TECHNO-ECONOMIC ANALYSIS OF GAS TURBINE-BASED CHP PLANT OPERATION UNDER A FEED-IN TARIFF SYSTEM

by

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This paper deals with the techno-economic analysis of gas turbine-based combined heat and power production, within a current local legislation frame for the promotion of such production of energy in the Republic of Serbia. Since the legislation includes plants with electric power below 10 MW, an overview of the relevant technical characteristics for a number of appropriate gas turbines was prepared. The relevant thermodynamic parameters are calculated in order to estimate the economic feasibility of combined heat and power production using these plants. The production cost of useful heat is determined by taking into account the incomes from the sale of electricity to the electric grid under a feed-in tariff. It is compared with the production cost from an equivalent boiler for the separate production of the heat. One of the main objectives is to determine the effectiveness of the implemented legislative measures in the promotion of combined production of heat and power. Clear conclusions were drawn based on the results obtained.

Key words: *combined heat and power, cogeneration, feed-in tariff, gas turbine, heat recovery unit, heat-only-fired boiler*

Introduction

In the Republic of Serbia, legislation was passed in 2013 that, in line with similar legislative provisions in the EU, aims to promote decentralized forms of combined heat and power (CHP) generation. It defines a set of different feed-in tariff prices for the purchase of electricity from small CHP plants that are higher than the basic price. Related documents [1, 2] set out the technical conditions and legal procedures for acquiring the status of an eligible electricity producer. Included requirements define the types of fuel used by the plant, the maximum allowable installed capacity and the minimum permitted efficiency of CHP production (cogeneration) achieved in the annual energy balance. The regulation can be applied to producers whose nominal installed electric power is less than 10 MW. The prescribed minimum annually averaged CHP efficiency for plants that use natural gas as a fuel is 75%. For a producer that meets these conditions, the applied feed-in tariff for electricity is 0.0820 EUR/kWh for an installed power of less than 0.5 MW and 0.0746 EUR/kWh for plants with an installed power higher than 2 MW, and for the intermediate category linear interpolation is applied. Correction factors for changes of the price of natural gas and inflation are also included.

The ultimate goal of the promotion of CHP production is a reduction of the primary energy consumption and related negative environmental consequences connected with fossil

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fuel combustion. However, although the thermodynamic and environmental advantages of CHP are indisputable, economic criteria, unfortunately, often do not support it. Stimulation is applied to make CHP production economically feasible, because otherwise it is mostly unprofitable under local conditions. These targets industrial and communal energy producers.

General research in order to develop energy and economic quality indicators for CHP projects has been carried out by many workers. The thermodynamic parameters are discussed in references [3, 4] and the economic parameters have been analyzed in reviews such as [5]. This research aimed to examine the possibilities for the feasible operation of a gas turbine CHP plant considering the feed-in tariff system and the price of natural gas in the Republic of Serbia. One of the aims was to explore whether the tariff system can contribute to the wider application of CHP production.

Field of application

The following applications were considered: district heating, production of sanitary hot water, and production of process heat for industry. District heating is widespread but implies a small number of operating hours annually. In contrast, the remote production of sanitary hot water requires a large number of annual operating hours but is not widespread. For example, the heat consumption for domestic hot water preparation in Belgrade is 70 MW, whereas the total installed district heating capacity is 2868 MW [6]. Since high efficiency is demanded, the production of low temperature process heat can be considered, which is mostly used in the textile, food, chemical, and machine industries. The production of steam for industrial processes is widespread and generally requires a large number of working hours per year. However, the CHP efficiency depends on the vapor pressure required and the related saturation temperature. Higher process steam pressures cause a decrease in the CHP efficiency, which in most cases can be under the prescribed limit. This case will be discussed only briefly and not considered in detail.

Basic technical concept

A cogeneration plant consists of a gas turbine set containing a compressor (C), a combustion chamber (CC), a gas turbine (T), an electric generator (G), and a heat recovery (HR) unit, fig. 1(a). Such a gas turbine unit (GT) uses the primary heat rate from the fuel to produce electric power. The fuel considered is natural gas. The gas turbine exhaust temperature ranges from 450 to 550 °C. The smallest turbines in the power range considered operate using internal heat recuperation, fig. 1(b), and have exhaust temperatures below 300 °C.

