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IMPACT OF REDUCED HEATING DEMAND ON GREENHOUSE GASES EMISSION UNDER COST-OPTIMAL OPERATION OF COGENERATION PLANTS

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Abstract. *Demand-side energy efficiency measures in buildings are usually considered advantageous from the environmental aspect. Similarly, the implementation of modern flexible energy-efficient cogeneration plants is often beneficial in terms of energy consumption and the environmental impact. However, the joint effects of these two approaches towards energy efficiency and greenhouse gases emission reduction are: dependent on many factors, more complex and harder to estimate. This paper analyses the impact of residential buildings heating demand reduction on greenhouse gases emission from a cogeneration plant. It illustrates realistic scenarios in which the reduction of heating demand might lead to the increase of greenhouse gases emission when an energy supply system operates in a cost-optimal manner.*

Key words: *buildings energy supply, cogeneration, greenhouse gases emission, operation optimization.*

1. INTRODUCTION

Buildings use approximately 40 % of global primary energy and contribute to around 30 % of CO_2 emission [1]. Buildings-related energy efficiency measures are important for primary energy saving and greenhouse gases emission (GHGE) reduction. Such measures can be classified into two categories: (1) measures on the side of consumers, i.e. final energy demand reduction, and (2) measures on the side of the components for energy conversion, i.e. supply. The later often involves the implementation of cogeneration and/or energy storage. High-efficiency cogeneration is indicated and promoted in the European Union as one of the key technologies for reducing GHGE, increasing energy efficiency and ensuring the security of energy supply [2]. It is a mature technology, possibly advantageous for the

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owners of the buildings and the operators of the plants [3]. Heat storage is an important addition to cogeneration plants since it can notably improve energy and cost efficiency by shifting heat production and better utilizing base-load components [4], [5].

Joint effects of mentioned two types of measures are complex and require special attention when evaluating the environmental impact of complex energy systems, especially when cogeneration plants operate in cost-optimal regimes. For example, [6] and [7] investigated a concern that a cut of heating demand due to energy efficiency improvements in buildings might cause a reduction of cogeneration components operation and consequently the increase of GHGE.

This paper analyses the operation of a cogeneration plant supplying a residential settlement and the impact of heating demand reduction on GHGE. It studies scenarios related to Serbian conditions in which the reduction of demand might lead to the increase of GHGE when an energy supply system (ESS) operates in a cost-optimal manner.

The rest of the paper is organized as follows. Section 2 describes the case study including the examined settlement and energy supply options. Section 3 illustrates the mathematical model used to optimize the energy supply plant and evaluate GHGE. Section 4 presents and analyses the obtained results. Section 6 brings the conclusions related to the performed analysis.

2. CASE STUDY

2.1. Description of buildings

The impact of reduced heating demand is studied on the example of a realistic urban residential settlement located in Niš, Serbia. The settlement consists of 20 five-story buildings. It is a typical Serbian settlement built in the period 1991–2000. The total heated area is 27045 m2. The buildings are modeled with the EnergyPlus software [8] in order to calculate heating demand and illustrated in Fig. 1. For the whole settlement, 402 conditioned and 122 unconditioned zones have been modeled. The usage of the buildings was scheduled throughout the day and year making a distinction between weekdays and weekends/ holidays. The schedules are based on measured data and conform to the typical occupant behavior in Serbia.

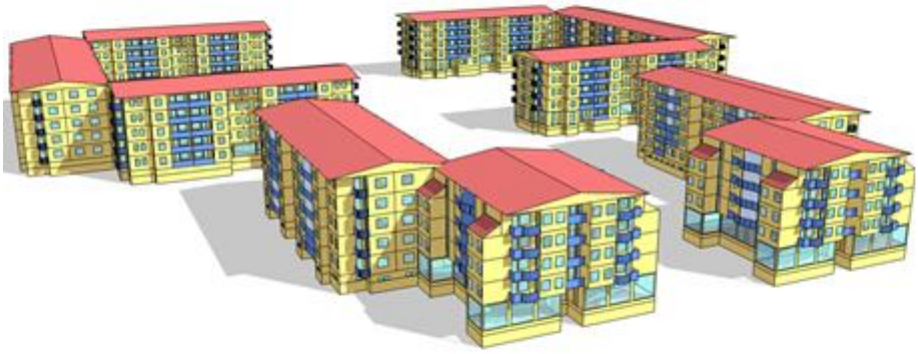

Fig. 1 The model of the examined settlement

Annual heating demand is determined using the EnergyPlus software with the time step of 1 h. Total annual heating requirement is around 1409 $\mathrm{MWh_t}$. The hourly profile is shown in Fig. 2. Electrical demand with the hourly resolution is estimated using the results of performed measurements. Total evaluated annual demand is approximately 2255 $\mathrm{MWh_e}$.

