

COGENERATION AND TRIGENERATION SYSTEMS

KOGENERACIJSKI IN TRIGENERACIJSKI SISTEMI

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Abstract

This paper describes a cogeneration plant using wood biomass as fuel. Forests cover 56% of the surface area in Slovenia, providing plenty of waste wood to be used as an energy source. Waste wood unsuitable for the lumber industry is ground into biomass of G50 size, which are chips of, measuring on average 3–5 cm and up to 8 cm. Biomass is dried in a drier to reduce its moisture content to 15%. Wood biomass gasification takes place in a gasifier. Carbon monoxide and hydrogen, gasification end products, are used as fuels for a boiler and two gas engines. The boiler heat is used for wood-drying purposes. The cogeneration plant uses a 1 MW Caterpillar generator set and a 0.45 MW MAN generator set. Cooling water waste heat of both gas engines and exhaust gases are used for heating the wood drier and the nearby residential area.

Povzetek

V članku je opisana kogeneracija, ki uporablja za gorivo lesno biomaso. Slovenija je dežela, katere površina je 56% pokrita z gozdovi zato ima veliko odpadnega lesa, ki se lahko uporablja kot gorivo. Odpaden les, ki je za industrijsko rabo neuporaben zmeljemo v biomaso granulacije G50. To so sekanci velikosti do 8cm, ki v povprečju merijo od 3-5cm. Biomasa se posuši v sušilcu na vlažnost do 15%. V uplinjevalcu se lesna biomasa uplini. Končni produkt uplinjevanja je ogljikov monoksid in vodik, ki se uporabljata kot gorivo za kotel in plinska motorja. Toplota kotla se uporablja za sušenje lesa. Kogeneracija ima en Caterpillar genset moči 1 MW in MAN genset moči 0,45 MW. Odpadno toploto hladilne vode obeh plinskih motorjev in izpušnih plinov uporabimo za ogrevanje sušilnice lesa in bližnje stanovanjsko naselje.

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1 INTRODUCTION

The demand for thermal and electrical energy is typically met by supplying power from the local distributor's network and generating heat by burning fuel in a furnace or a boiler. Cogeneration technology, however, provides significant fuel saving and reduction in the emissions of harmful substances into the environment. Cogeneration or combined heat and power (CHP), [1], is the concurrent production of two or more types of useful energy from a single primary energy source. The two most frequently used forms are mechanical energy, used for powering an electric generator, and thermal energy used for heating or for the technological requirements of production in the pharmaceutical and other industries. Trigeneration differs from cogeneration in that waste heat is used for both heating and cooling, typically in an absorption refrigerator, [2, 3].

Large amounts of heat are released into the atmosphere via steam condensers and cooling towers during the operation of conventional power plants. In cogeneration systems using internal combustion engines, however, the waste heat of engines and exhaust gases may be exploited. Most of such thermal energy can be used to meet the demand for heat. The efficiency of a conventional power plant, ranging between 30% and 40%, is increased to 80%-90% efficiency in a cogeneration system.

For the production of mechanical energy that drives an electric generator, gas turbines are usually used for power levels over 5 MW, while for lower levels a diesel or spark ignition engine is used. Diesel engines are used with diesel fuel or biofuel, [4, 5]. A spark ignition engine is used in the case of natural gas, [6]. Another variant is the wood gasifier CHP plant in which wood pellets or wood chip biofuel is gasified in a zero oxygen, high temperature environment; the resulting gas is then used to power the gas engine.

In Slovenia, approximately 2% of electricity is generated using cogeneration systems. Industrial and district heating networks ensure the growth of such technology. Today, many existing systems are outdated, providing myriad opportunities for reconstruction. One concept for the development of households and industry envisages the construction of several small biomass units and the application of natural gas as a fuel with a relatively extensive distribution network. This concept has good development potential in Slovenia [7]. Forests cover 56% of the surface area in Slovenia, which has, as a result, a lot of waste wood to be turned into biomass. Biomass is an important fuel in Slovenia. Biomass is gasified in a gasifier, and the wood gas obtained is used to power the gas engine.

The most efficient example of the use of biomass is the energy plant in Güssing, Burgenland, Austria, where the total energy demand of the village is met by biomass. Significant power plants include a 2 MW electric power 4.5 MW thermic wood gas generator power plant in Güssing and in nearby Strem, a 0.5 MW electric power 0.5 MW thermic biomass gasification power plant using green silage re-growing raw materials, such as grass, clover, maize and sunflower [13].

