EFFECTS OF IMPLEMENTATION OF CO-GENERATION IN THE DISTRICT HEATING SYSTEM OF THE FACULTY OF MECHANICAL ENGINEERING IN NIŠ

by

Mladen M. STOJILJKOVIĆ, Mirko M. STOJILJKOVIĆ*, Bratislav D. BLAGOJEVIĆ, Goran D. VUČKOVIĆ, and Marko G. IGNJATOVIĆ

Faculty of Mechanical Engineering, University of Niš, Niš, Serbia

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Implementation of co-generation of thermal and electrical energy in district heating systems often results with higher overall energy efficiency of the systems, primary energy savings and environmental benefits. Financial results depend on number of parameters, some of which are very difficult to predict. After introduction of feed-in tariffs for generation of electrical energy in Serbia, better conditions for implementation of co-generation are created, although in district heating systems barriers are still present.

In this paper, possibilities and effects of implementation of natural gas fired co-generation engines are examined and presented for the boiler house that is a part of the district heating system owned and operated by the Faculty of Mechanical Engineering in Niš. At the moment, in this boiler house only thermal energy is produced. The boilers are natural gas fired and often operate in low part load regimes. The plant is working only during the heating season.

For estimation of effects of implementation of co-generation, referent values are taken from literature or are based on the results of measurements performed on site.

Results are presented in the form of primary energy savings and greenhouse gasses emission reduction potentials. Financial aspects are also considered and triangle of costs is shown.

Key words: *district heating, co-generation, primary energy savings, greenhouse gasses*

Introduction

Small and medium-scale co-generation technologies today represent a key resource to increase generation efficiency and reduce greenhouse gasses emissions. Implementation of

* Corresponding author; e-mail: mirko.stojiljkovic@masfak.ni.ac.rs

co-generation of heat and electricity in district heating systems, as well as in other systems, often results with higher overall energy efficiency of the systems, primary energy savings and environmental benefits.

On the other hand, financial impacts of implementation of co-generation are various depending on several factors like: price of electrical energy, price of fuel, availability of renewable energy sources and technologies, demand profiles for heating, cooling and electrical energy, both yearly and daily, *etc*. Today in Serbia, price of electrical energy is low, influencing poor financial indicators when it is about implementation of co-generation.

Being aware of benefits that co-generation brings, both from energy efficiency and environmental point of view, Serbian Government decided to introduce feed-in tariffs as an incentive mechanism to support electrical energy generation from co-generation plants (and from renewable technologies as well). These incentives are supposed to make some projects financially attractive.

One important question that arises now, after feed-in tariffs are introduced in Serbia, is whether this mechanism, with new prices adopted for exported electrical energy, generated in co-generation plants, is strong enough to make projects related to installation of co-generation equipment in district heating systems financially attractive. Serbian district heating companies as well as heat plants and distribution networks are generally owned by cities and municipalities and are mainly in poor condition. Heating energy is mainly charged according to the heated area, instead according to the consumption. Domestic hot water is mainly prepared using electrical energy that is relatively inexpensive today. Maybe the most significant technical barrier to co-generation implementation in Serbian district heating plants today is that most of these plants work only during heating season. Also, the most of the district heating companies don't supply consumers during night hours, except when outside temperatures are extremely low. Thus, it wouldn't be possible to use and charge thermal energy from co-generation units that might be introduced during summer months, or during night and it would be hard to run co-generation units for more than 2500–3000 hours per year (in financially optimal regime).

In this paper, possibilities for primary energy savings and greenhouse gasses emission reduction for the case of implementation of natural gas fired co-generation engines are examined and presented for the case of one smaller district heating plant. This is the boiler house that is a part of the district heating system owned and operated by the Faculty of Mechanical Engineering in Niš. At the moment, in this boiler house only thermal energy is produced. The boilers are natural gas fired and often operate in low part load regimes. The plant is working only during the heating season and rarely exceeds 8 MW of thermal power.

Description of site and chosen technology

District heating system of the Faculty of Mechanical Engineering in Niš supplies several faculties and schools, one dormitory with restaurant and several residential buildings with heating energy. Energy supplied is measured at the exit of the boiler house each 18 minutes. These measured data for one representative year are used for the estimations presented in this paper. Electrical power requirement for entire boiler house and primary network rarely exceeds 50-60 kW. The fuel used is natural gas, with the possibility to use fuel oil also. No demand rise is foreseen for the time horizon of the potential co-generation implementation project.