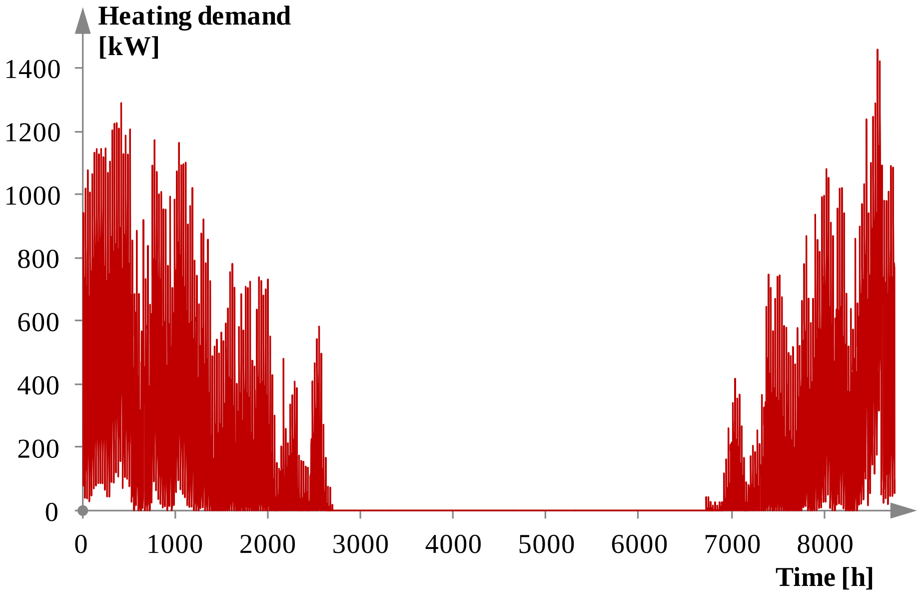

Fig. 2 Heating demand variations of the examined settlement during a year

2.2. Energy supply

New and improved ESS should be able to satisfy the entire heating demand of the residents. Electricity is needed for demand satisfaction and the operation of ESS components. It is generated in a cogenerator (CG) or imported from the electrical distribution grid. Electricity can be exported to the grid as well. Heating demand is satisfied either from CG or natural-gas-fired hot-water boiler (CH). Useful excess heat from CG may be stored into and retrieved from a heat storage tank (TS) or rejected to the environment. It is presumed that ESS will always operate in a cost-optimal regime without the possibility of simultaneous electricity import and export.

Three cases of ESS design are considered here, each one involving one CG, two CHs with the capacities of 490 kWt each and one 80 t TS with water as a storage medium and operating temperatures regime 90/70 °C. Considered CGs have the following nominal capacities: (1) Case 1 — 315 kWe; (2) Case 2 — 570 kWe; and (3) Case 3 — 803 kWe.

3. METHODOLOGY

Operating parameters of ESS are determined following the assumption on cost-optimal operation. Optimal operation regimes are determined using the moving-horizon approach and series of short-term optimization procedures, according to the methodology described in Ref. [9]. The considered horizon is one year, with the time resolution of 1 h. Since cost-optimal operation is presumed, the objective is minimal ESS variable costs, Zv, expressed in [EUR] and calculated according to Eq. (1):

$$Z_{\mathrm{v}} = \sum_{i,j}\left(\zeta_{\mathrm{e,I}}^{i,j} W_{\mathrm{e,I}}^{i,j} - \zeta_{\mathrm{e,E}}^{i,j} W_{\mathrm{e,E}}^{i,j} + \zeta_{\mathrm{f}} \left(\sum_{k=1}^{n_{\mathrm{CG}}} Q_{\mathrm{f,CG},k}^{i,j} + \sum_{k=1}^{n_{\mathrm{CH}}} Q_{\mathrm{f,CH},k}^{i,j} \right) + \sum_{k} Z_{\mathrm{om,v},k}^{i,j} \right) \tag{1}$$

where, respectively, i and j are day and hour indices; ζe,I, ζe,E and ζf are the prices of purchased and sold electricity, and fuel based on the lower heating value, in [EUR/kWh]; We,I, We,E, Qf,CG and Qf,CH are purchased and sold electricity, and fuel consumed in CGs and CHs, in [kWh]; nCG and nCH are the numbers of installed CGs and CHs; and Zom,v is variable operation and maintenance cost, in [EUR]. Here, the calculations are performed with the price of purchased electricity of 0.1 EUR/kWh during daytime (16 hours per day) and 0.025 EUR/kWh during nighttime (8 hours per day). The price of sold electricity is adopted to be 0.1 EUR/kWh, having in mind [10] and [11]. The price of fuel, i.e. natural gas is 0.04 EUR/kWh.