This paper describes a biomass cogeneration system as the first of this type in Slovenia (Fig. 1), located in Ruše.

2 DESCRIPTION OF A WOOD BIOMASS COGENERATION

Waste wood ground into biomass is used as input fuel. The schematic diagram of a wood CHP plant and the fuel flow are shown in Fig. 2. Wood gas, generated in a gasifier, is used as a fuel for the boiler, producing heat for the wood-drying facility. Most of the wood gas is used for powering the Caterpillar and MAN gas engines. The former drives the 1MW_e and the latter the 450kW_e electric generator. The electricity thus generated is sold to the Slovenian power grid at a price of EUR 0.27/kWh, with the Slovenian government subsidising energy-related facilities with total efficiency exceeding 80%. The generated heat of engine exhaust gases, cooling water, and heat from intercoolers is used for the wood-drying facility and the heating of a nearby residential area. The heat is sold at a price of EUR 0.02/kWh.



Figure 1: Cogeneration plant

3 DRIER

Waste wood unsuitable for lumber industry is in the form of stem wood. The wood has the following composition: 40–50% cellulose, 20–30% lignin, and 20–30% components such as carbohydrates, fats, tannin and minerals.

It is first dried in the open air and then transported by means of a forklift truck to a grinder mill, where it is ground to G50 biomass, i.e. 8 cm chips, mostly measuring 3-5 cm. Subsequently, the biomass is transported to a weekly storage container. It serves as a reservoir with a system that spreads the biomass evenly over the entire storage surface. At its bottom, the container is fitted with a system of movable rods, moving the biomass, by means of a hydraulic pump, towards the

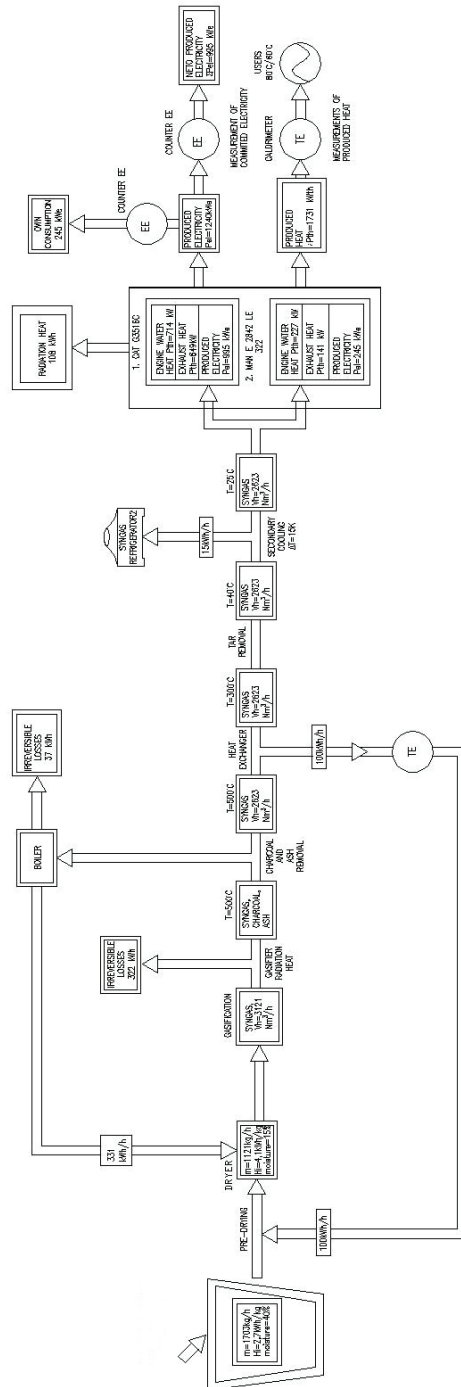


Figure 2: Diagram of the plant and the fuel flow

outlet from the weekly storage container, where the biomass is discharged onto a conveyer belt. From there, the biomass is fed into a screening machine, where it is divided into three parts: the smallest are used for the biomass boiler and transported by the conveyer belt into the storage container, while the oversized ones are reground. The G50 biomass is transported via the screening-storage container conveyer belt into the biomass storage area. The lower heating value (LHV) of this biomass is 2.7 kWh/kg and its moisture content 40%. The biomass is transported from here into a drier for pre-drying. The heat for biomass drying is partly provided by the boiler and partly by the heat exchanger, cooling the wood gas from 500 °C to 300 °C (Fig. 2). The biomass is dried to 15% of moisture content in the drier, and its lower heating value (LHV) increases to 4.1 kWh/kg. The chemical composition of such biomass is 50% carbon, 42% oxygen, 6% hydrogen, 1% methane, 1% nitrogen and minerals. The wood biomass is fed from the drier, where pre-drying takes place, into the gasifier.

