexibility, allowing for high flexibility in power output while using solid biomass, see Figure 5 [5]. It was possible to change power output within less than one minute from 100% to 20%, and vice versa. Due to the good insulation of the gasification chamber, it was also possible to stop the system and restart within a certain period without long heat-up times.

Further research on small-scale CHP with gasifier and reciprocating engines is reported in literature, e.g. in [7–10].

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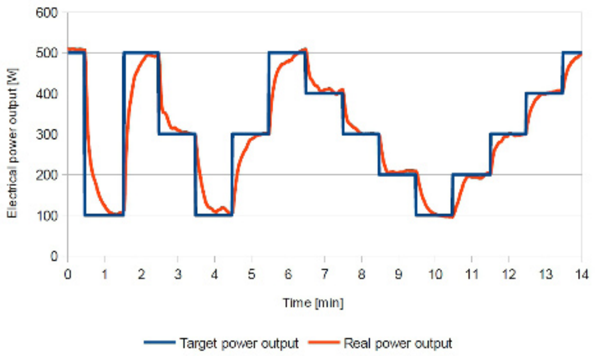

Figure 5. Fast alternation of power output in gasification based CHP.

4 Integration into buildings

To provide thermal energy and electrical power in a smart way for buildings, some criteria for the CHP system have to be fulfilled. Besides high efficiency and flexibility, it should be low in emissions (e.g. CO, NO_x, dust). Handling (fuel feeding, operation and cleaning) should be as easy as possible. A high degree in automation allows that several strategies can be considered depending on the frame conditions.

Heat-led operation is favored for many installations. Design of the system will usually be in such a way that it can provide a minimum heat load, with additional boiler or storage for peak load.

Base load or constant power production is also a common option and can be advantageous under certain conditions. By base load power production, a high number of full load hours of the system can be achieved, which leads to positive economic effects. For most systems, this also means continuous heat production. Depending on the building and its usage, this might require different heat usage strategies, including heat storage and seasonal operation.

Finally, electricity-led operation is the third main option for CHP integration. The system can be controlled to either produce power according to the demand of the local building, or in a way that it stabilizes the power grid. For both options, integration into communication systems and the implementation of advanced control technologies is important for optimized operation. This may not only include model predictive control of the CHP system itself, but also integration of weather forecast as well as self-learning algorithms that optimize system operation in the context of user behavior.

Against the background of increasing solar and wind power that bring stress to the electrical power grid, the last possibility has the potential to help stabilizing the grid with renewable energy.

For all options, proper transient simulation of the building [11] can help to design not only the technology, but also the control algorithms and the necessary communication infrastructure. Additionally, user satisfaction should be considered from the very beginning as one of the main promoters for the integration of renewable energies into buildings [12,13].

For owners of buildings, there are several aspects that have to be considered when integrating biomass-bases small-scale CHP technologies into buildings, including availability of technology and fuel [14].

5 Conclusions

There are numerous options to integrate combined heat and power systems fueled by solid biomass into buildings. This includes several thermo-chemical conversion processes like pyrolysis, gasification and oxidation as well as different options for electrical power generation like water-steam-cycles, ORC or gas engines.

Such systems can use different fuels including woody biomass, agricultural residues and biogenic fraction of municipal solid waste. By mechanical and thermal pretreatment (e.g. pyrolysis), fuel properties can be adapted to different CHP technologies. Products from gasification as first conversion step can be used in highly flexible technologies, while solid products are advantageous in terms of storability, grind ability and energy density.

Current examples show, that these technologies can provide thermal and electrical power in a flexible way to allow for different integration strategies (heat-led, base-load or electricity-led operation). For a small-scale gasification system with reciprocating engine, power output has been varied between 20% and 100% within less than one minute. Additional research is required to furtherly increase efficiency and flexibility.

Integration of CHP systems into building has to be conducted under consideration of thermal load, electricity consumption, user satisfaction and availability of technology and fuel.

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