ENERGY AND ECONOMIC EFFECTS OF CHP WITH COMBINED TECHNOLOGIES OF CORN COBS GASIFICATION AND GAS TURBINES

by

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This paper presents the performance and economic analysis of the gas turbine with co-firing gas from corn cob gasification and natural gas. Adiabatic and non--adiabatic expansion in the turbine is considered. The analysis is performed parametrically with corn cob gasification gas and natural gas ratio. The volumetric energy content of fuels with different share of gas from the corn cob gasification, therefore, with different calorific values, is compared by means of the Wobbe Index. In energy and economic analyses, the following configurations are dealt with: single manifold, dual manifold, and separate gas systems.

Key words: *co-firing, corn cob gas, gas turbines, co-generation, calculations and economic predictions*

Introduction

The most effective way of biomass utilization is its transformation into fuel for power production. Gas turbines fueled by gas from biomass gasification are a promising option for electricity generation from renewable resources. Gasification of agricultural origin biomass and further mixing of obtained gas with natural gas enables the use of biomass as a secondary energy at a wide territory, as well as, simple connection to different energy consumption sectors [1]. Gas turbines, due to stable flame through combustion, are very flexible and thus, suitable for biomass utilization. One possible way of introducing gas from biomass gasification is biomass integrated gasification/gas turbine cycle (BIG/GT) with co-firing of gas derived from biomass and natural gas, which is analyzed in the reference [2], where modeling results show that no significant modifications or de-rating is necessary if natural gas content in the mixture is higher than 35-50%.

The problem of burning LCG in gas turbines of different designs is the subject of interest of various researchers and turbine designers. However, in published literature, the term LCG is used for gas of NCV in ranges from 13.0 to 22.84 MJ/sm^3 [3], 18 to 21 MJ/sm^3 [4], 5.96 MJ/sm^3 [5], 2.5 to 4 MJ/sm^3 [6], or generally LCG as in [7]. The configuration of a multiple fuel system related to the calorific value of gas fuel that is intended for burning in a gas turbine is analyzed in [7]. In the analysis, the following configurations are treated: single manifold, dual manifold (fig. 1), and separate gas systems (fig. 2).

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The volumetric energy content of different gas fuels, caused by, for example, different calorific values, can be compared by means of the Wobbe index (*WI*). The general expression for *WI* is given in reference [3, 8], while in [7], the expression that includes the temperature effect on the gas compressibility is given. The ratio of *WI* of the fuel for which the turbine is designed and *WI* of the LCG fuel indicates the necessary change in pressure drop if no design changes are made in fuel supply, injection and control systems.

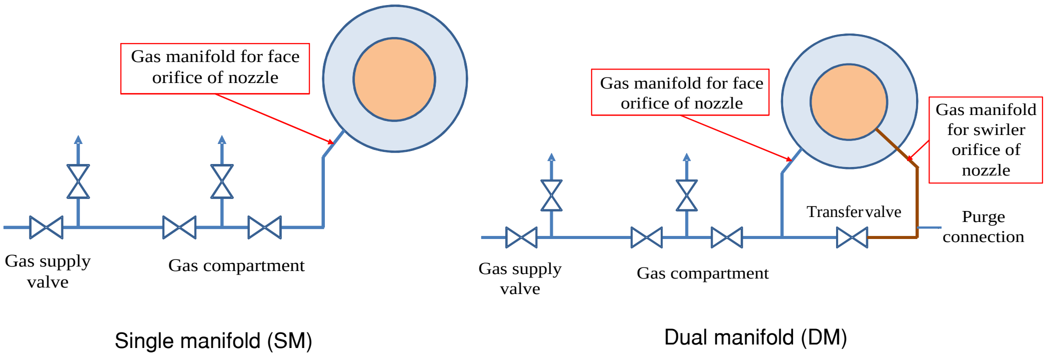

Figure 1. Schematic presentation of dual manifold gas system based on [7]