4 GASIFICATION AND WOOD GAS PREPARATION SYSTEM

A gasifier is the device in which sawdust and G50 chip gasification process takes place. The cylindrical gasifier is a downdraft unit, which means that the wood biomass and wood gas flow in the same direction, i.e. from the top to the bottom. The biomass in the form of wood chips is fed by means of conveyer belts and an elevator into a dispenser with double pneumatic flaps. From the dispenser, it enters the upper part of the gasifier via a longitudinal fixed grid.

Wood biomass gasification involves five phases [8, 9]:

1. Biomass drying phase takes place in the drying zone, where biomass is dried at temperatures from 100 °C to 150 °C. Moisture in the biomass evaporates and in the reduction zone it reacts with carbon to form hydrogen and carbon monoxide.
2. Pyrolysis of the dried biomass takes place in the pyrolysis zone at temperatures from 200 °C to 500 °C. Pyrolysis is the application of heat to biomass, in an absence of air, in order to break the biomass down into charcoal and various tar gasses and liquids. It is essentially the process of charring. The biomass breaks down into solids, liquids and gases at temperatures of over 250 °C. The solids that remain are charcoal. The gases and liquids that are produced are collectively called tars.
3. The heat needed for drying, pyrolysis and reduction is obtained through combustion in the combustion zone. Tar gases and charcoal from pyrolysis are used as a fuel. The necessary amount of air for combustion is blown into the combustion zone through nozzles. The cracking of biomass also takes place in this zone. Large molecules, such as tar, break down into lighter gas molecules, whereby heat is intensely supplied. The tar gas break-down process is crucial for proper internal combustion engine operation. Heavy molecules of tar gases are condensed at a spark plug and at valves of the engine and cause engine malfunction. Combustion and cracking are running from 800 °C to 1200 °C. The carbon content in the biomass is the highest and, therefore, the basic reaction in the combustion zone is:



4. Reduction in a gasifier is accomplished in the reduction zone by passing carbon dioxide or water vapour across a bed of red hot charcoal. The carbon in the hot charcoal is highly reactive with oxygen; it has such a high oxygen affinity that it strips the oxygen off water vapour and carbon dioxide, and redistributes it to as many single bond sites as possible. The oxygen is more attracted to the bond site on the carbon than to itself; thus, no free oxygen can survive in its usual diatomic O_2 form. All available oxygen will bond to available carbon sites as individual oxygen until all the oxygen is gone. The reduction reactions are



Through this process, carbon dioxide is reduced by carbon to produce two carbon monoxide molecules, and H_2O is reduced by carbon to produce H_2 and carbon monoxide. Carbon monoxide and hydrogen are end products of a gasifier and used as a fuel for the boiler and both gas engines. The gasifier capacity is 2623 Sm^3 of wood gas per hour. The temperature of the gas at the outlet from the gasifier is 500°C . The gasifier waste heat flow is 322 kW .

A reactor retains charcoal to reduce some wood gas components due to a higher heating value (LHC), while it allows the ash at the bottom of the gasifier to be discharged. The gasifier is fitted with a grid at the bottom, through which fuel dosing takes place. The gasifier is insulated by a thick layer of thermal concrete and fitted with connections for the lateral air inlet and outlet of gasification products towards the boiler and the engine. Syngas thus generated is too hot and too dirty to enter the internal combustion engines; as a result, it requires adequate prior treatment.