For the purpose of this paper, effects of implementation of natural gas fired co-generation engine-generator set are examined. Examined engine-generator set has electrical power of 2000 kW and thermal power of approx. 2250 kW, accounting only high temperature engine cooling circuit and exhaust gasses thermal outputs. Thermal energy available during the engine operation might be divided in four parts: (1) high temperature energy of exhaust gasses, (2) high temperature energy at approximately 85 to 95 °C from the engine cooling system, (3) low temperature energy at approximately 40 to 50 °C from the engine cooling system and (4) very low temperature energy radiated from different parts of the engine generator set to the environment. All mentioned types of energy depend on electrical power output (*i. e.* part load ratio) and are modeled according to manufacturers' data. Only first and second parts are usable for district heating purposes. Simplified scheme is shown in figure 1.

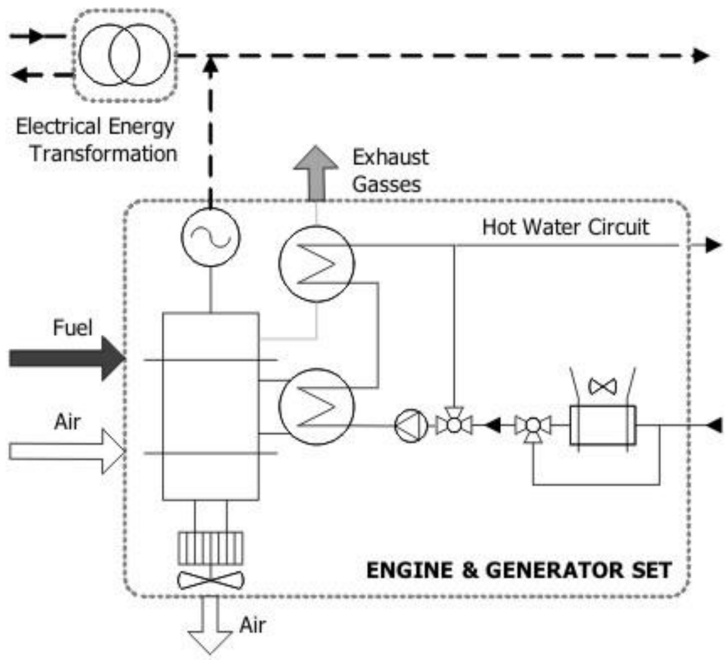

Figure 1. Simplified scheme of the engine generator set with electrical energy transformer

Engine-generator sets are suitable because of high efficiency, part load flexibility, good load following capability and good start-up time. More details on advantages and disadvantages of this and other types of co-generation units might be found in [1-3].

In order to implement such an engine-generator set, slightly decreasing water temperature in primary network might be desirable compared to the design parameters, but it seems to be feasible because network is relatively short, installations are oversized and real operating supply and return water temperatures are already often lower than designed, approximately at the level suitable for engine-generator set operation.

When modeling co-generation system, financially optimal operation regimes are assumed to be achieved. Financially optimal operation regimes are those that influence net present value of the co-generation implementation project to be maximal and lead to the maximal financial benefits of the plant owner. In this case, financially optimal regimes mostly coincide with heating load tracking mode, *i. e*. co-generation unit is run in a way to track heating demand, while electrical energy not consumed on-site is sold to the electrical grid. Heating demand for typical working day and Saturday in December, as well as sources of energy are illustrated in figures 2 and 3.

