Cost – benefit analysis of biogas CHP (Combined Heat and Power) Plant

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***Abstract* - Paper presents cost – benefit analysis of biogas CHP plant. It will cover the technical characteristics of different biogas CHP plant with emphasis on energy efficiency and costs for biogas power plants. Comparison of electrical efficiency and overall (CHP) efficiency for different types of biogas power plants will also be presented.**

I. INTRODUCTION

Increase of organic waste today is a one of big problems. If this organic waste isn't properly aggregated, then that is a big environmental issue. Quality care and bringing the waste in anaerobic digestion process can be managed very effectively. Anaerobic digestion is the fermentation of organic material without the presence of oxygen. That is a process of getting biogas. The resulting biogas is used for production of heat or/and electricity. It is interesting to investigate a case of getting both, electricity and heat (combined heat and power - CHP). In this article the possible ways of using biogas as fuel for combined production of heat and power will be described. The efficiency (power generation efficiency and CHP efficiency) for different technologies will be compared. In addition, the comparison of specific investment ($ / kW_e) for various technologies will be made. Following CHP technologies will be described in short terms: gas turbines, micro turbine, reciprocating engine and steam turbine.

II. KNOWN CHP TECHNOLOGIES

A. Gas turbines

Gas turbines are available in sizes ranging from 500 kilowatts (kW) to 250 megawatts (MW). Gas turbines can be used in power-only generation or in combined heat and power (CHP) systems. They produce high-quality exhaust heat that can be used in CHP configurations to reach overall system efficiencies (electricity and useful thermal energy) of 70 to 80 percent.

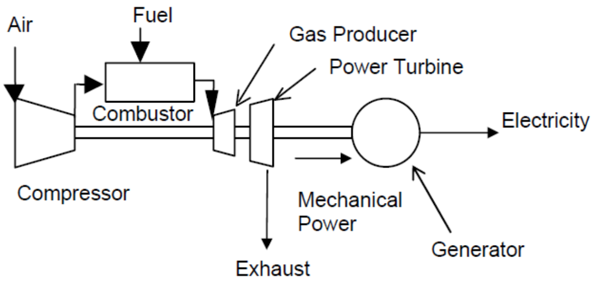

Figure 1 Components of a Simple-Cycle Gas Turbine

TABLE I
TYPICAL PERFORMANCE PARAMETERS FOR GAS TURBINE CHP*

Cost & Performance Characteristics[1]	**System 1**	**System 2**	**System 3**	**System 4**
Electricity Capacity [kW]	1 150	5 457	10 239	25 000
Basic installed cost [$/kW][2]	3324	1314	1298	1097
Complex installation with SCR[$/kW][3]	5221	2210	1965	1516
Electrical efficiency (%) HHV	21,27	27,72	28,44	34,3
CHP Characteristics				
Total CHP efficiency [%] HHV[4]	66,3	69,8	68,4	70,7
Effective electrical efficiency (%)[5]	49	58	57	63

*For typical systems commercially available in 2007. Source: Energy and Environmental Analysis, Inc. an ICF Company[2]

[1] Characteristics for "typical" commercially available gas turbine generator system. Data based on: Solar Turbines Saturn 20 – 1 MW; Solar Turbines Taurus 60 – 5 MW; Solar Turbines Mars 100 – 10 MW; GE LM2500+ – 25 MW;
[2] Installed costs based on CHP system producing 10,34bar saturated steam with an unfired heat recovery steam generator, no gas compression, no building, no exhaust gas treatment in an uncomplicated installation at a customer site.
[3] Complex installation refers to an installation at an existing customer site with access constraints, complicated electrical, fuel, water, and steam connections requiring added engineering and construction costs. In addition, these costs include gas compression from 3,8bar, building, SCR, CO catalyst, and CEMS.
[4] Total Efficiency = (net electric generated + net steam produced for thermal needs)/total system fuel input
[5] Effective Electrical Efficiency = (CHP electric power output)/(Total fuel into CHP system – total heat recovered/0.8);

Gas turbine systems operate on the thermodynamic cycle known as the Joule (Brayton) cycle. In a Joule (Brayton) cycle, atmospheric air is compressed, heated, and then expanded, with the excess of power produced by the expander (also called the turbine) over that consumed by the compressor used for power generation. The power produced by an expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through the device. In figure 1 components of a simple-cycle gas turbine are presented.