Annual operation-phase-related GHGE of ESS, mGHG, in [kg CO2e], is calculated according to Eq. (2):

$$m_{\mathrm{GHG}} = \sum_{i,j}\left(\psi_{\mathrm{e}}^{i,j} (W_{\mathrm{e,I}}^{i,j} - W_{\mathrm{e,E}}^{i,j}) + \psi_{\mathrm{f}} \left(\sum_{k=1}^{n_{\mathrm{CG}}} Q_{\mathrm{f,CG},k}^{i,j} + \sum_{k=1}^{n_{\mathrm{CH}}} Q_{\mathrm{f,CH},k}^{i,j} \right) \right) \tag{2}$$

where ψe and ψf are GHGE conversion factors of the national electrical grid and fuel based on LHV, in [kg CO2e/kWh]. The value ψe might vary with time, but is usually considered constant due to the lack of more precise data. Similar expressions are widely used to quantify GHGE in the literature, e.g. in Refs. [1], [12]–[14]. The value of the fuel-to-GHGE conversion factor is 0.20245 kg CO2e/kWh [15]. The value of the electricity-to-GHGE factor might vary depending on e.g. the available options for electricity generation and presents the interaction with the grid for electricity transmission and distribution. In Serbia, this value is approximately 0.74 kg CO2e/kWh, according to [16].

4. RESULTS AND DISCUSSION

Cost-optimal operation regimes are determined with the mentioned approach from [9] and Section 3. Generally, in all the examined cases, CGs are used as primary heat-generation components, while CHs usually cover peak loads. CGs operate for almost as many hours as required to satisfy heating demand, mostly at full loads. Typically, there is no useful heat rejection to the environment. Excess heat is stored in TS and used later, e.g. during the hours with peak demand. Generated electricity is primarily used to satisfy the needs of the consumers. If there is excess electricity, it is sold to the grid. If the amount of generated electricity is insufficient to satisfy on-site requirements, it is purchased from the grid. Exceptions are the periods with lower import electricity price, when the use of CGs is mostly not cost-optimal. Then, heating demand is satisfied from TS or CHs.

Figures 3 and 4 illustrate heating demand and the use of the demand-satisfaction options in Case 1 for two typical weeks, in January and March respectively. In the cases when CG and TS are sufficient to satisfy heating demand, CHs are not used at all and TS is applied to satisfy peek loads and heating demand during low-electricity-price periods, as shown in Fig. 4.