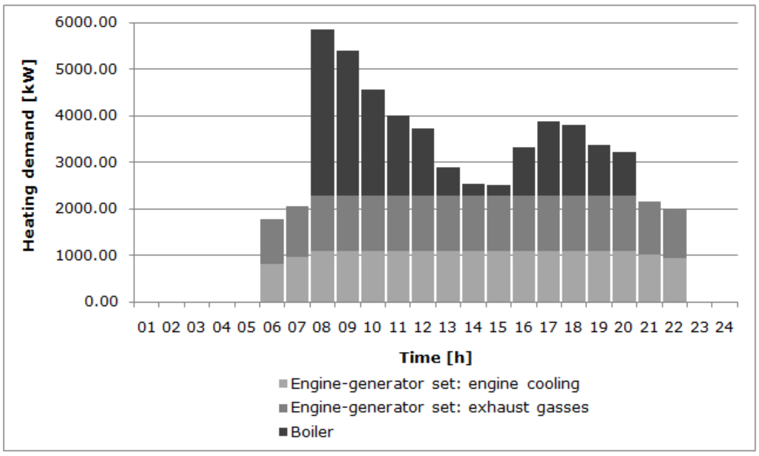

Figure 2. Heating demand for typical working day in December

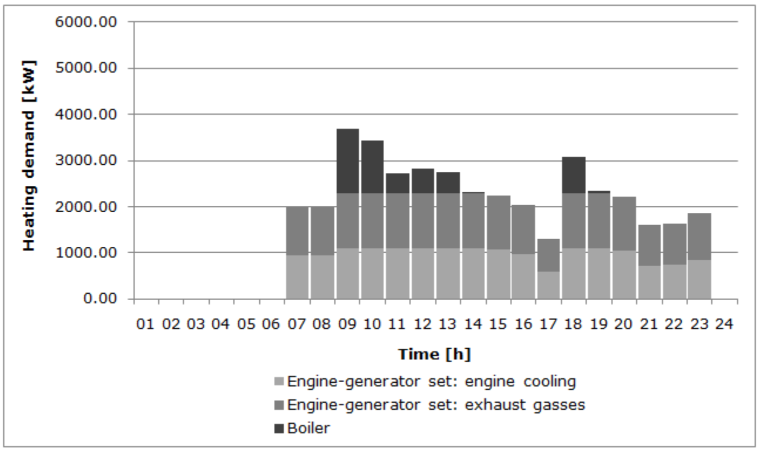

Figure 3. Heating demand for typical saturday in December

Load duration curve and demand duration curve constructed according to methodologies described in [2, 4] are shown in figure 4 illustrating that co-generation unit couldn't be run for over 2500 hours.

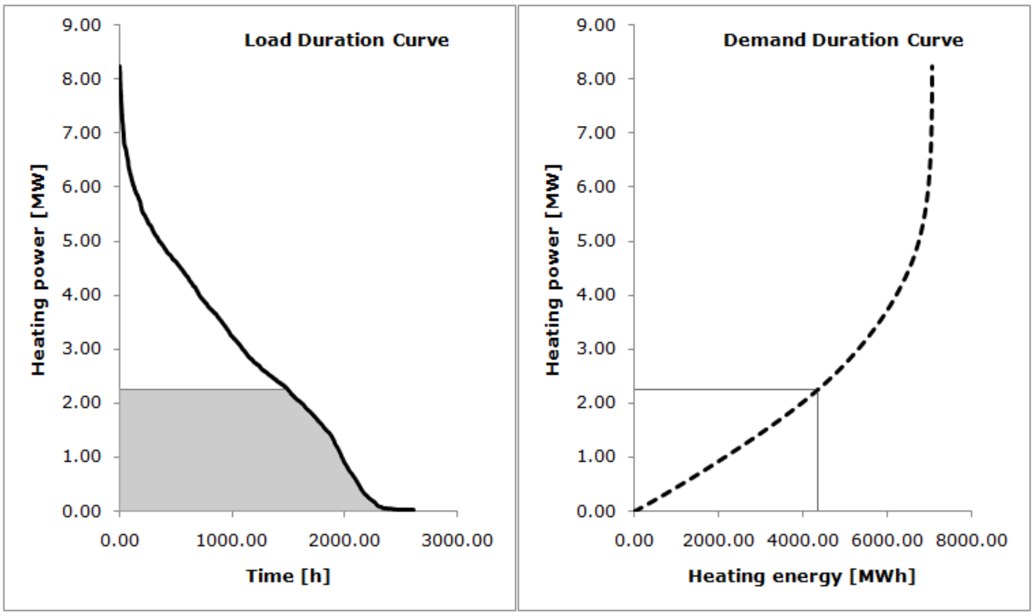

Figure 4. Load duration curve and demand duration curve

Evaluation indicators and methodologies

In order to evaluate implementation of described co-generation system, tree types of indicators have been set-up:

1. Financial indicators: net present value and internal rate of return,
2. Energy based indicators: exergetic efficiency and primary energy savings, and
3. Environmental indicator, *i. e.* greenhouse gasses reduction potential.