When power less than rated is required from a gas turbine, the output is reduced by lowering the turbine inlet temperature. In addition to reducing power, this change in operating conditions also reduces efficiency. Figure 2 shows a typical part-load derate curve. Emissions are generally increased at part load conditions, especially at half load and below.

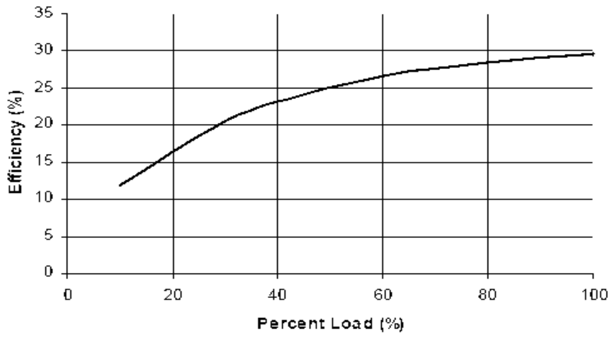

Figure 2 Part Load Power Performance (Source: EEA/ICF)

B. *Micro-turbines*

Micro-turbines are small electricity generators that burn gaseous and liquid fuels to create high-speed rotation that turns an electrical generator. They are available in sizes from 30kW to 250kW. Like a gas turbines they can be used for electricity generation only or in CHP systems. In CHP systems waste of heat is useful for hot water produce, heating and other thermal needs. In figure 3 scheme of micro turbine-based CHP system is shown.

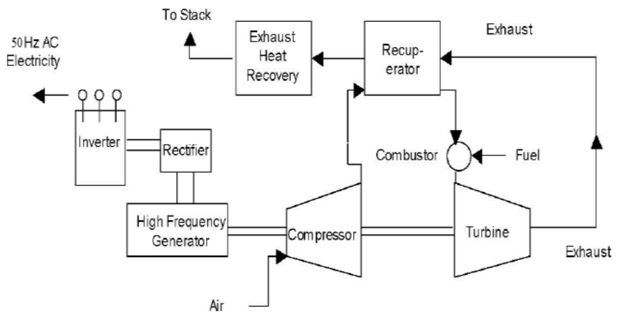

Figure 3 Microturbine-Based CHP System (Single-Shaft Design)

Similar to gas turbines, they can be used for electricity generation only or in CHP systems. In CHP systems waste of heat is useful for hot water produce, heating and other thermal needs.

Figure 4 presents the part load power performance for micro turbine.

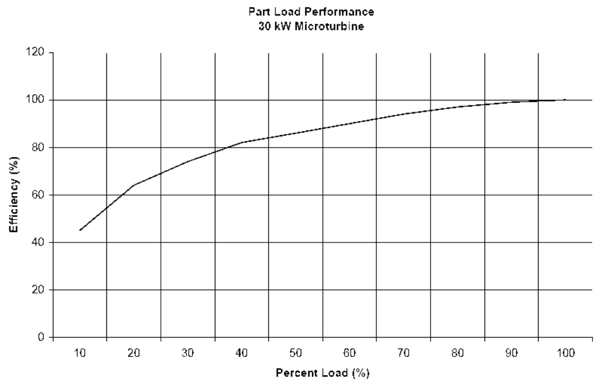

Figure 4 Micro-turbine Part Load Power Performance

Microturbines also operate on the same thermo dynamical cycle, known as Joule (Brayton) cycle. In table 2 are shown the typical performance characteristics.

