OPTIMIZATION MODEL FOR IMPROVEMENT OF DISTRICT HEATING SYSTEM BY INTEGRATION OF COGENERATION

by

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Modelling of a complex district heating system by increasing the energy system efficiency and by reducing emissions through the implementation of new and low carbon technologies is presented. One of these technologies is cogeneration which is used to increase energy efficiency and to reduce CO_2 emissions. Presented model uses linear programming as a basis for mathematical modelling of the energy system. The mathematical calculation is set pragmatically, so it can be efficiently and reliably used to assess the impact of most important parameters on the efficiency of the regional energy system. The model analyzes the effects of integration of cogeneration into the existing energy system using a given goal function. The basic criterion is set to be the reduction of environmental impact. The model is successfully tested on the complex district heating system with the power of about 600 MW.

Key words: *cogeneration, district heating, emission reduction, natural gas*

Introduction

District heating (DH) systems have a role to provide comfortable, safe and economical heating for citizens. It is noticed that human needs (or energy services) dictate the energy system and its advancement – the insatiable human desire is the constant source and driving power for the improvement and growth of energy systems [1]. Shesho *et al.* [2] have indicated that higher energy efficiency could help to achieve higher living standard of citizens, better energy security, safe and reliable energy supply, cleaner environment, and nevertheless more competitive business opportunity. Connolly *et al*. [3] suggests that DH systems can play an important role in the cost-effective decarbonisation of the EU energy system. Therefore, the DH may become a tool to achieve the reduction of carbon emissions and to use primary energy at lower cost.

Today, the big and complex DH system uses mostly fossil fuels. Puning, *et al.* [4] have stated current strategic heat sources for the reduction of GHG emissions that include cogeneration or combined heat and power production (CHP), waste to energy conversion, large scale heat pumps, solar energy, *etc*. Nowadays, energy system developers, as well as scientists, work together to include more RES in the DH system and to promote their use and further advancement. Future development of DH systems also includes intelligent control as the fourth generation of DH systems [4].

Decarbonisation measures involve utilization of more efficient technologies and less polluting fossil fuels, such as natural gas instead of coal [5]. This can bring additional stability to DH systems that are mostly based on RES. If coal is replaced with natural gas-based cogeneration, this can be considered as a measure for decarbonisation due to overall lower emissions

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[6]. In the following analysis, the reduction of emissions is compared in combined and in separate heat and power production. Felipe Andreau, *et al.* [7] have analyzed recently published papers and they conclude that primary energy saving (PES) and GHG emission reduction in the DH system operation can be achieved by using natural gas for CHP and heat storage in the DH and by solar energy integration.

The vision of a new and sustainable energy system is based on carbon recycling and on the use of renewable energy. Many documents in the EU and also in other countries in the world deal with changes of the energy system with a final goal to attain the reduction of GHG emissions [8][*]. In fact, each new energy system tends to have more severe and far-reaching adverse impact on the environment than the previous energy system it has superseded [1]. In order to fulfil daily energy needs of different kind of consumers, new sustainable energy system has to meet the following main requirements: the source of energy has to be inexhaustible and available everywhere on the planet with zero GHG emissions when burning new fuels, accessible at any place and at any time, compatible with existing infrastructure and involving only minor adjustments and implemented in parallel with the present energy system. It also has to be competitive (with fossil fuels price which includes all external-non acknowledged environmental costs) [8]. Meeting all these requirements is very complex and cannot happen in a short period of time. The energy crisis and environmental impacts of fossil fuels are the main motivation for engineers to find more efficient energy conversion technologies. The use of CHP for DH and cooling has advantages such as: minimization of energy distribution losses, improvement of energy efficiency, reduction of environmental impacts, fuel flexibility, and fuel supply security, reliable and cost-effective technologies [9].