Financial indicators

Net present value and the internal rate of return of co-generation implementation project are calculated according to [5]. Investment is estimated to EUR 1.2 millions. Natural gas price is assumed to be EUR 0.04 per kWh, based on net calorific value, at the beginning of the project and to increase 6% per year. Electrical energy price is assumed to be EUR 0.05 per kWh and EUR 6 per kW at the beginning of the project and to increase 8% per year. Annual discount rate is assumed to be 8%. Finally, price of electrical energy exported to grid, according to feed-in tariffs, is calculated using eq. (1):

$$b_e = 10.667 - 1.333 \cdot W_{CGU} \cdot \left(0.7 \cdot \frac{c_{NG}}{31} + 0.3 \right) \tag{1}$$

where b_e is price of electrical energy exported to grid in [cEUR per kWh], W_{CGU} is installed electrical output of co-generation unit in [MW] and c_{NG} is price of natural gas in [RSD per m^3].

Levelized costs of natural gas, thermal and electrical energy are calculated according to [6, 7].

Triangle of costs for co-generation unit is constructed using the levelized costs and eg. (2):

$$Z_{\mathrm{CI}} + Z_{\mathrm{OM}} + C_{\mathrm{NG}} = C_{\mathrm{e}} + C_{\mathrm{t}} \tag{2}$$

where Z_{CI} is capital investment in EUR, Z_{OM} are operation and maintenance costs in EUR, C_{NG} is natural gas cost in EUR, C_{e} is total cost of electrical energy in EUR and C_{t} is total cost of thermal energy in EUR.

Energy based indicators

Energy based indicators chosen for the purpose of this paper are exergetic efficiency and primary energy savings.

It is generally inappropriate to compare different commodities. It is appropriate to define efficiency of a co-generation plant based on the Second Law of Thermodynamics using the concept of exergetic efficiency as the ratio of total exergy output to exergy input. The exergetic efficiency (sometimes also called second-law efficiency, rational efficiency or thermodynamic effectiveness) provides, according to Bejan *et al.* [7], a true measure of the performance of an energy system from the thermodynamic viewpoint.

Exergetic efficiency might be defined in several ways, depending on the situation, but it is always ratio between exergy of product (output) and exergy of fuel (input) [7]. Exergetic efficiency in this case is going to be defined in a manner similar to the approach from [8, 9], eg. (3):

$$\varepsilon = \frac{W_{\mathrm{net}} + Ex_{\mathrm{t}}}{Ex_{\mathrm{NG}}} = \frac{W_{\mathrm{net}} + m_{\mathrm{water}} \cdot [h_{\mathrm{e}} - h_{\mathrm{i}} - T_0 \cdot (s_{\mathrm{e}} - s_{\mathrm{i}})]_{\mathrm{water}}}{V_{\mathrm{NG}} \cdot ex_{\mathrm{NG}}} \tag{3}$$

where W_{net} is net electricity (difference between exported and imported electricity) of the system in [kJ], Ex_{t} is the exergy of the water from the pipelines, m_{water} is mass of this water in [kg], h_{e} and h_{i} are enthalpies of water leaving and returning to boiler house in [kJ·kg^{-1}], s_{e} and s_i are entropies of water leaving and returning to boiler house in [kJ·kg^{-1}·K^{-1}], and T_0 is referent environment temperature in [K]. Water temperatures are assumed to be 105 °C and 75 °C, while referent environment temperature is 288.15 K. Ex_{NG} is chemical exergy of natural gas in [kJ], while ex_{NG} is specific exergy of natural gas in [kJ·m^{-3}]. V_{NG} is consumed volume of natural gas in [m^3]. Ratio between ex_{NG} and volume based net calorific value of natural gas is taken from [10] and has the value of $ex_{\mathrm{NG}} \cdot (NCV_{\mathrm{NG}})^{-1}$=1.04.