TABLE II
MICROTURBINE CHP - TYPICAL PERFORMANCE PARAMETERS*

Cost & Performance Characteristics[6]	**System 1**	**System 2**	**System 3**
Electricity Capacity [kW]	30	65	250
Package cost [$/kW][7]	1290	1280	1410
Total installed cost [$/kW][8]	2970	2490	2440
Electrical efficiency (%) HHV	22,6	24,6	26,09
CHP Characteristics			
Total CHP efficiency [%] HHV[9]	63,8	71,2	64,0
Effective electrical efficiency (%)[10]	46,7	58,9	49,6

* For typical systems commercially available in 2007. Source: EEA/ICF

[6] Characteristics presented are representative of "typical" commercially available or soon to be available microturbine systems. Table data are based on: Capstone Model 330 – 30 kW; Capstone C65 – 65kW, Ingersoll Rand Power MT250 – 250 kW ;
[7] Equipment cost only. The cost for all units except for the 30 kW unit includes integral heat recovery water heater. All units include a fuel gas booster compressor;
[8] Installed costs based on CHP system producing hot water from exhaust heat recovery. The 70 kW and 100 kW systems are being offered with integral hot water recovery built into the equipment. The 30 kW units are currently built as electric (only) generators and the heat recovery water heater is a separate unit. Other units entering the market are expected to feature built in heat recovery water heaters;
[9] Total Efficiency = (net electric generated + net steam produced for thermal needs)/total system fuel input ;
[10] Electrical efficiencies are net of parasitic and conversion losses. Fuel gas compressor needs based on 0,069 bar inlet supply.

C. Reciprocating engine

There are two basic types of reciprocating engines:

- Spark ignition reciprocating engine and
- Compression ignition reciprocating engine.

Spark ignition engines are using gaseous fuel (natural gas, biogas, landfill gas, propane,…), while compression spark engines (diesel engines) are using diesel fuel or heavy oil. Spark ignition engines are interesting for because they can operate on biogas. They are available in range size from few kW to over 5MW. Reciprocating engines are well suited to a variety of distributed generation applications. Reciprocating engines start quickly, follow load well, have good part load efficiencies, and generally have high reliabilities. In figure 5 is shown scheme of Closed-loop recovery system.

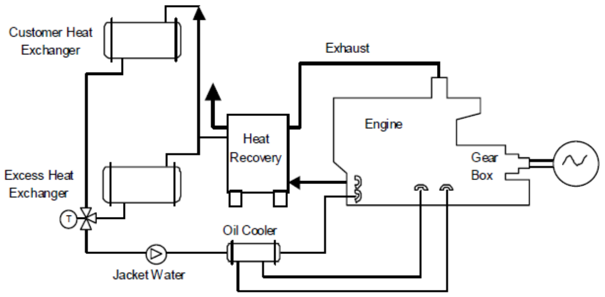

Figure 5 Closed – loop recovery system

Table 3 shows typical performance parameters for gas CHP.

D. Steam turbines

Steam turbines are one of the most versatile and oldest prime mover technologies still in general production used to drive a generator or mechanical machinery. Power generation using steam turbines has been in use for about 100 years, when they replaced reciprocating steam engines due to their higher efficiencies and lower costs. Steam turbines are available in sizes from 50kW to several hundred MWs. Unlike gas turbine and reciprocating engine CHP systems where heat is a byproduct of power generation, steam turbines normally generate electricity as a byproduct of heat (steam) generation. They are widely used for CHP. In figure 6 are shown primary components of steam turbine system. Steam turbines operate on Rankine thermo-dynamical cycle. Table 4 shows typical performance parameters for steam turbine CHP.

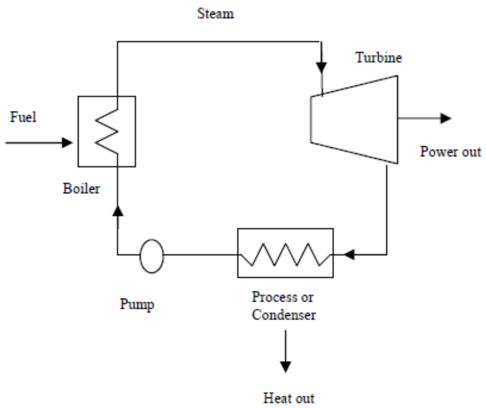

Figure 6 Components of a boiler/steam turbine system

TABLE III
GAS CHP – TYPICAL PERFORMANCE PARAMETERS

Cost & Performance Characteristics[11]	**System 1**	**System 2**	**System 3**	**System 4**	**System 5**
Base load Electricity Capacity [kW]	100	200	800	3 000	5 000
Total installed cost [$/kW][12]	2210	1940	1640	1130	1130
Electrical efficiency (%) HHV	28,4	34,6	35	36	39
CHP Characteristics					
Total CHP efficiency [%] HHV	79	78	79	73	74
Effective electrical efficiency	0,78	0,76	0,78	0,68	0,69