A portion of the gas is fed to the boiler (Fig. 2), generating heat for biomass drying. The gas outlet heat power is 368 kW . The remaining amount of gas (2623 Nm^3) enters the gas-water tubular heat exchanger where it is cooled down from 500°C to 300°C . The heat exchanger thermal capacity is 100 kW and is used for biomass pre-drying (Fig. 2). Gas is fed from the heat exchanger to a tar removal device. Tar has to be removed from gas as it causes coking at engine spark plugs and plugging of the wood gas-air mixing valve nozzles. After 1200 hours of engine operation, traces of tar and tar combustion products were observed on the engine valves. Wood gas then enters the tubular heat exchanger, where it is cooled down to 40°C (Fig. 2). This heat is lost in the process; heat losses amount to 344 kW . The gas then enters the dust remover and a series of fine filters. During cogeneration, the filters are replaced on a weekly basis. The filtered gas enters a wood gas cooler 2, where it is cooled down to 25°C . Gas cooling takes place in the water-wood gas heat exchanger. Afterwards, the filtered and cooled down gas enters the gas engines.

5 GENERATOR SET

Cogeneration has two generator sets, a Caterpillar G CAT 3516C with mechanical power of 1030 kW and electric power of 995 kW and an ER MAN E 2842 LE 322/LSA 47.2 S5 with mechanical power of 270 kW and electric power of 245 kW (Fig. 2).

The Caterpillar ER CAT 3516C engine exhaust gas flow rate is 7254 kg/h and outlet temperature 394 °C. The gases are cooled down to 120 °C in the tubular heat exchanger. The heat exchanger thermal capacity is 649 kW.

The engine is water cooled. The cooling water flow rate is 42 m³/h; cooling water also cools the engine oil. The cooling system outlet water temperature is 90 °C and the inlet temperature 70 °C. The cooling water heat is transformed in a plate heat exchanger into the wood cooling facility heat. The heat exchanger thermal capacity is 694 kW.

The wood gas-air mixture is cooled down in the intercooler from 80 °C to 40 °C and additional 20 kW of thermal power is obtained. The total thermal power of the engine cooling water and the mixture cooling is 714 kW.

The intercooler cooling water flow rate is 20 m³/h.

The total thermal power of the Caterpillar G CAT 3516C generator set is 1363 kW and its total efficiency 83%.

The electric generator efficiency is 96.7 %, $\cos \phi=0.9$.

According to the available information, this is the first Caterpillar generation set application using wood gas.

The ER MAN E 2842 LE 322/LSA 47.2 S5 engine exhaust gas mass flow rate is 1302 kg/s, with the outlet temperature of 440 °C. Exhaust gases are cooled down to 120 °C in the tubular heat exchanger. The heat exchanger thermal power is 141 kW.

The engine is water cooled. The cooling water flow rate is 15.2 m³/h; cooling water also cools the engine oil. The cooling system outlet water temperature is 90 °C and the inlet temperature 70 °C. The cooling water heat is transformed in a plate heat exchanger into the wood cooling facility heat. The heat exchanger thermal capacity is 227 kW.

The total thermal power of the ER MAN E 2842 LE 322/LSA 47.2 S5 generator set is 368 kW.

The efficiency of the Leroy Sommer LSA 47.2 S5 electric generator is 93.8%, $\cos \phi=0.8$.

The generator set total efficiency is 82%.

The total electric power of both generator sets is 1240 kW, and the total thermal power used for heating the drier is 1731 kW.

The outlet water temperature for the wood drier or heating is 80 °C, the inlet temperature is 60 °C, and the mass flow rate 20.6 kg/s.

6 ECONOMIC ANALYSIS OF COGENERATION

The wood biomass cogeneration investment costs totalled €6 million [10, 11, 12]. Out of the total electric power of 1240 kW, 245 kW of power is used for own consumption and 995 kW sold into the Slovenian power grid at a price of EUR 0.27/kWh, subsidised by the Slovenian government. Heat is fully sold at a price of €0.02/kWh. The electricity sold generates the highest revenue. The cogeneration plant operates at full capacity 80% of time in a year or 8760 hours per year or 7008 hours of operation. The revenue from the sold electricity is

$$7008 \text{ hours} \times 995 \text{ kW} \times \text{€}0.27/\text{kWh} = \text{€}1,882,699.20.$$

The revenue from the heat sold is

$$7008 \text{ hours} \times 1731 \text{ kW} \times \text{€}0.02/\text{kWh} = \text{€}242,616.96.$$

The total revenue is

$$\text{€}242,616.96 + \text{€}1,882,699.2 = \text{€}2,125,316.16.$$

The annual operating costs are estimated at 2% of the value of investment or €120,000.