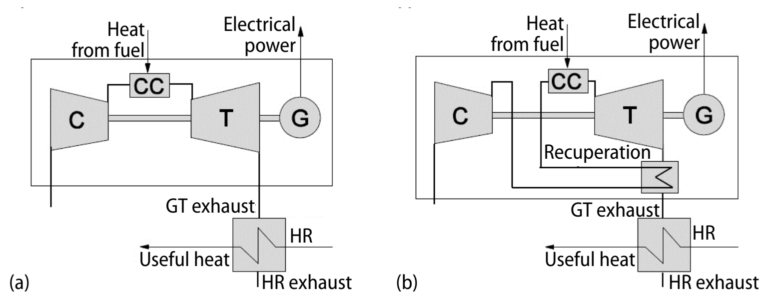

Figure 1. Scheme of gas turbine cycle with CHP; (a) gas turbine with the basic thermodynamic cycle and (b) gas turbine with internal heat recuperation

Thermodynamic parameters for separate and combined production of heat and power

Here the separate production of electricity from a gas turbine is rated using the electric efficiency, the separate production of heat from a gas-fired boiler using the heat efficiency (the boiler efficiency) and the combined production is rated applying the CHP efficiency, all defined as in [3]. Precise definitions are given in *Appendix A*. These parameters are evaluated by applying a gas turbine nominal electric efficiency, electric power, mass-flow, rate and the exhaust temperature.

Overview of performance of the gas turbine models considered

This study considers the application of 23 specific gas turbine models with nominal power ranging from 30 kW to 9.45 MW [7, 8]. The electric power, the thermal efficiency and the fuel input heat rate for the plants considered are given in tab. 1. The CHP efficiency is

Table 1. List of considered gas turbine models with parameters of separate and combined energy production for nominal conditions

No.	Producer	Model	Electric power*	Useful heat rate**	Fuel heat rate*	Electric efficiency*	CHP efficiency**
–	–	–	kW	kW	kW	%	%
1	Capstone Turbine	C30	30	64	115	26.0	81.6
2	Capstone Turbine	C65	65	124	225	28.9	84.0
3	Capstone Turbine	C200	200	280	604	33.1	79.4
4	Vericor	VPS1	504	1 556	2 419	20.8	85.2
5	Kawasaki Heavy Industries	M1A-13D	1 485	3 828	6 197	24.0	85.7
6	Kawasaki Heavy Industries	M1A-17D	1 685	3 787	6 341	26.6	86.3
7	Opra Turbine	OP16-3A	1 910	4 443	7 102	26.9	89.4
8	Orenda Aerospace	OGT2500	2 670	6 071	10 000	26.7	87.4
9	Kawasaki Heavy Industries	M1T-13D	2 930	7 688	12 403	23.6	85.6
10	Solar Turbines	Centaur 40	3 515	7 396	12 609	27.9	86.5
11	Centrax Gas Turbines	CX501-KB5	3 897	7 835	13 416	29.0	87.4
12	Solar Turbines	Centaur 50	4 600	8 844	15 679	29.3	85.7
13	Rolls-Royce	501-KB7S	5 245	9 425	16 675	31.5	88.0
14	Siemens Energy	SGT-100	5 400	9 944	17 421	31.0	88.1
15	Solar Turbines	Taurus 60	5 670	10 137	17 996	31.5	87.8
16	Mitsubishi HI	MF-61	5 925	12 085	20 681	28.6	87.1
17	Orenda Aerospace	OGT6000	6 200	11 343	20 531	30.2	85.4
18	Solar Turbines	Taurus 65	6 300	10 367	19 156	32.9	87.0
19	MAN Diesel & Turbo	GT6	6 630	11 097	20 305	32.7	87.3
20	Siemens Energy	SGT-200	6 750	12 119	21 412	31.5	88.1
21	Centrax Gas Turbines	CX300	7 900	14 659	25 834	30.6	87.3
22	Solar Turbines	Taurus 70	7 965	12 395	23 238	34.3	87.6
23	Solar Turbines	Mars 90	9 450	16 484	29 662	31.9	87.4

* For gas turbine operation under standard ISO conditions.

** For gas turbine operation in CHP mode under standard ISO conditions, a heat recovery unit exhaust temperature of 75 °C and a heat recovery unit efficiency of 98%.

highly dependent on the temperature of the exhaust gases behind the heat recovery unit. The basic value of this temperature was selected as 75 °C, which can be related to the application of heating regimes of, for example, 120/65 °C. The heat recovery unit efficiency related to the convection and radiation losses is 98%. The output rate of useful heat is calculated according to the expressions given in *Appendix A*.

Figure 2(a) shows the values of the overall thermal efficiency of the considered gas turbines in the separate production of electricity from tab. 1. The CHP efficiency of each unit is shown in fig. 2(b). It can be seen that for an heat recovery exhaust temperature of 75 °C the CHP efficiency exceeds the threshold value of 75% for all models considered.