* For typical systems commercially available in 2007. Source: EEA/ICF

TABLE IV
STEAM TURBINE CHP – TYPICAL PERFORMANCE PARAMETERS*

Cost & Performance Characteristics[13]	**System 1**	**System 2**	**System 3**
Nominal Electricity Capacity [kW]	500	3 000	50 000
Equipment cost [$/kW]	658	278	252
Total installed cost [$/kW][14]	1117	475	429
Turbine Isentropic Efficiency (%)[15]	50	70	80
Generator/Gearbox Efficiency (%)	94	94	97
CHP Characteristics			
Total CHP efficiency [%] HHV	79,6	79,5	79,7
Effective electrical efficiency (%)	75,6	75,1	77,8

* For typical systems commercially available in 2008.Source: EEA/ICF

[11] Characteristics for "typical" commercially available natural gas engine gensets. Data based on: IPower ENI85 – 85 kW; GE Jenbacher JMS 312 GS-N.L – 625 kW; GE Jenbacher JMS 320 GS-N.L – 1050 kW; Caterpiller G3616 LE – 3 MW; Wartsila 5238 LN - 5 MW; Energy use and exhaust flows normalized to nominal system sizes.

[12] Installed costs based on vendor quote or on CHP system producing hot water from exhaust heat recovery (138^{0}C exhaust from heat recovery heat exchanger), and jacket and lube system cooling;

[13] Characteristics for "typical" commercially available steam turbine generator systems. Steam turbine data based on information: TurboSteam, Inc.

[14]Equipment cost includes turbine, gearbox, generator, controls and switchgear; **boiler and steam system costs are not included.**

[15] The Isentropic efficiency of a turbine is a comparison of the actual power output compared to the ideal, or isentropic, output. It is a measure of the effectiveness of extracting work from the expansion process and is used to determine the outlet conditions of the steam from the turbine.

III. COMPARISON OF TECHNOLOGIES

In this chapter comparison of efficiencies for all types of facilities are presented. We will compare the efficiency of electricity generation, efficiency of CHP and specific investment for all four types of facilities for 250 kWe, 1000 kWe and 5000kWe power plants.

Figure 7 shows the efficiency for a 250 kW facilities. As we can see, efficiency of electricity production for 250kW facilities is highest for the systems with reciprocating engine and micro turbine, while on the other hand, the lowest in the system with a steam turbine and a gas turbine. The highest CHP efficiencies are for facilities with steam turbines, while the lowest are for micro-turbine facilities.

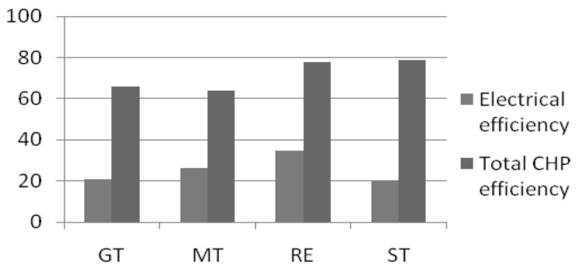

Figure 7. Comparison for 250kW$_e$ facilities

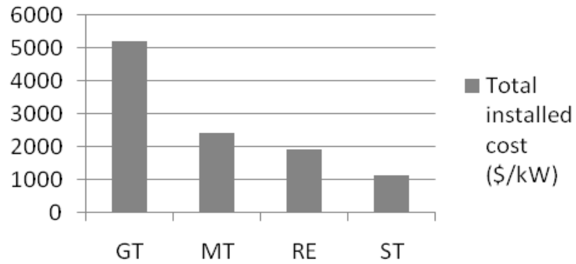

Figure 8. Comparison of cost for 250kW$_e$ facilities

As for the cost of investment, lowest costs there are for systems with a steam turbine, as presented on Figure 8, followed by the facilities with reciprocating engine and micro turbine, while the facilities with gas turbine have the largest investment costs.