The cogeneration plant employs eight people. The costs of their salaries and personal equipment needed for the maintenance of the facility amount to €200,000 per year.

The primary energy consumption of both cogeneration engines at 82% efficiency is

$$(P_{\text{el}} + P_{\text{heat}})/\eta = (1240\text{kW} + 1731\text{kW})/0.82 = 2971\text{kW}/0.82 = 3623\text{kW}. \quad (6.1)$$

The biomass consumption of both engines by taking into consideration the below indicated biomass lower heating value (LHC) of 2.7 kWh/kg and 40% moisture content is

$$\dot{m} = \frac{P_{\text{tot}}}{H_i} = \frac{3623}{2.7 \cdot 3600} = 0.372 \frac{\text{kg}}{\text{s}} = 1431 \text{kg/h} \quad (6.2)$$

The overall consumption of the system of both engines and the boiler, generating the heat for biomass drying and pre-drying and for covering the losses is 1703 kg/h of biomass. The yearly consumption of biomass at 7008 operating hours is 11,934,624 kg. The annual biomass cost at the price of €0.05/kg is €596,731.2.

The total efficiency of the entire plant when the consumption of heat for wood drying and pre-drying is taken into account and for powering other auxiliary units is

$$\frac{P_{\text{el}} + P_{\text{heat}}}{H_i \cdot \dot{m}} = \frac{1240 + 1731}{2.7 \cdot 3600 \cdot 0.473} = 0.646 \quad (6.3)$$

The operating costs, costs of employee salaries and of their equipment and the wood biomass price are

$$€200,000 + €120,000 + €596,731.2 = €916,731.2.$$

The cogeneration net annual revenue amounts to

$$€2,125,316.16 - €916,731.2 = €1,208,584.96.$$

The investment in cogeneration is repaid in

$$\frac{6,000,000}{1,408,584.96} = 4.96 \text{ years}$$

7 DISCUSSION

This paper describes a cogeneration plant for the production of electricity and heat used in a wood drying facility. The heat may also be used for heating in a nearby residential area. Waste wood, in particular stem wood unsuitable for industrial applications, is the fuel. The cogeneration plant described in this paper is the first in Slovenia and one of the first in the world in the power range of up to 1.5 MW, operating on biomass.

Waste wood comprising 40–50% cellulose, 20–30% lignin, and 20–30% components such as carbohydrates, fats, tannin and minerals is first dried in the open air and then transported into a grinder mill where it is ground to G50 biomass, i.e. wooden chips with the size of up to 8 cm. The lower heating value (LHC) of the biomass is 2.7 kWh/kg and its moisture content 40%. Biomass is dried in the drier to a moisture content of 15% prior to entering the gasifier to increase its LHC to 4.1 kWh/kg. The biomass prepared in this fashion has the following chemical composition: 50% carbon, 42% oxygen, 6% hydrogen, 1% methane, and 1% nitrogen and minerals.

The gasifier is of a downdraft model and produces 3121 Nm³ of wood gas per hour, containing carbon monoxide and hydrogen as the burning substance. The two gas engines consume 2623 Nm³ and the rest the boiler generating heat for wood drying.

Electricity is generated by two generator sets: a Caterpillar G CAT 3516C (995 kW electric power, 1363 kW thermal power, 83% total efficiency), and an ER MAN E 2842 LE 322/LSA 47.2 S5 (245 kW electric power (Fig. 2), 368 kW thermal power, 82% total efficiency). The cogeneration system consumes 245 kW of power for its own use.

The generated power is sold to the Slovenian power distribution grid at a price of €0.27/kWh, subsidised by the Slovenian government. Heat is fully consumed in the wood drier. The price of the heat sold is low at only €0.02/kWh. Technically speaking, the sale of heat for sanitary water heating and heating of the nearby residential area is also possible. Unfortunately, heat for district heating purposes can only be sold in winter.

The total efficiency of the facility is 64.6% and the investment is to be repaid in five years.

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Nomenclature:

(symbols)	(symbol meaning)
H_i	lower heating value (LHC) [J/kg, kWh/kg]
P_{el}	electrical power [W, kW]
P_{heat}	thermal power [W, kW]
\dot{m}	mass flow [kg/s]
P_t	total power [W, kW]