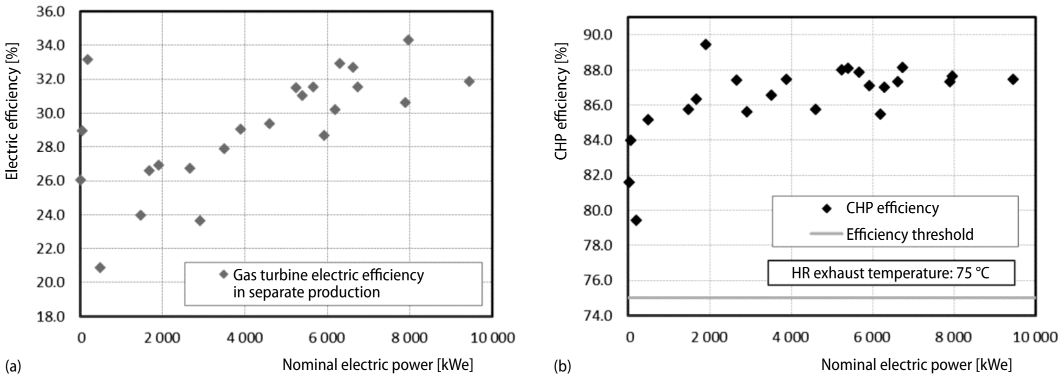

Figure 2. Efficiency of the considered gas turbine plants for nominal conditions; (a) electric efficiency in separate production and (b) CHP efficiency for a heat recovery unit exhaust temperature of 75 °C, with the threshold value for application of feed-in tariff

Heat recovery unit exhaust temperature and ambient conditions

The effects of variation of the heat recovery exhaust temperature on the value of the CHP efficiency are shown in fig. 3(a). The CHP efficiency threshold is exceeded for all temperature values considered except in certain cases for the smallest units.

The thermodynamic parameters of CHP production from tab. 1 are given for a plant operating under standard ambient conditions according to [9]: temperature 15 °C, pressure

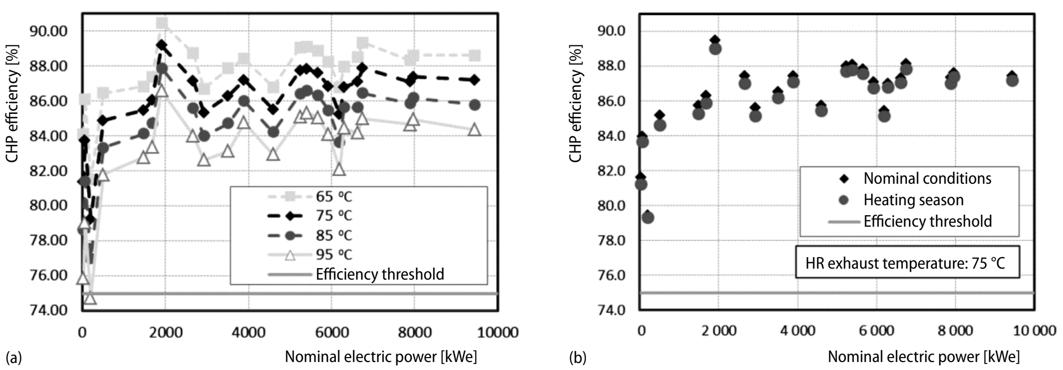

Figure 3. The CHP efficiency of the gas turbine plants considered: (a) variation of the heat recovery exhaust temperature and (b) influence of the ambient temperature

1.013 bar, and relative humidity 60%. The operational quality of a gas turbine is mostly affected by the variation of the ambient temperature. A decrease in the ambient temperature increases both the electric power and the electric efficiency. Although the turbine exhaust temperature is lowered, the mass-flow rate rises and the useful heat output also increases. However, the increase in useful heat output lags behind the increase in the electric power produced and the increase in the heat input from the fuel, and the CHP efficiency is degraded.

Using the internally available data, the appropriate correlations for the electric power, the thermal efficiency and the useful heat output were tailored and these corrections are presented in fig. 4. If a CHP plant is considered for district heating, the turbine will operate during the winter period, when the average temperature is approximately 5.5 °C, while the average annual temperature is 12.5 °C [10]. Corresponding values of the correction coefficients for winter operation and operation during the entire annual period are given in tab. 2. Figure 3(b) shows corrected CHP efficiency according to the corrected values of electric power, electric efficiency and useful heat rate for operation during the winter season only.