Facilities of 1000 kW we cannot realize with the micro turbines, therefore, there aren't data for this facility in Figures 9 and 10.

For 1000kW facilities we can observe that the highest efficiency of electricity generation have facilities with reciprocating engine, while the highest CHP efficiency have facilities with a steam turbine. Facilities with gas turbine have the lowest electrical and CHP efficiency.

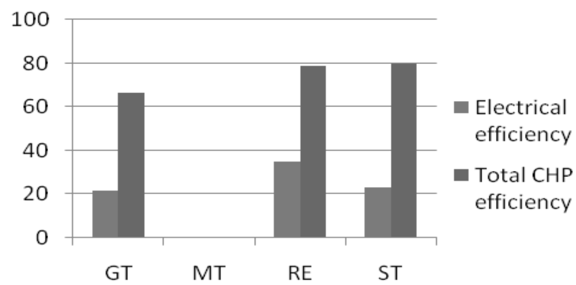

Figure 9. Comparison for 1000kW$_e$ facilities

In Figure 10 we can see that specific investments are the lowest for steam turbines and reciprocating engines, while for gas turbines they are much higher (twice).

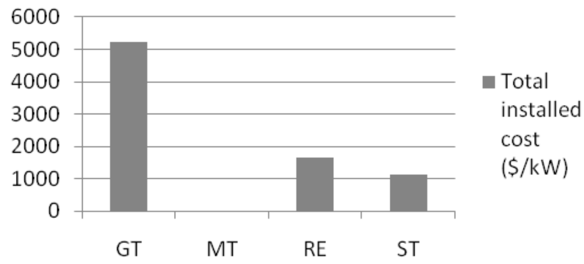

Figure 10. Comparison of cost for 1000kW$_e$ facilities

Also the facilities of 5000kW we cannot realize with micro turbines. In Figures 11 and 12 we can observe that the highest efficiency of electricity production have the facilities with reciprocating engine and steam turbine, while the lowest have facilities with gas turbine.

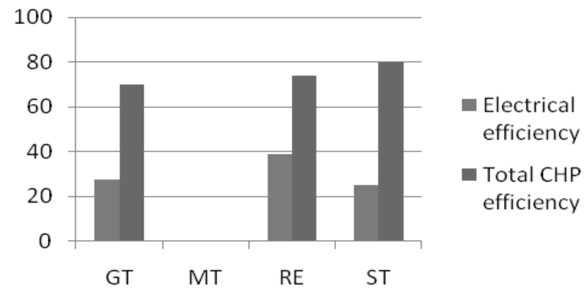

Figure 11. Comparison for 5000kW$_e$ facilities

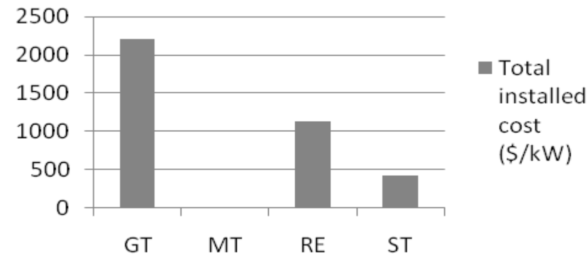

Figure 12. Comparasion of cost for 5000kW$_e$ facilities

IV. CONCLUSION

This paper presented the possible technologies for the exploitation of biogas. The micro-turbine can be used only for power to 250 kWe. According to data for individual facilities, we can conclude that best efficiency of electricity generation have facilities with a reciprocating engine. As far as cogeneration, the best efficiency we can realize with facilities with a steam turbine.

As the best solution for rated power up to 5000 kW, exhibit facilities with reciprocating engine, since they have the highest efficiency (electricity production), CHP efficiency is close to CHP efficiency of facilities with steam turbines. They are also the most sustainable one since their specific investment costs are among the lower.

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