Distributed generation is one of the ways to ensure the security of energy supply and the reduction of costs. On a national level, cogeneration is one of the most appropriate concepts to achieve the objectives of energy efficiency and emission reduction. In many developed countries, cogeneration plants make an important source of thermal energy and also of electricity. In recent years, the awareness of the community has grown regarding the huge environmental impact that conventional power plants and DH systems have. This paper gives a proposal for the development of existing DH systems which can be easily and quickly applied and which lead to the better use of primary energy and to the reduction of CO_2 emissions at the national level. The research presented in this paper is the model of the regional energy system and the study of its behavior when conducting its technological improvement in order to increase the system energy efficiency and to reduce emissions.

In this paper, the basic criterion for the optimization of operations of a complex DH system is set to be minimum CO_2 emissions. A universal scheme of the energy system is defined with various sources of energy. In particular, an emphasis is put on cogeneration which, as a rule, has very high efficiency. The concept of the model primarily satisfies real needs of end users in such a way that minimum CO_2 emissions are ensured. The model presented here is not restricted only to cogeneration but it enables that any other modern technology can be included in the analysis in line with the shown procedure.

In order to integrate CHP into the existing DH system, it is necessary to look at all characteristics of regional and local energy systems, requirements on the consumer side, and

[*] In some papers or documents, GHG reduction is mentioned, in other ones, the reduction of CO_2 while in third ones, the reduction of CO_2 equivalent emissions. In cited papers, the specified term is indicated. Although there are differences, the connection between them is unambiguously known. (https://ecometrica.com/white-papers/greenhouse-gases-co2-co2e-and-carbon-what-do-all-these-terms-mean)

legislation, for the purpose of determining whether there are some technical barriers to the construction of a cogeneration plant at certain locations, *etc.* Increasing energy efficiency of technologies, their investment acceptability, reliability and exploitation attractiveness, which belong to distributed energy technologies, have caused changes in the regulatory environment and in energy markets, as well. Given the energy and environmental benefits of CHP, this technological practice is generally encouraged through national incentive programs based on performance parameters [10]. This is confirmed by the IEA, which states five factors that contribute to this evolution. These factors are: development of technology itself (smaller and larger units) for distributed power and/or heat generation, restrictions on the construction of new transmission lines, increased requirements from users to secure electricity supply, liberalization of electricity market, and reduction of GHG emissions which affect global climate change [11]. However, it is not always certain that cogeneration will bring emission reduction in total. It depends on the cogeneration system itself and on technologies that are used for separate production of heat and power. It also depends on the type of fuel that is used in these processes (in cogeneration and in separate production at the national level).

By increasing the number of installed cogeneration plants, common electricity distribution network will be significantly relieved. There is a need to emphasize that there are certain barriers for the introduction of cogeneration and for its introduction into the existing energy system. All barriers for applying cogeneration in existing energy system have to be identified and the effects of their impact have to be evaluated. The occurrence of such situations has to be assessed. One of potential effects of cogeneration is that increased share of distributed production can lead to new difficulties and to overloading other networks, such as, for example, natural gas pipeline. In any case, it is necessary to avoid the construction of new transmission lines as the electricity distribution network should be available as a reserve mode of electricity supply. In many countries, it is necessary to make additional efforts in energy policy design in order to overcome existing obstacles and to strengthen the position for the use of cogeneration in a liberalized energy market. In Europe, the introduction of high-efficiency cogeneration regulations has radically changed the incentive scheme for cogeneration power plants that, in turn, inevitably affects the evaluation of techno-economic feasibility of new cogeneration plants [10].

Energy systems

Mathematical programming has been used for decades to optimize and plan complex systems such as energy systems. This approach uses optimization algorithms to search for a feasible design according to specified criteria and limitations [12]. There are several papers that deal with optimum planning of energy systems and with energy and economic assessment of the implementation of cogeneration in some sectors of the existing energy system. Erdogdu [13] uses ARIMA models for time series forecasting of electricity demand. Gvozdenac, *et al.* [14] analyze large and complex national energy system in Thailand that is based on the use of natural gas, basic fuel for the production of electricity. Gvozdenac Urošević [15] gives detailed analyzes of a complex energy system, as well as individual sources of heat with their characteristics. These individual sources of heat are integrated into the complex energy system that is the subject matter of optimization accompanied by meeting criteria for minimum CO_2 emissions.