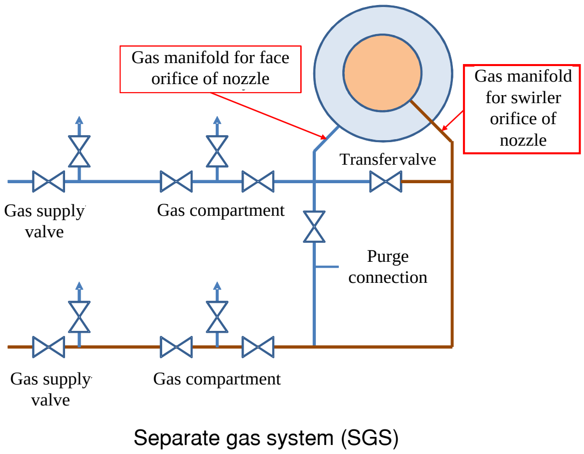

Figure 2. Schematic presentation of separate gas systems based on [7]

Gases with relatively close Wobbe indices can, in principle, run in the same fuel control system. On the contrary, gases with unlike Wobbe indices need different configurations of fuel system including necessary nozzle pressure drop. In [7], where *WI* is defined by the eq. 1, ±5% is quoted as possible variation in *WI* that can handle some of standard fuel gas control systems without adjustments; however, in reference [3], eq. 2, that range is ±10%.

$$WI = LHV/\sqrt{(SD)} \tag{1}$$

$$WI = LHV/\sqrt{(T_g \times SD)} \tag{2}$$

For the calculation of co-firing with the mixture of gas from corn cob gasification and natural gas, a simulation model is developed. The basis for the use of developed simulation model is briefly explained in the following section.

Mathematical model

A mathematical model for energy transformation in a gas turbine includes models for each of the processes that are performed in the facility. The main processes are: (1) compression of air from the pressure at the compressor inlet to the final pressure at its outlet, (2) combustion of injected fuel in the combustion chamber and (3) expansion of combustion products in the gas turbine. It is also possible to take into consideration additional processes such as air flow from the air inlet through air filters to compressor inlet and from compressor outlet to combustion chamber inlet, fuel flow from the gas supply valve to the nozzle, and combustion products flow from the turbine outlet through the silencer into the environment. The main indicators of overall energy transformation are efficiency η_{GT} and specific work L_{GT} of gas turbine facility.

The variation in fuel quality mostly influences processes of combustion and expansion of combustion products in the gas turbine. The combustion of gas fuels, with Wobbe Index different than the one for which the gas fuel system and entire gas turbine have been designed, represents an off-design regime for the gas turbine. In such case, it is, in principle, not possible to maintain design turbine inlet temperature (T_{IT}). New operation regime of the gas turbine with new parameters of energy transformation processes including new T_{IT} can be estimated by numerical simulation. The simulation model should comprise both possible expansion processes in gas turbines: adiabatic process when no cooling of turbine blades is applied and non-adiabatic expansion process when cooling of blades exists. For analyzing gas turbine off-design regime with corn cob gas and natural gas co-firing, a simulation model based on references [9-12] is developed. The general approach in mathematical modeling of processes in gas turbine facility when pure natural gas is combusted is based on those explained in [9], and in this paper, it is called a *method for overall expansion*.

The first step in this analysis is the calculation of efficiency of the gas turbine facility which burns natural gas as a fuel. For this calculation, usual values of the main turbine, or gas turbine cycle parameters, such as turbine inlet temperature and pressure ratio, are used. The mathematical model is formed for hypothetical 6 MW four stage gas turbine for the research project purpose; therefore the general approach to analysis of the gas turbine parameters is required. The applied parameters of hypothetical gas turbine facility are following: inlet gas turbine temperature is 1400 K, compressor pressure ratio is 8, compression efficiency 0.85, low heating value of natural gas is 34032 kJ/m^3, gas turbine efficiency is 0.87, and temperature at the economizer inlet is 378.15 K. The mathematical model is verified by comparison of obtained results with results from literature, when similar gas turbine is applied.

In the calculation procedure for the efficiency of adiabatic and non-adiabatic expansions in case of natural gas combustion, the main variable is the ratio of fuel mass flow and air mass flow at the combustion chamber inlet, *b*. The variation of fuel and air mass flow ratio affects the gas specific heat capacity c_{pg}. The value is calculated through several iterations until stable amount is reached and after that, the efficiency of the gas turbine facility is calculated.

Gas from corn cobs gasification (biogas) has low content of methane and therefore, its heating value is very low. For the utilization of pure corn cob gas, it is necessary to make certain modifications of the gas turbine. Sometimes, it is not possible at all to combust pure biogas in the gas turbine designed for natural gas. In such cases, co-firing of natural gas and biogas is one of promising solutions.