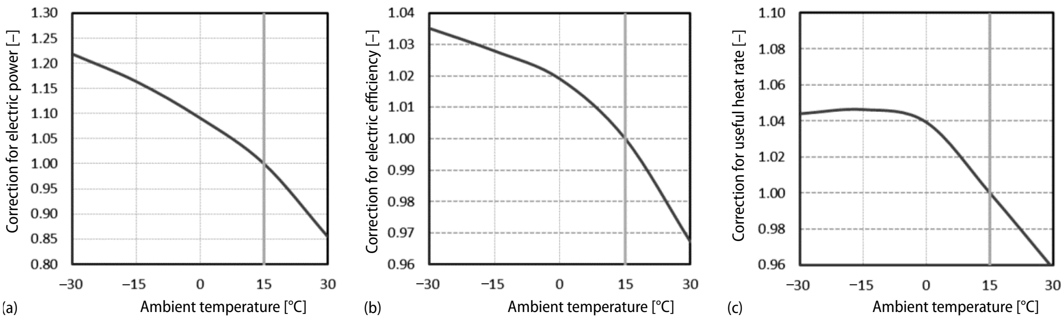

Figure 4. Typical correction coefficients for the influence of variation of the ambient temperature; (a) electric power, (b) electric efficiency, and (c) useful heat rate for an heat recovery exhaust temperature of 75 °C

Table 2. Correction coefficients for the electric power, efficiency, and output heat rate

Correction factor	Unit	Heating season	Annual
Electric power	–	1.06	1.02
Electric efficiency	–	1.015	1.005
Useful heat output rate	–	1.03	1.01

Initial investment

Investment costs for the turbo set with additional equipment are taken from [8, 11]. Total costs for the basic equipment also include the heat recovery unit, transportation, customs and assembly expenses. Additional costs include the purchase and installation of a pressure control and metering station for natural gas with a suitable compressor and the purchase of the electrical equipment for connection to the public grid. Construction costs include the foundation works and installation of chimneys. Other expenses include consulting and plant acceptance testing. These overall investment costs were estimated from [11] for the smallest turbines and from [12, 13] for larger plants. A comparative overview of these costs for small and large plants is given in tab. 3. According to these data, a value of 2.08 was taken as a representative ratio between the known turbo set cost and the overall investment. Accordingly, the specific investment costs are as shown in fig. 5(a).

Table. 3. The structure of costs and the total investment for a gas turbine CHP plant

Electric Power	[kW]	30	8 000
Item			
Turbo set	EUR	45 000	4 800 000
Heat utilizer	EUR	10 000	700 000
Transportation, customs, and installation	EUR	20 000	1 200 000
Additional electric equipment and grid connection	EUR	–	1 030 000
Gas metering and regulation station and connection	EUR	5 000	220 000
Consulting and testing	EUR	15 000	1 600 000
Construction works	EUR	–	360 000
Total investment	EUR	95 000	9 910 000
Ratio of total investment to turbo set cost	–	2.11	2.06

Each gas turbine CHP case will be compared with the separate production of heat from a gas-fired boiler with an identical useful heat output. For this purpose, according to the equipment costs from [14-16], a data-fit relation was obtained for a gas-fired-boiler specific investment, fig. 5(b).

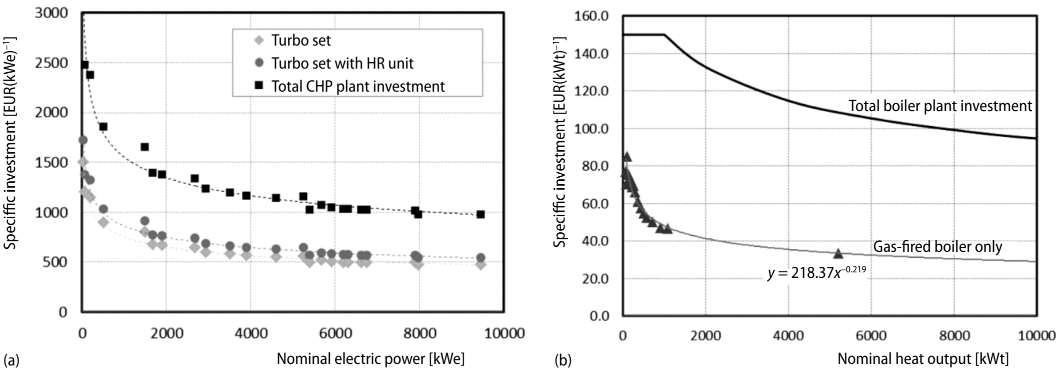

Figure 5. The structure of investments; (a) gas turbine CHP plant and (b) gas-fired boiler plant

The construction costs are estimated according to [9, 10]. The boiler house construction cost was assumed to be three times higher than the cost of the boiler itself. For the cases of lowest heat output, the specific investment is limited to 150 EUR/kWt.

Production cost of useful heat

Since the feed-in electricity tariff is an input parameter, the financial analysis can be carried out by comparing the costs of useful heat for the CHP and for the separate heat production applying a gas-fired boiler with identical output of useful heat. The analysis was performed by applying the parameters in tab. 4. The feed-in tariff is guaranteed for a period of 12 years. The CHP plant operation and maintenance (O&M) costs are given per unit of electric work produced while the costs for the gas-fired boiler are given annually, per unit of installed useful heat rate capacity. The analysis considers a bank loan-financed project, hence the loan period and the interest rate are additional parameters. Technical parameters such as the HR exhaust temperature and the gas-fired boiler efficiency are identical with those in the previous considerations, tab. 4.