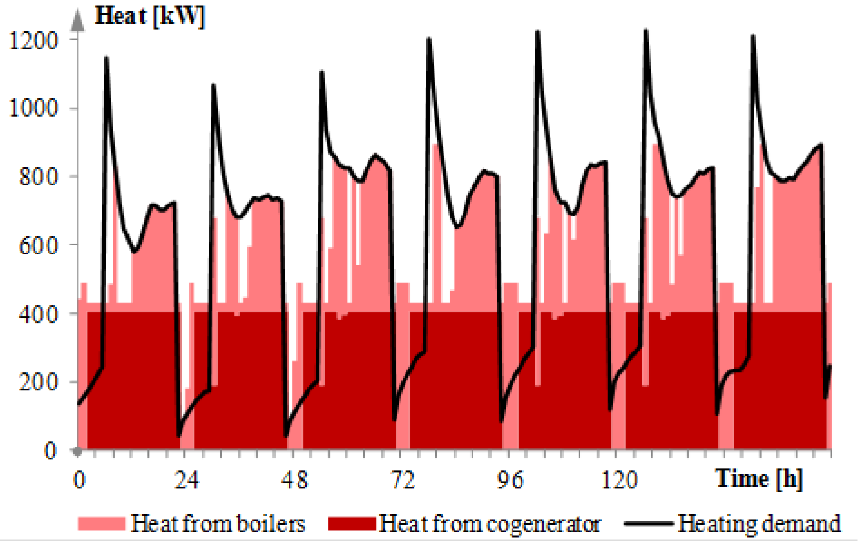

Fig. 3 Heating demand satisfaction for a week in January

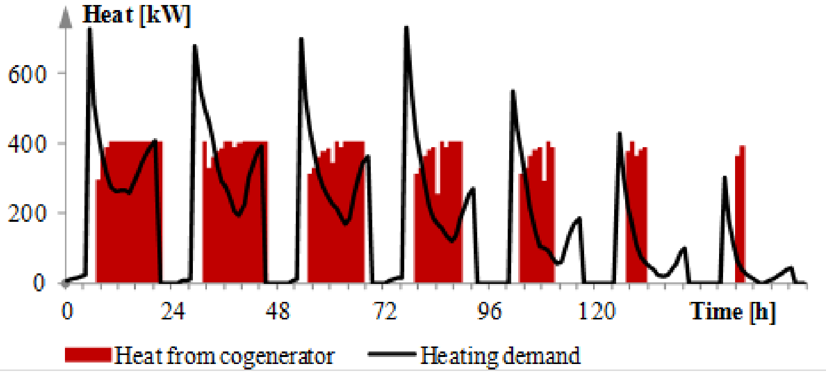

Fig. 4 Heating demand satisfaction for a week in March

In two other cases, the capacities of CGs are larger and the use of CHs is significantly lower than in Case 1. In Case 1, heat from CHs represents 22.56 % of total heat generated, in Case 2, this share is much less, i.e. 2.05 %, while in Case 3, it is only 0.45%. It could probably be said that in two latter cases CGs are oversized, although the optimal structure and design of the plant depend on many factors and are beyond the scope of this paper.

Figure 5 presents annual GHGE related to Case 1 for different values of the electricity-to-GHGE factor (ψe) and heating demand. The factor ψe is used to estimate the impact of imported and exported electricity to GHGE. Lower values of ψe correspond to electricity systems with lower GHGE, e.g. with larger share of renewable energy sources. Contrary, larger ψe values correlate with the systems with lower efficiencies and mostly based on fossil fuels, primarily coal. The values of heating demand are obtained multiplying the demand calculated using the simulation for each hour (Fig. 2) by the varying demand factor. Figure 5 shows that the reduction in heating demand — e.g. obtained implementing demand-side measures — not necessarily leads to the decrease in GHGE of cogeneration plants with cost-optimal operation. This dependence is complex and is generally not monotonic. The change of GHGE with heating demand reduction is influenced by many factors, e.g. energy prices, the structure and design of the plant, etc. The reduction of heating demand has two consequences:

(1) The decrease in CHs use which is mostly due to lower peaks and needed heat quantities. The result of this is reduced fuel combustion in CHs which leads to GHGE cut, according to Eq. (2).

(2) The decrease in CGs use which has more complex impact on GHGE. Clearly, this also leads towards lower fuel consumption and GHGE reduction. On the other hand, decreasing heat generated in reciprocating engines (and gas turbines) implies a reduced amount of obtained electricity available for both export and on-site use. Thus, the amount of exported electricity drops and imported electricity rises, implying higher GHGE, according to Eq. (2). This effect is significant for larger ψe values and almost negligible for very small ones, as shown in Fig. 5.

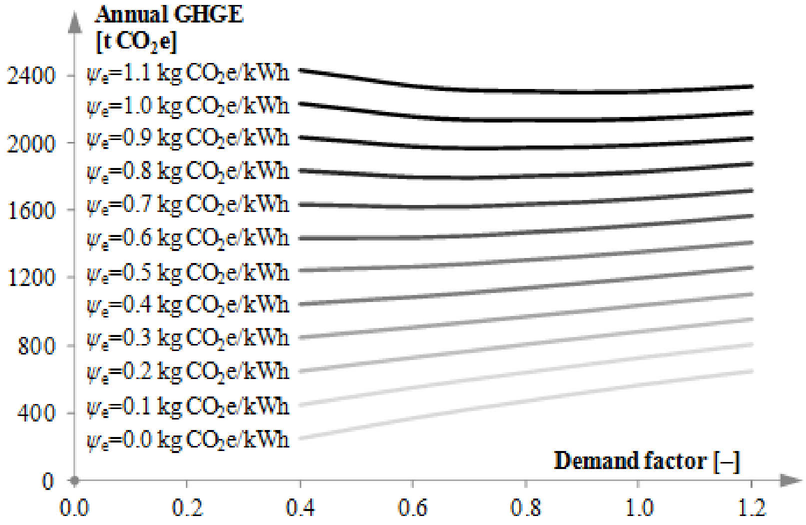

Fig. 5 Annual GHGE dependence on heating demand and electricity-to-GHG conversion factor for Case 1