In case of firing a fuel mixture of natural gas and corn cob gasification gas in the gas turbine, the turbine inlet temperature and the numerical value of b are unknown variables. In case of constant air mass flow from the compressor discharge to the combustion chamber, the numerical value of b depends on the value of fuel gas flow into the chamber. It is assumed that volumetric flows of natural gas and the mixture of natural gas and corn cobs gasification gas in the gas fuel system are equal to the volumetric capacity of considered gas fuel system. Therefore, in case of firing the mixture of natural gas and corn cobs gasification gas, the value of unknown variable b can be calculated. In order to adopt the basic mathematical model for simulation of gas turbine facility operation described in [9], for combustion of mixture of gas from corn cob gasification and natural gas, it is necessary to introduce certain modifications in some of the basic equations. The value of gas turbine inlet temperature when mixture of gases is combusted is calculated iteratively with new value of variable b_{M}:

$$b_M = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} = \frac{c_{p_{\mathrm{gM}}}^{(1-3)} \cdot (T_{\mathrm{ITM}} - T_0) - c_{p_a}^{(1-2)} \cdot (T_{2t} - T_0)}{\eta_{CC} \cdot LHV - c_{p_{\mathrm{gM}}}^{(1-3)} \cdot (T_{\mathrm{ITM}} - T_0)} \tag{3}$$

Gas turbine work specified by air flow is calculated with parameters for gas mixture combustion:

$$L_{iT} = \bar{c}_{p_{\mathrm{gM}}}^{(3-4)} \cdot T_{\mathrm{ITM}} \cdot \left(1 - \Pi_T^{\eta_{pT} \cdot \frac{R_{\mathrm{gM}}}{\bar{c}_{p_{\mathrm{gM}}}^{(3-4)}}}\right) \tag{4}$$

Specific turbine work when non adiabatic expansion is applied is defined as sum of the work during expansion of gas mixture combustion products and cooling air expansion work:

$$L_T = \bar{c}_{p_{\mathrm{Mmix}}}^{(3-4)} \cdot \frac{(1 - z_p - r_a) \cdot (1 + b_{\mathrm{M}}) \cdot T_{ITM} + r_a \cdot C \cdot T_{at}}{(1 - z_p - r_a) \cdot (1 + b_M) + r_a} \cdot \left(1 - \Pi_T^{\eta_{pT} \cdot \frac{R_{\mathrm{Mmix}}}{\bar{c}_{p_{\mathrm{Mmix}}}^{(3-4)}}}\right) \tag{5}$$

The turbine outlet temperature for non-adiabatic expansion of gas mixture combustion products is calculated by the equation:

$$T_{OT\mathrm{M}} = T_0 + \frac{(1 - z_p - r_a) \cdot (1 + b_{\mathrm{M}}) \cdot \overline{c_{p\mathrm{M}}}^{(1-3)} \cdot (T_{I\mathrm{TM}} - T_0) - r_a \cdot \overline{c_a}^{(1-2)} \cdot (T_{2t} - T_0) - [(1 - z_p - r_a) \cdot (1 + b_{\mathrm{M}}) + r_a] \cdot L_{iT}}{[(1 - z_p - r_a) \cdot (1 + b_{\mathrm{M}}) + r_a + z_p] \cdot \overline{c_{p\mathrm{M}a}}^{(4-1)}} \tag{6}$$

Gas specific heat values are functions of gas composition and temperature; therefore, they are also unknown variables. Numerical values of specific heat are calculated according to the equation presented in references [10, 11] in the iteration process.

After a number of iterations, upon reaching the stable value of turbine inlet temperature for corresponding value of the variable b, the efficiency calculation is finally performed. Results of performed numerical simulations are briefly explained in the following section.

Generated electricity is calculated multiplying the nominal gas turbine power with number of operating hours per year. It is assumed 6000 h/a as for the facility that operate in base load. Generated heat is calculated multiplying the obtained heat in economizer with number of operating hours. For heat generation it is assumed 1730 h/a, as a conservative approach.

Results of numerical simulation

The analysis in this paper is performed for gas from corn cobs gasification based on available experimental data published in references [13,14]. Gas obtained in the process has very low calorific value and thus belongs to so called low calorific gases (LCG). Calculations are performed with different ratios of gas obtained in the process of corn cob gasification and natural gas as known parameter. The volumetric energy content of different gas fuel mixtures at different temperatures is compared by means of *WI*.