Primary energy savings represents the difference between primary energy consumed by the co-generation plant and primary energy consumed by the referent, separate production plants that produce the same amounts of energy of each kind, *i. e.* thermal and electrical energy. There are several approaches to estimate primary energy savings. European

Commission defines primary energy savings for co-generation plants in [11, 12]. Similar indicator, called fuel energy savings, is defined in [2]. In [13, 14], co- and tri-generation primary energy savings are defined in the slightly different manner. The same parameter is defined in [15], but called, again, fuel energy savings. In [15, 16], both absolute and relative primary (fuel) energy savings are defined. European legislative recognizes the difference between the impact of electrical energy consumed on site and electrical energy exported to the grid, while in [13-15] this difference is not recognized. In this paper, relative primary energy savings are used, defined by the authors and shown in eg. (4). New formula is derived in order to preserve convenient form of equations given in [13-15] and still keep the difference between the impact of electrical energy consumed on site and electrical energy exported to the grid:

$$PES = \frac{\left(\dfrac{Q_{\mathrm{HD}}}{\eta_{\mathrm{t,SP}}} + \dfrac{W_{\mathrm{e}} \cdot \eta_{\mathrm{D}} + W_{\mathrm{D}}}{\eta_{\mathrm{G,SP}} \cdot \eta_{\mathrm{T}} \cdot \eta_{\mathrm{D}}}\right) - \left(Q_{\mathrm{NG,EGS}} + Q_{\mathrm{NG,B}} + \dfrac{W_{\mathrm{i}}}{\eta_{\mathrm{G,SP}} \cdot \eta_{\mathrm{T}} \cdot \eta_{\mathrm{D}}}\right)}{\left(\dfrac{Q_{\mathrm{HD}}}{\eta_{\mathrm{t,SP}}} + \dfrac{W_{\mathrm{e}} \cdot \eta_{\mathrm{D}} + W_{\mathrm{D}}}{\eta_{\mathrm{G,SP}} \cdot \eta_{\mathrm{T}} \cdot \eta_{\mathrm{D}}}\right)} \tag{4}$$

where W_{D}, Q_{HD}, W_{e}, and W_{i} are electrical demand, heating demand, exported and imported electrical energy, respectively, in [kWh], $Q_{\mathrm{NG,EGS}}$ and $Q_{\mathrm{NG,B}}$ are primary energy amounts consumed in engine-generator set and boiler, respectively, in [kWh], while $\eta_{\mathrm{G,SP}}$, η_{T}, η_{D}, and $\eta_{\mathrm{t,SP}}$ are, respectively, referent efficiencies of electrical energy generation, transmission and distribution, and thermal energy generation and distribution efficiency for separate production.

Some referent values for efficiencies are suggested in [12, 13]. In this paper referent value for total electrical energy generation efficiency is estimated according to [12, 13] and taken to be 0.4 and for boiler plant efficiency is 0.82, estimated based on the on-site measurements.

European legislative [11] defines the condition high efficiency co-generation production should satisfy. It is related to primary energy savings and assumes that high efficiency co-generation production is one that has primary energy savings of at least 10%.

Environmental indicator

As an environmental indicator, greenhouse gasses emission reduction potential is taken. This indicator is defined in [15, 17, 18], analogous to primary energy savings. It represents the difference between greenhouse gasses emitted by the co-generation plant and greenhouse gasses emitted by separate production plants when producing the same amount of heating and electrical energy, in [kg CO_2e]. For the purpose of this analysis, similar indicator is defined, but, again, with the possibility of making difference between electricity consumed on site and exported to grid. Besides that, unlike approach in [14, 17, 18], emission for natural gas is based on the input energy, instead of output. Greenhouse gasses emission reduction potential is calculated according to eq. (5):

$$GHGER=\left[\mu_{\mathrm{NG}}\cdot\frac{Q_{\mathrm{HD}}}{\eta_{t,SP}}+\mu_{\mathrm{e}}\cdot\left(W_{\mathrm{e}}\cdot\eta_{\mathrm{D}}+W_{\mathrm{D}}\right)\right]-\left(\mu_{\mathrm{NG}}\cdot Q_{\mathrm{NG,EGS}}+\mu_{\mathrm{NG}}\cdot Q_{\mathrm{NG,B}}+\mu_{\mathrm{e}}\cdot W_{\mathrm{i}}\right) \tag{5}$$