In numerous papers, different models and methods for optimization of energy systems are used. Models differ in their structure, character, type of input data, but also in already programmed assumptions, so the comparison between them is difficult. Connolly, *et al.* [16] has reviewed with detail comparison 37 tools used for typical application from analyzing single-

-building systems to national energy systems. Very often, even after the adjustment of input data, they can provide different results. The study of large and complex energy systems is a difficult task. There are many techniques and methods for analyzing energy systems in order to obtain results about their behavior, efficiency and other essential aspects. Most common mathematical techniques used in energy models are linear, mixed-integral and dynamic programming. Mojica, *et al.* [12] show a very detailed case study for the optimization of the expansion of a DH system and evaluates, through the timing for investment decision, the type of capacity increase and fine-scale operational modes. Very extensive analysis of available computer tools is given in [16]. It is obvious, conclude the authors, that there is no energy tool that can cover all specificities that can occur in the concrete, complex energy system. Dicorato *et al.* [17], performed the linear programming optimization procedure based on the model of the flow of energy (Energy Flow Optimization Model), which is proposed to evaluate the effects of distributed generation and energy efficiency. The frame design that is presented in this work has been improved and it includes the description of the contribution of distributed generation in increasing energy efficiency, all in order to reduce the environmental impact and operating costs.

The subject of research in this paper is the regional energy DH system that is observed not only as a technical system but also as a rather complex set of components that act together to achieve a goal and to perform a task within the boundaries of the system. For defining purposes, the regional energy system will not be used as energy capacity of its elements but above all as its content, which includes sources in a very broad sense. The most widespread technologies of CHP are with steam turbines, gas turbines, combined cycle gas turbine (CCGT), gas engines with spark ignition and Diesel engines [6].

The planning process needs to predict the system behavior during the period of several decades. Since the energy system has a relatively long service lifetime and many hardly predictable disturbances that affect it, in this paper, a robust model, which can serve as a tool for creating energy policy of the region, has been developed. For proper integration of cogeneration, the first step is the definition of the energy system so that the model can take into account all elements and related legal regulations. The model that has been developed includes all necessary elements that can have an impact on the existing energy system in finding the right way to upgrade the system and to provide continuous heat and power supply to consumers. The bases used for economic valuation are taken for the Republic of Serbia: valid regulations for cogeneration, criteria for PES, incentive tariffs for the purchase of electricity, substrates for financial and functional analysis through collected prices and working characteristics of equipment from multiple sources, and market prices of certain types of energy [18]. The main criterion in the search for optimum DH system configuration is the minimum emission of CO_2. The position of this criterion is principally a defining feature of this model because most other models give priority to economic criteria. It seems that at this point, because of the growing importance of the climate change, the priority should be given just to the reduction of emissions CO_2. Due to the importance of the reduction of GHG emissions, it is considered that the application of this criterion has neither an alternative nor a price. The proposed model allows setting up other functions for optimum configuration of the system. The development of large energy systems and the use of new energy technologies are to the greatest extent dependent on current national energy policy and very often on regional policies. For this paper, the following documents are also of great importance: directive on energy efficiency [19], specifying direction of the building sector development [20], precisely defining boundary values of efficiency of individual energy transformations [21], clearly determining the procedure for the control of energy systems [22], concretizing action plans [23], and, finally, with programmed strategic activities

[24]. All these documents are subject to constant changes and this requires permanent adaptation of relevant large systems. The proposed model of a complex energy system is actualy intended for continuous control of vital technical parameters of the system for the purpose of monitoring and supervising its operations and further development.