Developed simulation models are used for the analysis of energy effects at electricity and heat cogeneration using gas turbines fired with the mixture of natural gas and the gas from corn cob gasification. The analysis is performed parametrically with the mass ratio of corn cob gasification gas and natural gas (CGR) as a parameter. In the analysis, gas turbine design features are different. Three configurations of multiple gas fuel systems are considered, such as: single manifold, referred to as SM, dual manifold, referred to as DM (fig. 1) and separate gas systems, referred to as SGS (fig. 2). Two types of energy transformation processes in gas turbines are also considered: adiabatic, referred to as AD and non-adiabatic, referred to as NAD.

Regarding energy generation, pure electricity generation and cogeneration of electricity and heat for district heating system and/or for the industrial consumers are considered. For all these variants, basic Joule (Bryton) cycle is assumed.

In fig. 3, the variation of *WI* as function of CGR is presented. The field of possible operation for three considered configurations of fuel gas systems is also indicated. Light field corresponds to SM, medium to DM and dark field to SGS.

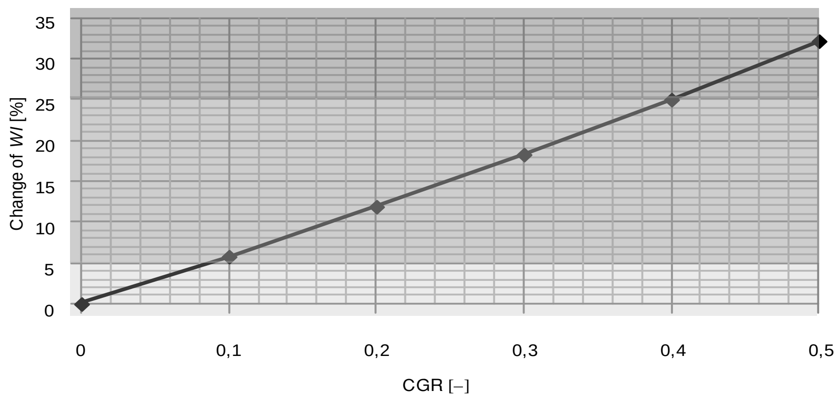

Figure 3. Variation of *WI* as function of CGR, for the considered configurations of fuel gas system

In fig. 4, the variation of calculated value of turbine inlet temperature as function of CGR is presented, for considered configurations of fuel gas systems. The design value of T_{IT} equal to 1400 K is arbitrarily selected for the purpose of off-design process analysis. In case of single manifold gas fuel system with increasing content of gas from corn cobs gasification in the fuel gas mixture, T_{IT} falls significantly. Dual manifold gas fuel system enables maintaining designed value of T_{IT} in CGR range of 0 to 10%, while separate fuel gas systems enable maintaining designed value of T_{IT} in CGR range of 0 to 40%.

Increased portion of gas from corn cob gasification in fuel gas mixture causes reduction of turbine inlet temperature, as well as the reduction of turbine exhaust temperature and therefore, appropriate reduction in efficiency as can be seen in figs. 4 and 5.

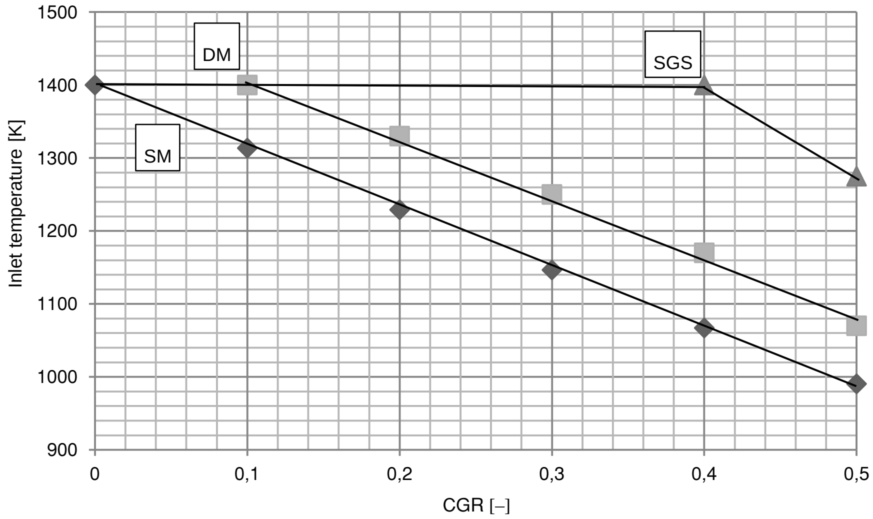

Figure 4. Variation of calculated value of T_{IT} as function of CGR for considered configurations of fuel gas systems