In Case 1, the amount of heat generated in CHs drops significantly, while the use of CG decreases slower with the reduction of heating demand down to the value of the demand factor between 0.6 and 0.7, as illustrated in Fig. 6. The impact of lower fuel consumption in CHs is dominant and GHGE decreases for larger ψe values. When the demand factor decreases from 0.6 down to 0.4, CG satisfies almost entire heating demand and consequently its use drops faster. Thus, the effect of available electricity cut becomes dominant and GHGE increase for larger ψe values.

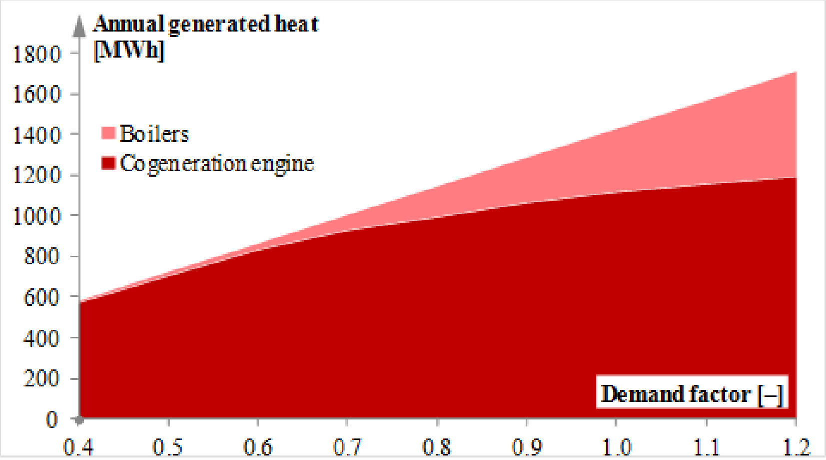

Fig. 6 The origin of generated heat for varying demand

Figures 7 and 8 present GHGE dependence on heating demand for Case 2 and Case 3 respectively. The trends are similar, but for larger ψe values GHGE increases with the demand decrease all the time. This is because the use of CG is more dominant than in Case 1, and the use of CHs is far less, making the effect of decreasing CHs use mostly insignificant.

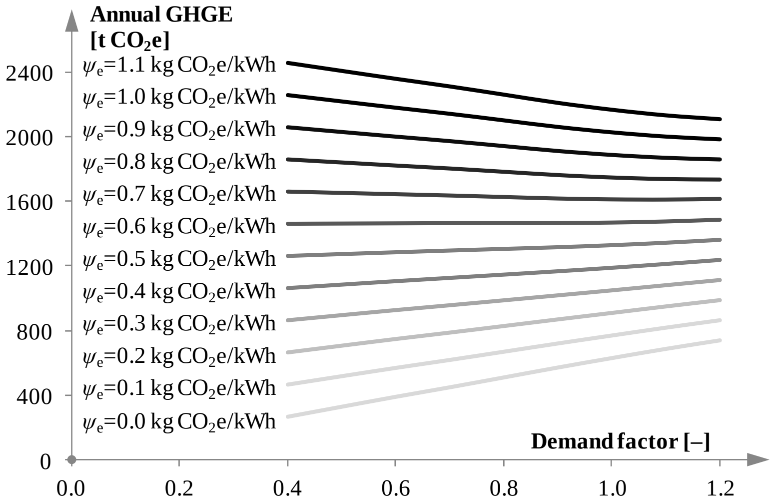

Fig. 7 Annual GHGE dependence on heating demand and electricity-to-GHG conversion factor for Case 2