Energy system modelling

The basic element of any energy system will be called the consumer *entity* in the model. The entity means an individual or a group of consumers that are connected to one basis. The entity can be a plant in which primary energy is converted into thermal energy. For example, the entity $E(1)$, fig. 1, is supplied with electricity with medium or high voltage and with thermal energy from the heating entity $T(k)$. It is expected that within the entity $E(1)$ there is a power transformer that provides the voltage of 0.4 kV. The entity $E(2)$ uses only medium or high voltage electricity. In case that there are entities $E(n)$ and that there is production of electricity within these entities, their excess electricity will go into the distribution network. Within each regional energy system there are points where some energy conversion or adjustment of energy parameters for future use is carried out. These parameters are, for example, heating, power transformers, natural gas stations, *etc.* There are also transformers and they are marked with a $T(k)$ in the model. Within transformers, there are: power stations, heating or/and power plant, hydropower, reduction station, *etc.* Within certain entities, it is also possible to have heat storage, solar thermal system DHW preparation system, *etc.* These options will not be analyzed here in details due to limited space.

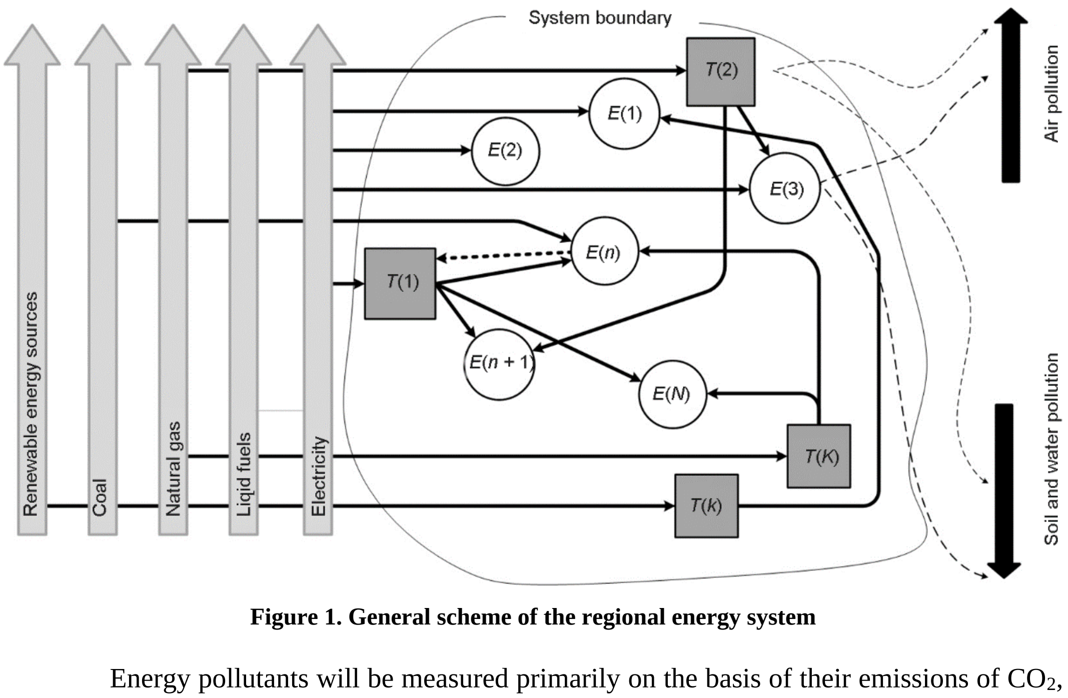

Figure 1. General scheme of the regional energy system

Energy pollutants will be measured primarily on the basis of their emissions of CO_2, as the primary and good representative of total emissions. This means that CO_2 emissions associated with each entity will be calculated. For the purposes of overall energy system modelling, its every element is modelled separately with the set of equations and constraints. Mathematical interpretation of every entity used as a test case will be presented in the paper. The prediction of the energy system behavior primarily involves assumptions that can be expressed only as appropriate, more or less reliable, probable (*e.g.*, the price of fuel, the price of products on the market, *etc.*). Every part of the energy system in the model is defined with the set of parameters.