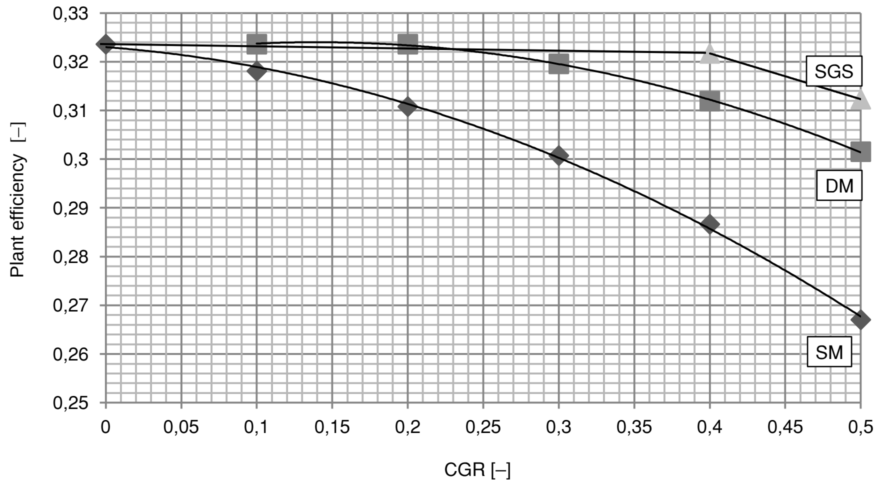

Figure 5. Efficiency versus CGR in case of adiabatic expansion for considered configurations of fuel gas systems

Data in fig. 5 correspond to adiabatic expansion. The reduction of efficiency is the greatest in case of single manifold gas fuel system and the smallest in case of separate gas fuel systems (fig. 5). For example, when gas from corn cob gasification participates with 50% in fuel gas mixture in case of separate gas fuel systems, the reduction of efficiency amounts to about 1.3 percent points while, in case of single manifold system the reduction of efficiency amounts to about 5.8 percent points. On the other hand, technical solution with separate gas fuel systems is the most costly out of three considered gas fuel systems.

In case of cogeneration of steam, heat recovery steam generator (HRSG) is used, while in case of cogeneration of hot water, appropriate boiler is used. In this analysis, it is assumed that in each design variant, gas temperature at the outlet of HRSG or at the outlet of water boiler amounts to 378 K while turbine inlet temperature is 1400 K.

Although the efficiency of plant is significantly affected by the ratio of gas from corn cobs gasification and natural gas, the cogeneration process enables significant increase of the gas turbine plant efficiency as can be seen in fig. 6. This efficiency increase is the basis for an economic gain of whole plant comprising both corn cobs gasification plant and gas turbine cogeneration plant. Curves in fig. 6 correspond to single manifold gas fuel system.

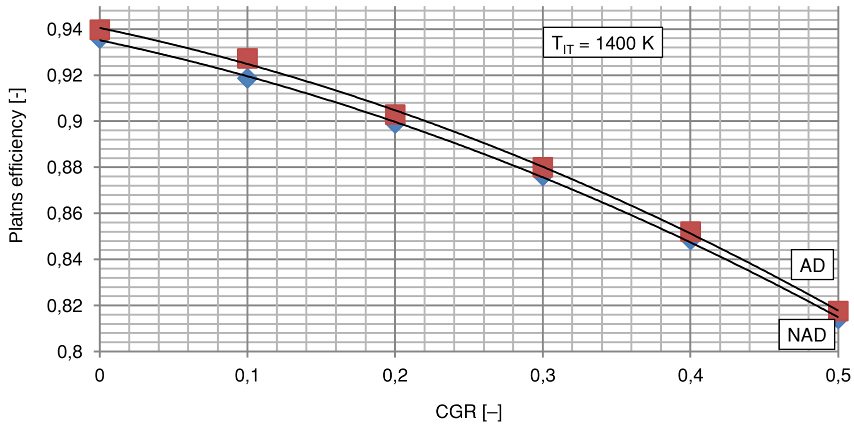

Figure 6. Cogeneration plant`s efficiency as functions of CGR for adiabatic and non-adiabatic expansion processes

Economic and viability analysis

Designed unit for corn cob gasification is described in [15]. The type and technical features of the gas generators are described in references [13, 14]. Nominal power of the selected hypothetical gas turbine, at generator terminals is 6 MW. The amount of average annual power generation is presented in fig 7.