Table 4. Input parameters for the economic analysis

Specific O&M costs for CHP plant	0.005	EUR/kWhe
Annual O&M costs for gas-fired boiler room	5	EUR/kWt/year
Feed-in tarif for electricity	0.082, $P_E \leq 0.5$ MW 0.08447 – 0.00493P, $0.5 < P_E < 2.0$ MW 0.0746, $P_E \geq 2.0$ MW (P_E [MW] is nominal electric power)	EUR/kWh
Fuel price (natural gas)	0.30	EUR/m^3
Fuel lower heating value	33300	kJ/m^3
Loan period	10	years
Interest rate	6	%
Technical conditions for the economic analysis: Heat recovery exhaust temperature 75 °C, heat recovery unit efficiency 98%, gas-fired boiler efficiency 96%		

The promotional tariff system also includes the correction of the feed-in tariff for inflation and for changes in the price of natural gas. These corrections were tested and for reasons of simplicity were not included in the current analysis since the change in tariff was satisfactory.

Two different options will be analyzed. The first considers the use of heat for district heating during the winter period and the second considers the use of heat for the production of sanitary hot water/process heat during the whole year. The numbers of operating hours for these two options are given in tab. 5. Additional hours of operation in separate production of electricity are not considered since related production cost of electricity is higher than the feed-in tariff.

Table 5. Annual number of operating hours

Heat usage type	District heating	Hot sanitary water/process heat
Operating hours [h per year]	3300	7800

District heating option

For this option, the correction coefficients in tab. 2 for the average ambient temperature during the heating season were used. Figure 6(a) displays the categories of annual expenses including the loan repayment rate, expenses for O&M and fuel expenses. An overview of specific expenses per kW of installed electric power is given in fig. 6(b).

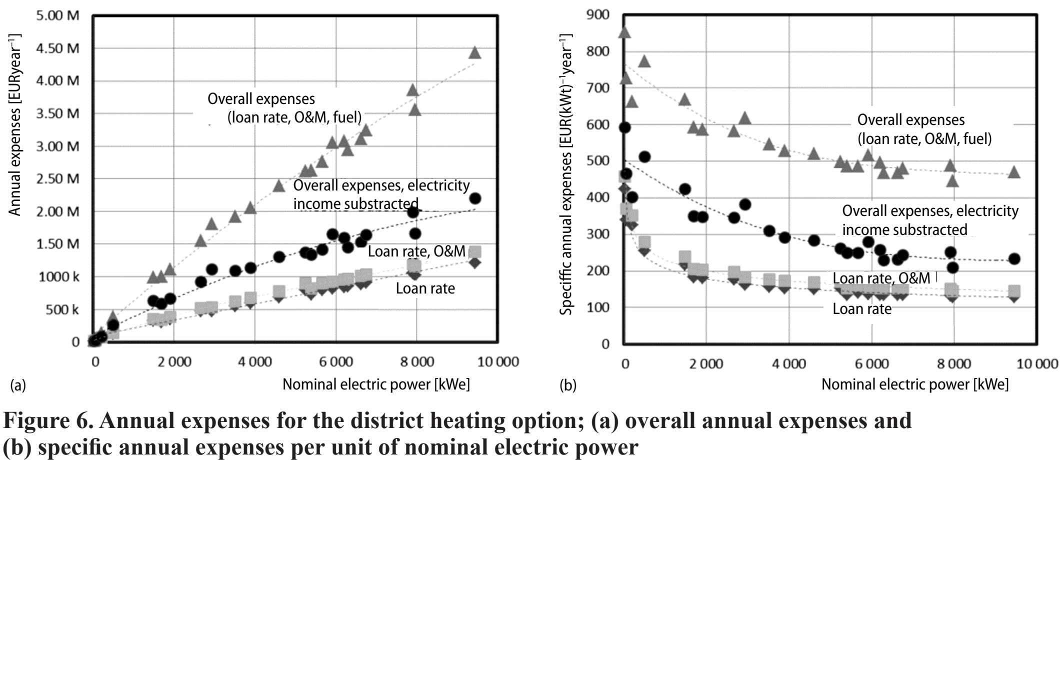

Figure 6. Annual expenses for the district heating option; (a) overall annual expenses and (b) specific annual expenses per unit of nominal electric power

The production costs of useful heat from CHP and from separate production using a gas-fired boiler are shown in fig. 7. Also shown is the approximate selling price of heat, which can vary slightly in different urban areas. The production cost of heat from CHP plant is reduced according to the additional income from the sale of electricity under the feed-in tariff. However, owing to the small number of annual operating hours the CHP plant generates higher costs than the gas-fired boiler. The savings related to the application of the CHP compared with the separate production of heat are negative, fig. 7(b). The costs are significantly higher than the usual selling price of heat, fig. 8(a) and it can be concluded that the application of a gas turbine CHP plant for district heating is not feasible.