where W_{D}, Q_{HD}, W_{e}, and W_{i} are electrical demand, heating demand, exported and imported electrical energy, respectively, in [kWh], $Q_{\mathrm{NG,EGS}}$ and $Q_{\mathrm{NG,B}}$ are primary energy amounts consumed in engine-generator set and boiler, respectively, in [kWh], while η_{D}, and $\eta_{\mathrm{t,SP}}$ are, respectively, referent efficiencies of electrical energy distribution and thermal energy generation and distribution efficiency. The μ_{NG} is greenhouse gasses emission factor for devices that burn natural gas, in kg CO_2e per kWh, based on net calorific value. It is calculated based on global warming potentials of CO_2, CH_4 and N_2O and, in this paper, assumed to be 0.20245 kg CO_2e per kWh, according to [19]. In [15] and [17] this factor is taken to be 0.2 kg CO_2e per kWh, while in [18] it is 0.202 kg CO_2e per kWh. This factor usually varies with the part load and with combustion technology used, but for the first approximation, constant value might be used [14, 15, 17–19]. The μ_{e} is greenhouse gasses emission factor for electrical grid, in kg CO_2e per kWh, defined per unit of electricity consumed or produced, and should be established on the national level. Different values are used in Serbia: from 0.8 to 1.16 kg CO_2e per kWh. Instead of defining emission factor for grid, results are presented in function of various emission factors.

Results

Results are summarized in tab. 1.

Table 1. Summarized results

1. Financial indicators		
Net present value (10 years)	[EUR]	–55887
IRR (10 years)	[%]	6.92
2. Energy indicators		
Exergetic efficiency	[%]	39.52
Primary energy savings	[%]	28.53
3. Environmental indicator		
Greenhouse gasses emission reduction	[t CO_2e]	Figure 7

In figure 5, cash flow and cumulative cash flow for the time horizon of the potential co-generation implementation project is illustrated. It can be seen that, after 10 years, net present value is still negative and internal rate of return is smaller than discount rate (8%). Thus, dynamic payback period is almost 11 years.