In order to conduct techno-economic analysis for different configurations of gas turbines regarding gas fuel system, we have made several assumptions. It is assumed that all produced heat is delivered to end users. The investment and estimation of costs are based on data from reference [16] and vendor quotes. The costs for the consultant's services, licensing, commissioning and miscellaneous purposes are also included. Total investment costs for single manifold, dual manifold and separate gas systems are 5.1051, 5.1817, and 5.2838 Mil€, respectively.

It is assumed that investment maintenance costs are 11% of the total investment value after every six years of operations. In addition, annual maintenance costs of 0.5 c€/kWh for produced electricity are taken into account as well as annual administrative and other costs of 6% of the produced value [16]. The techno-economic assessment conducted in [17] concludes that it is possible to produce syngas at the cost of about 23 c€/sm3. In [15], it is calculated that in Serbian condition, the corn cob gas price is 0.021 €/m3 with 4900 kJ/m3 net calorific value (NCV). Serbian average natural gas price is used. In the calculation of expected income from sold electricity, current Serbian feed-in tariffs are used (electricity from natural gas cogeneration - 8.89 c€/kWh, electricity from power plants from different kinds of biogas is 12.31 c€/kWh) and income from delivered heat is calculated using current market price of heat from district heating systems. Based on presented estimations, assumptions and expectations, the following graphs are made.

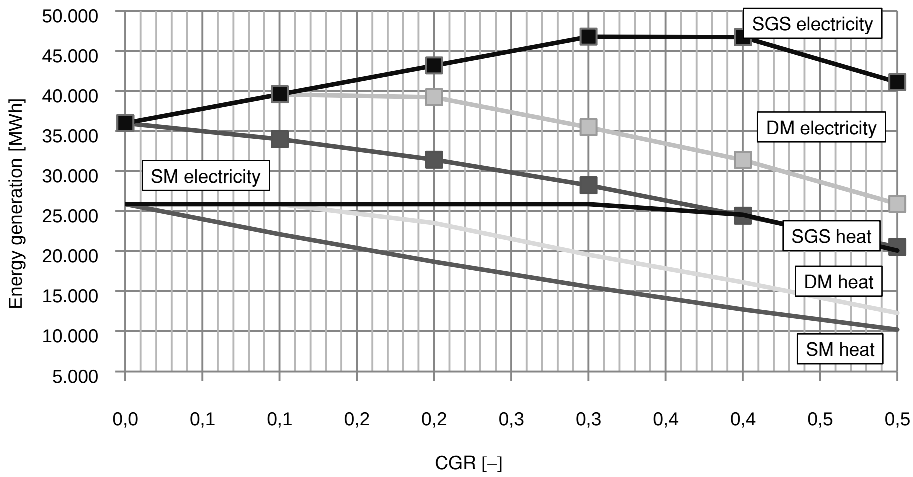

Figure 7. Annual electricity and heat generation versus CGR for considered configurations of fuel gas systems

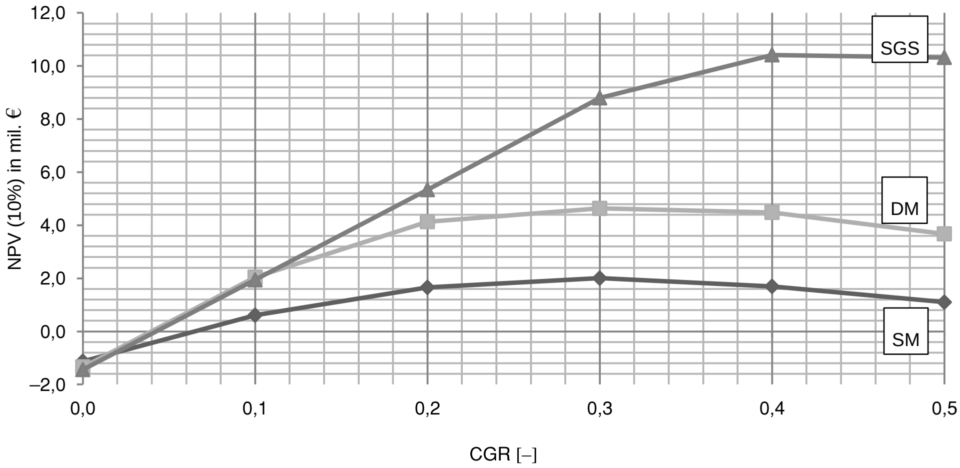

Figure 8. Net present value (10%) in 20 year period as the function of CGR for three analyzed fuel gas systems