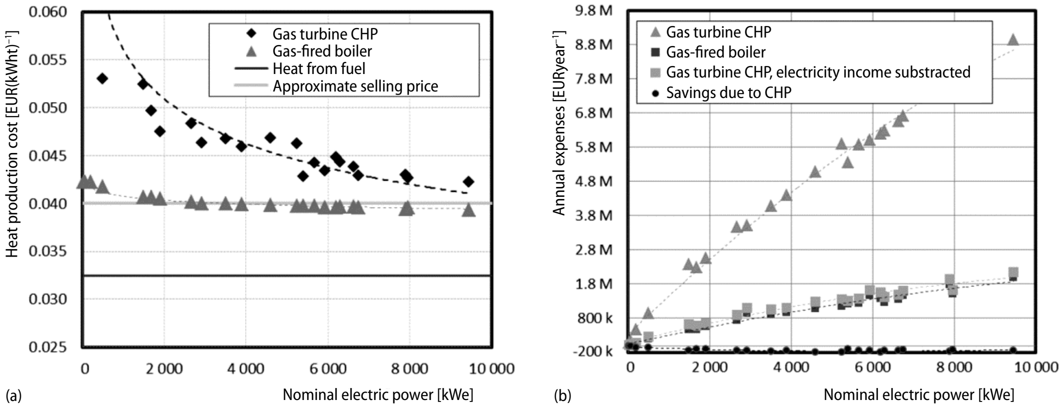

Figure 7. District heating option; comparison between CHP and gas-fired boiler; (a) production cost of useful heat and (b) annual expenses and savings in heat production

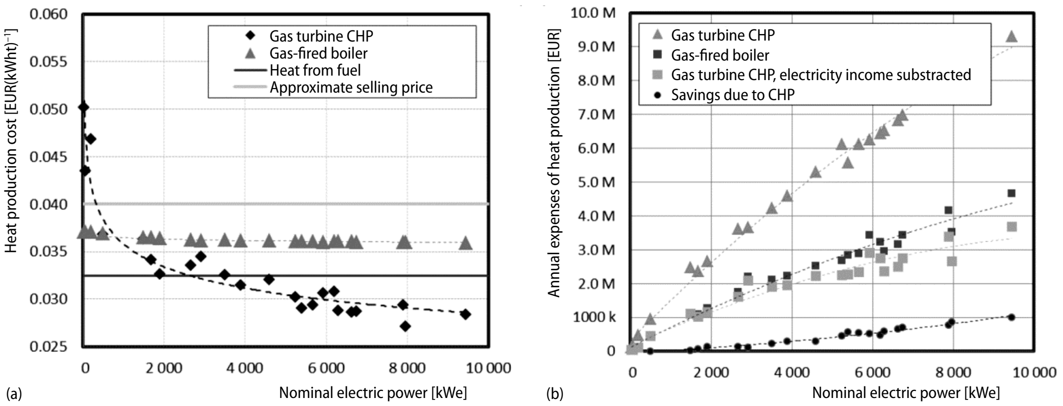

Figure 8. Hot sanitary water/process heat supply option; comparison between CHP and gas-fired boiler; (a) production cost of useful heat and (b) annual expenses and savings in heat production

Hot sanitary water/process heat supply option

The production parameters are the same as in the previous consideration with only a minor correction related to the annually averaged ambient temperature, tab. 4. The heat recovery exhaust temperature is again set at 75 °C. However, the annual number of operating hours is now increased, tab. 5.

Because of that, the relation between income and expenses now becomes different. For CHP plants with electric power above 1 MW, the production cost of useful heat becomes lower than that for the separate production using a gas-fired boiler. For plants with electric power above 3 MW, the cost of heat becomes lower than the cost of heat from fuel, fig. 8(a). The savings due to the application of CHP are now significant, fig. 8(b). Owing to the increased number of operating hours, the additional income from the sale of electricity outweighs the increased loan repayment rate for the CHP plant.

Payback period and net present value

According to the results from the previous section, only the sanitary water/process heat supply option will be analyzed further. In order to evaluate the possibilities for the commercial production of heat, it is necessary to consider the variation of the selling price of heat, since this parameter can vary at different locations. This covers three values of the price of heat, the lowest of which is set to be similar to the heat production price for large gas-fired boiler plants. These prices are given in tab. 6. For comparison, the current selling price of heat for the producers is approximately 0.040 EUR/kWh.