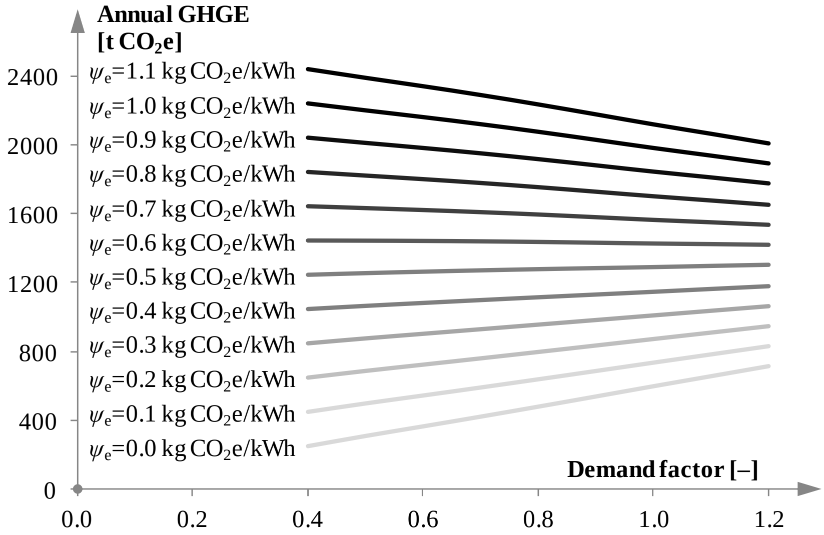

Fig. 8 Annual GHGE dependence on heating demand and electricity-to-GHG conversion factor for Case 3

For all three cases, the trends are similar for smaller ψe values, approximately up to 0.4–0.5 kg CO2e/kWh: GHGE decreases with the drop of heating demand and the positive effect of reducing fuel combustion is dominant over the effect of lowering available electricity from cogeneration. In such scenarios, natural-gas based cogeneration might not be a preferable electricity-generation option for GHGE reduction anyway.

5. CONCLUSIONS

This paper examines the impact of buildings' heating demand reduction on greenhouse gases emission related to the cogeneration plant. Although both demand-side energy efficiency measures in buildings and the implementation of modern cogeneration plants are considered beneficial from the environmental impact point of view, their joint effects are not straightforward.

Baseline heating demand is determined using buildings simulation in the EnergyPlus software. Cost-optimal operation is assumed for the energy supply plant consisting of a single natural-gas-fired reciprocating engine for cogeneration, two hot-water boilers and one heat storage tank. Optimal operation regimes are determined following a moving-horizon-based methodology.

This paper shows a complex and generally non-monotonic dependence between heating demand and greenhouse gases emission. Depending on many factors, emission might rise or drop with the decrease of demand due to optimal operation modes of the plant that correspond to different demand levels. As a consequence, in a general case, it is necessary to observe and evaluate demand- and supply-side energy-efficiency measures together, as an entirety.

This paper also stresses the importance of the consideration and — where appropriate — operation optimization of cogeneration systems in the design phase. Wrong assumptions on operation regimes can lead to large errors in the assessment of greenhouse gases emission (as well as primary energy consumption) and serious misinterpretations related to the effects of demand-side energy efficiency measures.

The results presented here are specific to the mentioned cases and would vary with the prices of energy commodities, conversion factors, buildings and plant structure and design, etc. However, this paper shows the general need for the scientific and detailed knowledge-based bottom-up approach for the precise assessment of greenhouse gases emission related to complex energy plants. For this purpose, sophisticated software solutions for buildings simulations and the optimization of related energy systems need to be used.

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UTICAJ SMANJENE POTREBE ZA GREJANJEM NA EMISIJU GASOVA SA EFEKTOM STAKLENE BAŠTE PRI FINANSIJSKI-OPTIMALNOM RADU KOGENERATIVNIH POSTROJENJA

Mere energetske efikasnosti u zgradama na strani potrošača se obično smatraju poželjnim sa aspekta uticaja na okolinu. Takođe, implementacija modernih fleksibilnih energetski-efikasnih kogenerativnih postrojenja često ima pozitivan energetski i ekološki uticaj. Ipak, zajednički efekat ova dva pristupa za povećanje energetske efikasnosti i smanjenje emisije gasova sa efektom staklene bašte je: zavistan od više faktora, značajno kompleksniji i teži za procenu. Ovaj rad analizira uticaj smanjenja potrebe za grejanjem na emisiju gasova sa efektom staklene bašte koja potiče od kogenerativnih postrojenja. Ilustrovan je realističan scenario u kome smanjenje potrebe za grejanjem može dovesti do povećanja emisije gasova sa efektom staklene bašte kada sistem za snabdevanje *energijom radi u finansijski-optimalnom režimu.*

Ključne reči: *energetsko snabdevanje zgrada, kogeneracija, emisija gasova sa efektom staklene bašte, optimizacija režima rada.*