The economic analysis is made by using generally accepted economic criteria (indices): net present value (NPV), internal rate of return (IRR), and discounted payback period (DPB) which we consider as the most appropriate for this purpose.

In all analyzed cases, the NPV value of the project is negative only when natural gas is used without mixing it with corn cob gas. All analyzed financial indicators in these cases are the lowest. The most financially promising results show SGS where CGR is from 0.2-0.5, fig 8.

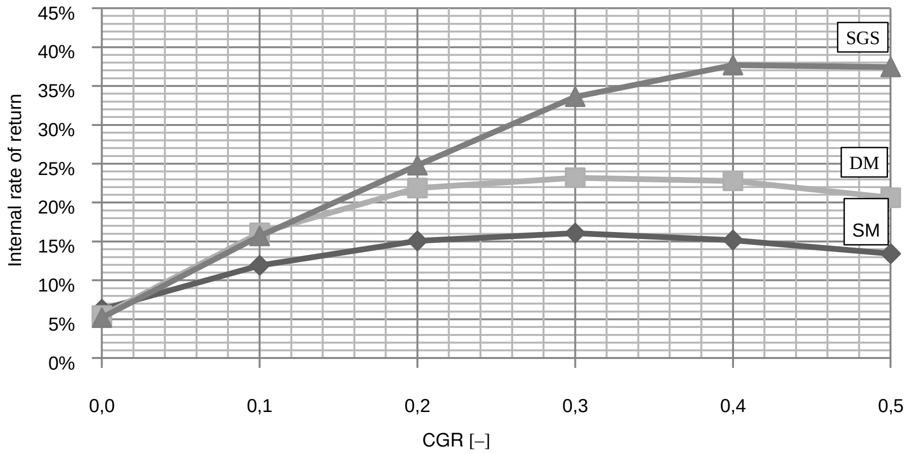

Figure 9. IRR as the function of CGR for three analyzed fuel gas systems

The Internal Rate of return also shows the highest numbers for SGS even for CGR from 0.1 and the best is when CGR is 0.4, as shown in fig 9. The relatively high price of natural gas in relation to the low price and heating value of corn cob gas gives this kind of financial results. The single manifold gas system is the solution where all economical and technical parameters shows significantly better results than other options, especially with the increased share of natural gas in the fuel mixture.

When analyzing presented economic parameters of the installation with separate gas systems with 0.4 and 0.5 CGR, it can be seen that this is the most economically justified option even thought this system has the highest investment costs. Accumulated case flows for SGS option when burning only natural gas will enter *positive zone* (dynamic payback period) in the 13^{th} year; the CGR is 0.1 in the 6^{th} year; the CGR 0.2 in the 4^{th} year and the CGR is 0.3, 0.4 or 0.5 in the 3^{rd} year.

Environmental justification

To prevent shortage and depletion of fossil fuels and subsequent problems in the world`s economy, political efforts are made all over the world to enforce a shift towards the use of renewable energy sources. The use of biomass, as a replacement for fossil fuels in power generation systems, is one of the most attractive applications for the reduction of CO_2 emissions.

Obvious advantages of energy production systems using biomass display several environmental and social advantages, such as: energy conservation (better fuel utilization due to better energy efficiency, production of cooling energy from waste heat shows better economic and environmental benefits), reduced CO_2 emissions leading to cleaner environment, wider range of fuel types used in national energy mix, lower investment costs for power system at the national level (no long distance transmission systems are required, *etc.*), and regional development (creating new jobs in rural areas, revival of villages, strengthening communities, *etc.*).