Table 6. Considered selling prices of useful heat at the plant boundary

	Price 1	Price 2	Price 3
Price of heat [EUR(kWht)$^{-1}$]	0.036	0.040	0.044

First, the simple payback period is calculated. The estimation does not take into account the loan repayment and considers a project that is financed from its own monetary resources. Figure 9(a) shows the simple payback period as a function of the nominal electric power of the plant for three different selling prices of heat. Figure 9(b) shows the simple payback period against the nominal rate of useful heat. This is compared with the payback period for a gas-fired boiler plant for the separate production of heat. For the price of heat of 0.044 EUR/kWh or 0.040 EUR/kWh, the heat-only boiler plant has a shorter simple payback period.

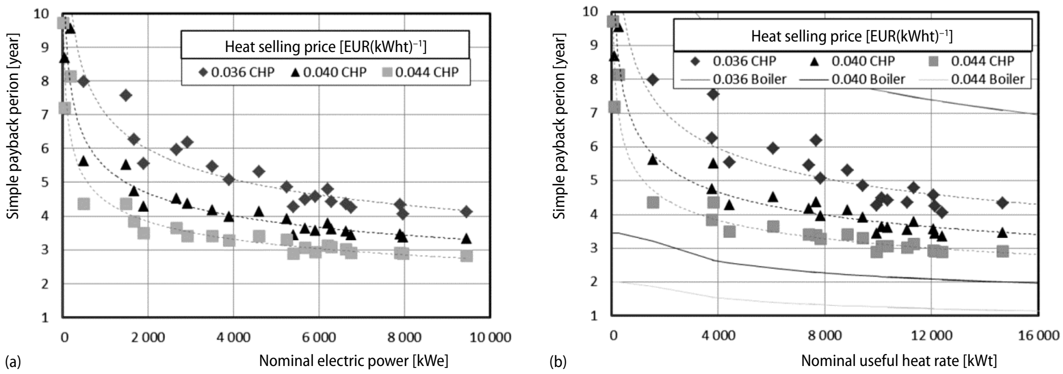

Figure 9. Simple payback period for the sanitary water/process heat option for different selling prices of heat; (a) the CHP plants and (b) comparison between CHP plants and gas-fired boiler plants

However, owing to the additional incomes from the sale of electricity, a CHP plant can feasibly operate with a lower price of heat of 0.036 EUR/kWh, when the payback period for the heat-only boiler plant becomes unfavorable.

The calculation of net present value is performed according to the parameters given in tab. 7. The value of the discount rate used was selected to allow the additional safety of

Table 7. Data for the calculation of net present value

Project period [years]	10
Discount rate [%]	15

the project in terms of inflation, possible increases in the price of fuel or decreases in the selling price of useful heat. The calculation model now again considers a loan-based project with the loan granted under previously considered conditions, tab. 4.

The project net present value as a function of nominal electric power is shown in fig. 10(a). It can be seen that, even with a very high value of the discount rate and for a low price of heat of 0.036 EUR/kWh, the project is feasible for most of the plants considered. For comparison, the loan repayment rate data are shown using an additional curve, fig. 10(a). Figure 10(b) compares the net present value of a CHP plant with that of an equivalent gas-fired boiler plant. For output heat rates below 4 MW, the net present values of CHP plant projects are similar to those of gas-fired boiler plants. When the price of heat is 0.036 EUR/kWh, the net present value for a boiler plant project is close to zero. However, for heat rates above 4 MW, a CHP project becomes more favorable compared with a gas-fired boiler plant for the separate production of heat.

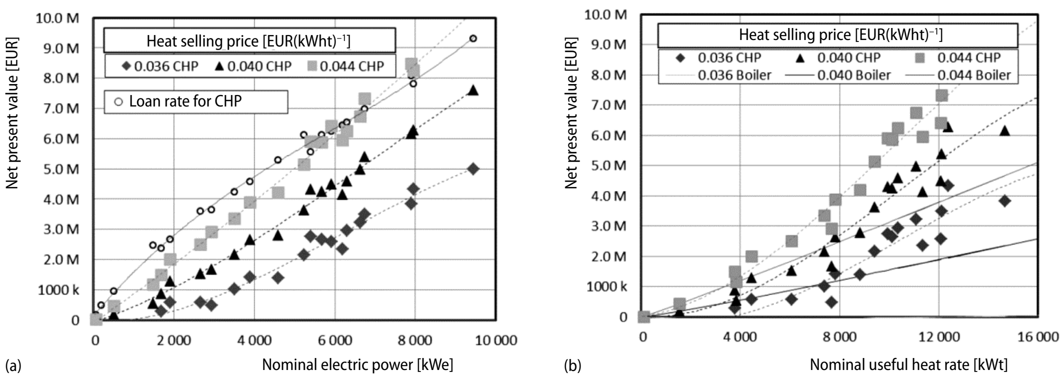

Figure 10. Net present value for the sanitary water/process heat option; (a) the CHP plants and (b) comparison between CHP plants and gas-fired boiler plants

Conclusion

This paper discusses the possibilities for the application of gas turbines for combined heat and electricity production in the Republic of Serbia. The analysis is related to the current price of natural gas, the value of the electricity feed-in tariff and the conditions under which such a tariff system is applied. For a gas turbine-based CHP this includes power plants with up to 10 MW of electric power with a minimum CHP efficiency of 75%.