Single boiler is defined only with two equations:

– Maximum thermal power of the boiler:

$$N_{\mathrm{t}} \le N_{\mathrm{t,max}} \tag{1}$$

– Dependence of fuel power and current thermal power of the boiler:

$$F \le \frac{N_{\mathrm{t}}}{\eta_{\mathrm{B}}} \tag{2}$$

where N_{t} [kW] is the actual (current) thermal power of the boiler, $\eta_{\mathrm{B}} = f\,(N_{\mathrm{t}}/N_{\mathrm{t,max}})$ [–] – the actual efficiency of the boiler, and F [kW] – power of fuel for the boiler.

This simplified definition of the boiler is suitable for calculation, but this simplification will not diminish the value of calculated results. Single boiler in the set of boilers will be defined as one-sided matrix with n elements. In the matrix, time is implicitly given as it contains monthly fuel consumption of twelve consecutive months and monthly number of hours of the boiler operation. The length of time periods and their number is arbitrary and adjusted according to the problem being solved. One boiler within the boundaries of the system is defined in the following way:

$$\mathrm{BOILER}(k) = (A_1, A_2, \ldots, A_N)\ (n = 1, 2, \ldots, N);\ (k = 1, 2, \ldots, K_{\mathrm{BOILER}}) \tag{3}$$

The N is the total number of parameters for each boiler, and K_{BOILER} – the total number of boilers within the boundaries of the analyzed system. Coefficients A_n are used to define boiler properties (they refer to all relevant parameters of the boiler, but also to the parameter that determines its use: number of operating hours, load per period, *etc.*). When analyzing the cogeneration plant, produced electricity is analyzed first and then released thermal energy. If a gas engine is used for electricity production, then the power of fuel for electricity production is equal to:

$$F \le \frac{N_{\mathrm{e}}}{\eta_{\mathrm{e}}} \tag{4}$$

where F [kW] is the fuel power, $\eta_{\mathrm{e,max}}$ [–] – the efficiency of fuel transformation into electricity, and η_{e} – the actual efficiency of energy transformation. Actual efficiency depends on the load of gas engine and can be described by the following equation:

$$\eta_{\mathrm{e}} = \eta_{\mathrm{e,max}} \left[\alpha_0 + \alpha_1 \left(\frac{N_{\mathrm{e}}}{N_{\mathrm{e,max}}} \right) + \alpha_2 \left(\frac{N_{\mathrm{e}}}{N_{\mathrm{e,max}}} \right)^2 \right] \tag{5}$$

where α_0, α_1, and α_2 are constants that determine dependence of efficiency of the plant load. The index *max* is related to the efficiency of the load of 100% ($N_{\mathrm{e,max}}$). The constants are determined for every gas engine from the manufacturer's data or on the basis of own measurements. It is possible to model any part of the energy system in a similar way [12].

For modelling the DH system, a linear programming method will be used.

In procedures for problem solving, it is necessary to specify a goal function in relation to given constraints. By means of specified mathematical functions, the optimum configuration of CHP integration into the DH system is calculated that meets pre-set parameters. For problem solving in the field of linear programming, there are numerous tools and programs. For the needs of linear programming of the energy system, the MS EXCEL in combination with the VISUAL BASIC FOR APPLICATIONS – VBA is used in this paper.