The fact that renewables are used for energy purposes can be advertised and marketed with the label *green* as overall positive contribution to the environment, national economy of the company`s or community`s environmentally friendly image. [18]

Analyses of environmental situation or background can be done by means of an indicator such as CO_2 emissions per population. This indicator in Serbia is 6.32 [tCO_2/capita] while in EU 27, it is 12% higher. However, it can be observed that in Serbia there is a considerable growth of CO_2 emission while in the EU 27 this emission is falling. Although CO_2 emission per capita in Serbia is lower than in EU 27, the growth of this emission is not the consequence of economic growth but of the decline of energy efficiency and insufficient or almost no use of renewable energy sources. [19]

Additional advantage of this and similar projects can help national energy sector to satisfactorily meet targeted values that various renewable energy systems and cogeneration systems should achieve.

The annual potential reduction of CO_2 will be achieved on the national level through the reduction of CO_2 for electricity and heat energy produced from corn cob gas, fig.10. Additional emission reduction can also be claimed by the amount of produced heat from cogeneration on natural gas. Emission reduction is calculated using average emissions from valid Serbian bylaw document: district heating systems 0.33 kgCO_2/kWh and electricity 0.53 kgCO_2/kWh. The fig. 10 shows that emission reduction of CO_2 on the national level can be achieved with SGS in the highest amounts.

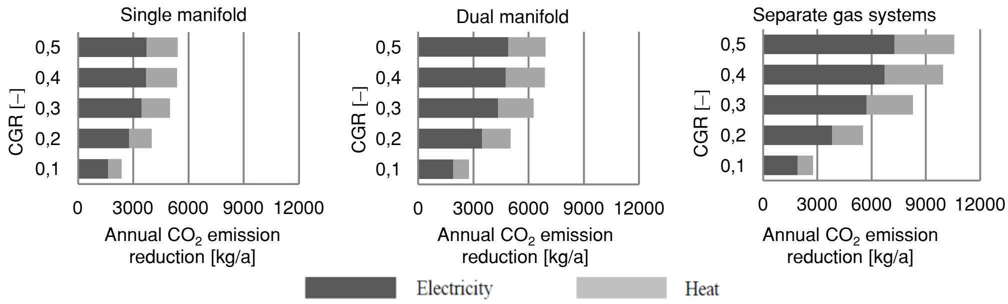

Figure 10. National annual reduction of CO_2 from the production of power and heat using corn cob gas as the function of CGR for analyzed fuel gas systems

Conclusion

Utilization of gas from biomass gasification has great potential in future energy generation, especially in agricultural regions. Analyses show that co-firing of corn cob gas with natural gas reduces the use of fossil fuels and increases the share of alternative fuels in the energy balance with acceptable investments and technical performance changes. Cogeneration energy plants based on corn cobs gasification integrated with gas turbine and HRSG can obtain good performance, provided multiple fuel system is selected that is consentient with the fuel gas mixture. Three different scenarios are analyzed and it is concluded that separate gas system provides the most acceptable values of analyzed energy and economic parameters, especially when it is used for CGR values from 0.1 to 0.4. The economic analysis points out certain benefits of such a plant that justifies the hypothesis. However, further work is necessary in order to define optimal mixture of corn cob gas and natural gas, as well as plant design features and other plants parameters.

Acknowledgment

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Nomenclature

AD – adiabatic expansion
b – ratio of fuel and air mass flow rate at the combustion chamber inlet
BIG/GT – biomass integrated gasifier/gas turbine
BIG/CC – biomass integrated gasifier/combined cycle
C – cooling air distribution type factor [–]
c_p – specific heat capacity [kJkg^{-1}K^{-1}]
CGR – corn cob gas ratio
CHP – combined heat and power
DM – dual manifold
IRR – internal rate of return, [%]
HRSG – heat recovery steam generator
L – specific work [kJkg^{-1}]
LCG – low calorific gas
NCV – net calorific value, [kJs^{-1}m^{-3}]
NAD – non adiabatic expansion
NPV – net present value, [mil €]
R – gas constant [kJkg^{-1}K^{-1}]
r – mass flow relative to compressor inlet mass flow [–]
SM – single manifold
SGS – separate gas system
T – temperature [K]
WI – Wobbe index, [kJm^{-3}]
η_p – polytropic efficiency [–]
Π – pressure ratio [–]

Subscripts

a – cooling air
CC – combustion chamber
g – gas
IT – inlet turbine
M – mixture of gas from gasification and natural gas
mix – cooling air and gas mixture

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