Considering 23 gas turbine models, it has been clearly demonstrated that in such an environment, the application of a CHP plant is economically viable only when it is applied for a large number of operating hours annually. In such a case, owing to the additional income from the production of electricity, gas turbine CHP plants with electric power above 1 MW can operate with a production cost of useful heat that is lower than in the case of the separate production of heat using a gas-fired boiler. Therefore, a CHP plant can offer a lower selling price of heat or achieve a higher income when same selling price is considered.

On the other hand, the application of CHP production from a gas turbine for district heating is not economically feasible owing to the ratio of the large initial investment and the small amount of energy produced due to small number of annual operating hours whereas the application of the separate production of heat using a gas-fired boiler is still feasible.

Acronyms

CHP – combined heat and power
O&M – operation and maintenance

Appendix A – Definitions of thermodynamic parameters

Definitions of efficiency

Since the legislation considers the annually averaged value of CHP efficiency, the efficiencies will be formally defined using annually produced amounts of heat and electricity. Therefore, the electric efficiency, η_E, represents the efficiency of a gas turbine plant in the separate production of electricity, the heat efficiency, η_H, or simply the boiler efficiency, represents the efficiency of a gas-fired boiler in the separate production of heat and the CHP efficiency, η_{CHP}, represents the efficiency of combined production applying a gas turbine and a heat recovery unit. These variables are:

$$\eta_E = \frac{E}{Q_{F,\mathrm{GT}}}, \quad \eta_H = \frac{Q_U}{Q_{F,\mathrm{B}}}, \quad \eta_{CHP} = \frac{E + Q_U}{Q_{F,\mathrm{GT}}} \tag{1}$$

where E is electric work, Q_U – the useful heat produced, and Q_F – the input heat from fuel, for a turbine ($Q_{F,\mathrm{GT}}$) or for a gas-fired boiler ($Q_{F,\mathrm{B}}$). Since the efficiencies η_E and η_H are known, the heat inputs from the fuel are calculated as $Q_{F,\mathrm{GT}} = E/\eta_E$ and $Q_{F,\mathrm{B}} = Q_U/\eta_H$.

Produced heat and electric work

For an annual number of operating hours, $\tau\,[\mathrm{h}]$, the amount of electric energy produced, E, the useful heat, Q_U, and the amount of heat from fuel consumed, $Q_{F,\mathrm{GT}}$ are calculated:

$$E = \tau P_E, \quad Q_U = \tau \dot{Q}_U, \quad Q_{F,GT} = \frac{E}{\eta_E} \tag{4}$$

The electric power, P_E, the useful heat rate, $\dot{Q}_U$, and the electric efficiency, η_E, are corrected values of rated electric power, $P_{E,n}$, useful heat rate produced for nominal conditions, $\dot{Q}_{U,n}$, and the efficiency in the separate production of electricity, $\eta_{E,nom}$:

$$P_E = k_E P_{E,n}, \quad \dot{Q}_U = k_H \dot{Q}_{U,n}, \quad \eta_E = k_\eta \eta_{E,n} \tag{5}$$

Here the correction coefficients for the electric power, the useful heat rate, and the electric efficiency, k_E, k_H and k_η, respectively, depend on the average ambient temperature for the operational season.

Useful heat output rate

The nominal output rate of useful heat, $\dot{Q}_{U,n}$, is calculated:

$$\dot{Q}_{U,n} = \eta_{HR} \dot{M}_n \overline{c}_p (t_{GTe,n} - t_{HRe,n}) \tag{6}$$

where η_{HR} is the heat recovery unit efficiency including convection and radiation losses and $\dot{M}_n$ – the nominal (rated) mass-flow rate of the exhaust gases. The temperature $t_{GTe,n}$ is the nominal turbine exhaust temperature and $t_{HRe,n}$ is the temperature of the cooled exhaust behind the heat recovery unit.

The averaged heat capacity of combustion gases is estimated using an original expression:

$$\overline{c}_p \Big|_{75\,^\circ\text{C}}^{t} = 0.12t + 1012 \ \ [\text{kJkg}^{-1}\text{K}^{-1}], \quad 250 \le t \le 600\,[^\circ\text{C}] \tag{7}$$

Now, all the required variables can be calculated using the given gas turbine parameters $P_{E,n}$, $\eta_{E,n}$, $\dot{M}_n$ and $t_{GTe,n}$ together with selected values of temperature $t_{HRe,n}$.

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