The focus in this paper is that the basic criterion should be the reduction of CO_2 emissions. This criterion is universal and widely accepted, but usually suppressed by economic parameters. The goal function in general terms is equal to:

$$\Phi = c(1)x_1 + c(2)x_2 + \ldots + c(n)x_n + c(N)x_N \tag{6}$$

and constraints are:

$$a(1,m)x_1 + a(2,m)x_2 + \ldots + c(n,m)x_n + \ldots + c(N,M)x_N (\leq) = (\geq) b(m) \tag{7}$$

where x_n is the independent variable, (n = 1, 2, 3, ... N), $c(n)$ – the coefficients of the goal function, $a(n, m)$ – the coefficients of the limitation function, (m = 1, 2, 3, ... M), $b(m)$ sets the limit function value. Constant values of coefficients $a(n, m)$ and $c(n)$ make the mathematical model linear. The values of $a(n, m)$, $b(m)$, and $c(n)$ can be larger, smaller or equal to zero. The number of independent variables can be greater, smaller or equal to the number of equations or to the unbalance of the constraint. If $m > n$, at least $m – n$ constraints do not affect the solution. In the case where $m < n$, at least $n – m$ are independent variables, they are zero. Depending on a desire, we can adjust the general function formula to our target. The presented can be used to analyze any complex energy system. Here, it will show its use for analyzing the DH system with a total power of about 600 MW.

District heating case study

The development of the DH system, as well as many other similar systems, depends on many factors: the economic development of the city, the change in the number of inhabitants, the intensity of the construction of residential and commercial buildings, the possibilities of investing in certain energy systems, the prices of individual types of energy, national energy policy, national energy action plan, status of other heating systems, expansion of pipeline for DHW, *etc.*

The analyzed DH system has the assignment to deliver heat energy to the urban area with around 250 thousand inhabitants and DHW in several districts of the DH system. The DH system consists of 6 substations (2 substations have significantly lower installed capacity, total 15 MW, and will not be included in modelling), main split station, hot water pipeline 220 km, more than 3800 local thermal substations in buildings and one combined heat and power plant (gas and steam turbine).

The proposed model has been tested at the DH demand side with the total heat output of 600 MW on the demand side. This power is distributed to four locations. Installed thermal power are: East = 150 MW, South = 150 MW, North = 100 MW, and West = 200 MW. The available power of existing boilers per location is 145, 225, 40, and 160 MW, respectively. Their total thermal capacity at the thermal power plant threshold is 570 MW. There is a possibility of redistribution of heat energy between individual districts. All districts can use part of the heat capacity of the local power plant. The available heat output from the power plant is 330 MW (CCGT). This means that the total available heating power on the supply side is 900 MW.

The proposed model will analyze simultaneous operation of boilers and power plants, as well as the possibility and effects of operating gas engines (CHP) that will be distributed in all four districts. This will increase the heating power on the supply side with the possibility of gradual reduction of the share of boiler capacity. Since preparation of DHW and its distribution do not exist in all districts, this will not be the part of this analysis.

Average duration of heating season is 192 days and mean outdoor air temperature is 4.2 °C. On a daily basis, the system is in operation for 16 hours for heating purposes. For simpler data manipulation, the heating season is divided into 16 periods of 12 days each. This is not the ultimate and it is possible to divide into longer and smaller periods. Since, on the average, daily heating lasts 16 hours (from 5:00 to 21:00), this means that the duration of active operation of the heating system in each period is 12 days multiplied by 16 hours per day that is 192 hours per period. When we subtract 192 hours from 288 hours, we get that boilers are off for 96 hours. Of course, the heating power depends mostly on outside temperatures and with reference to that, daily duration of the plant operation is shortened or extended in certain periods.

Figure 2 shows the load curve of the DH system subject to these analyzes. All analyzed options will satisfactorily display the load curve. The change in outdoor temperatures during the heating season is also shown. All available capacities (boilers, CCGT, and CHP) have been engaged to meet the load, but with the use of minimal CO_2 emissions at the national level. It is necessary to have in mind that the construction of the CHP plant is at the initial stage and that only boilers and the CCGT plant actualy exist. The parts of these existing plants are very old and there are some indications that further development of the DH system will be by means of the increase of the CHP share. Undoubtedly, there are possibilities for other development scenarios. However, with the proposed method, it will be possible analyze all options.