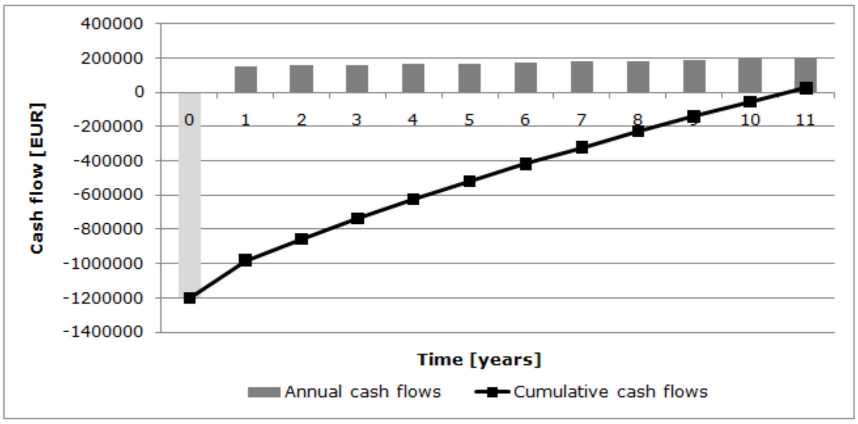

Figure 5. Cash flow and cumulative cash flow for the project

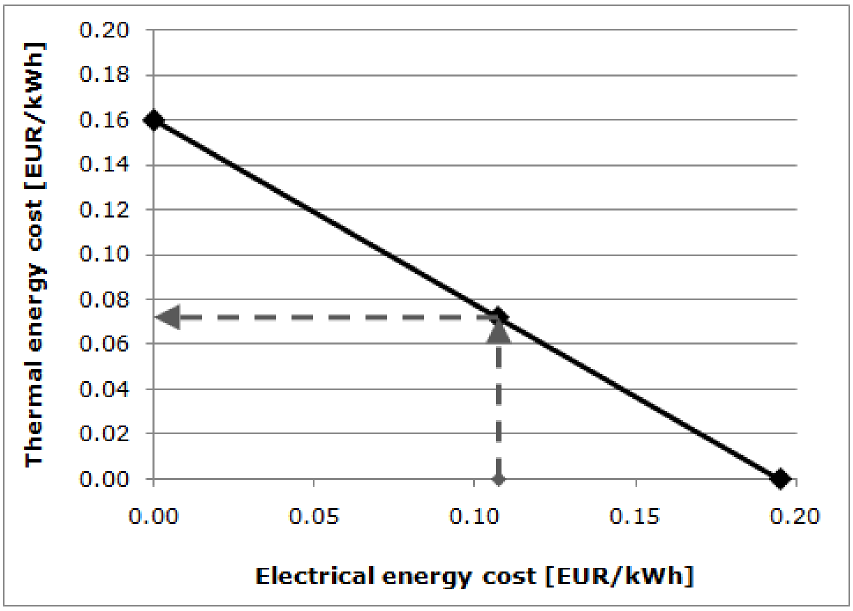

Figure 6. Triangle of costs for engine-generator set

Based on the levelized prices, triangle of cost for engine-generator set is constructed and illustrated in figure 6. Levelized natural gas price is EUR 0.0543. Feed-in electrical energy price for exported electrical energy corresponding to levelized natural gas price is EUR 0.1070. From triangle of costs, it can be seen that corresponding thermal energy cost at the exit from co-generation device is EUR 0.0722.

Greenhouse gasses emission reduction potential in the function of grid emission factor is illustrated in figure 7.

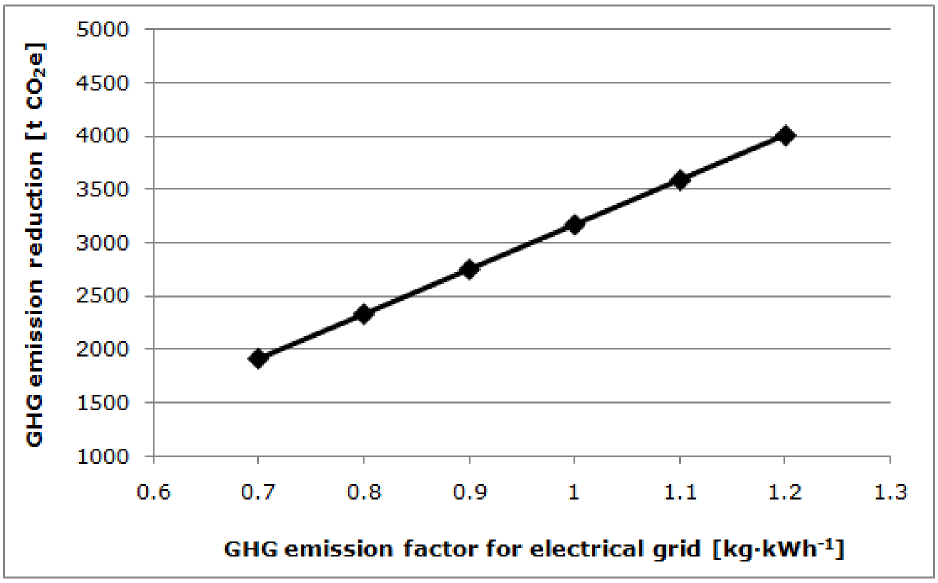

Figure 7. GHG emission reduction as a function of grid emission factor

Conclusions

From the results presented in the previous section, it can be concluded that implementation of engine-generator set in a small district heating system in Serbia would result in significant energetic and environmental benefits, *i. e.* primary energy savings and greenhouse gasses emission reduction.

On the other hand, financial indicators are still not very attractive. Dynamic payback period is higher than 10 years and levelized thermal energy cost at the exit of the engine is larger than EUR 0.07. There are several reasons for that like low electrical energy price, low electrical energy to natural gas price ratio and small number of hours of work for potential co-generation unit. It is obvious that new approach is necessary when Serbian district heating systems are in question in order to ensure financial attractiveness of co-generation projects.

Higher prices of electrical energy exported could make such projects attractive, but it appears not to be very realistic in the near future. Design of new buildings in the manner that domestic hot water is prepared using heat supplied from district heating systems and introduction of district cooling would, beside other benefits, ensure heat demand in summer months and more hours for operation of co-generation units in financially acceptable manner. The first option is much more realistic, especially in the urban areas where district heating systems are present.

It must be, however, underlined that, with introduction of feed-in tariffs in Serbia, co-generation projects obtained new perspective, higher financial attractiveness and significantly lower degree of uncertainties related to them.

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