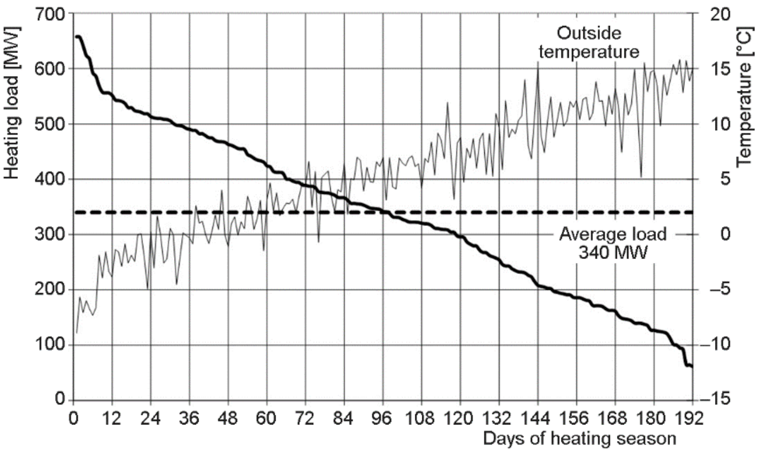

Figure 2. Load and outside temperature *vs.* days of heating season

The DH system is presented in fig. 3. The numbers that are inputted refer to the Option 2 and figures are only different for other two options. The purpose of this paper is to evaluate the effect of upgrading the system with a CHP plant that will be located in DH units. This will achieve flexibility in the operation of the entire DH system and ensure the security of supply.

Table 1. Data for analyzed options

Option 1					
Unit	Demand, *D*, [MW]	Supply, *S*			*S*/*D* [–]
		Boilers [MW]	CCGT [MW]	CHP [MW]	
East	150	145	25	30	1.33
South	150	225	25	10	1.73
North	100	40	25	20	0.85
West	200	160	25	10	0.98
	600	570	100	70	1.23
Option 2					
East	150	145	50	20	1.43
South	150	225	50	20	1.97
North	100	40	50	20	1.10
West	200	160	50	20	1.15
	600	570	200	80	1.42
Option 3					
East	150	145	0	10	1.03
South	150	225	0	20	1.63
North	100	40	0	20	0.60
West	200	160	0	10	0.85
	600	570	0	60	1.05

In all analysed options presented in tab 1, the DEMAND is identical, and the same load curve applies, fig. 2. The available power of all boilers is unchanged for all options but, there is variable participation of the CCGT and CHP. Because of that, the power in districts is different in different options. The supply and demand ratio ranges from 0.6 to 1.97. For the *S*/*D* below 1, there is a need to supplement the lack of heat energy, which can be provided by short connections among the districts. In all options, the total *S*/*D* is above 1. Nominal (maximum) efficiency of boilers is 0.90, of CHP plants (gas engines), it is 0.80, and of CCGT, it is 0.75. Efficiency decreases as loads are reduced and this is taken into account the calculation. The actual efficiency of boilers is determined according to eq. (5) taking into account previous measurements made on individual boilers. Similar is done for CCGT and CHP.

In this case, only natural gas is used as fuel. The emission factor for natural gas is 0.20 kg CO_2/kWh [16]. Natural gas is also used to produce electricity. The emission factor for final electricity for Serbia is 1.099 CO_2/kWh [16]. By using the energy balance of Serbia in 2017 [25], the degree of utility of energy transformation in power generation plants can be determined. In the specific case of energy mix, a different primary energy sources from which final electricity is produced was totally 7867 ktoe. The annual electricity used by consumers was 2418 ktoe. This means that the national electricity efficiency was 0.3074.

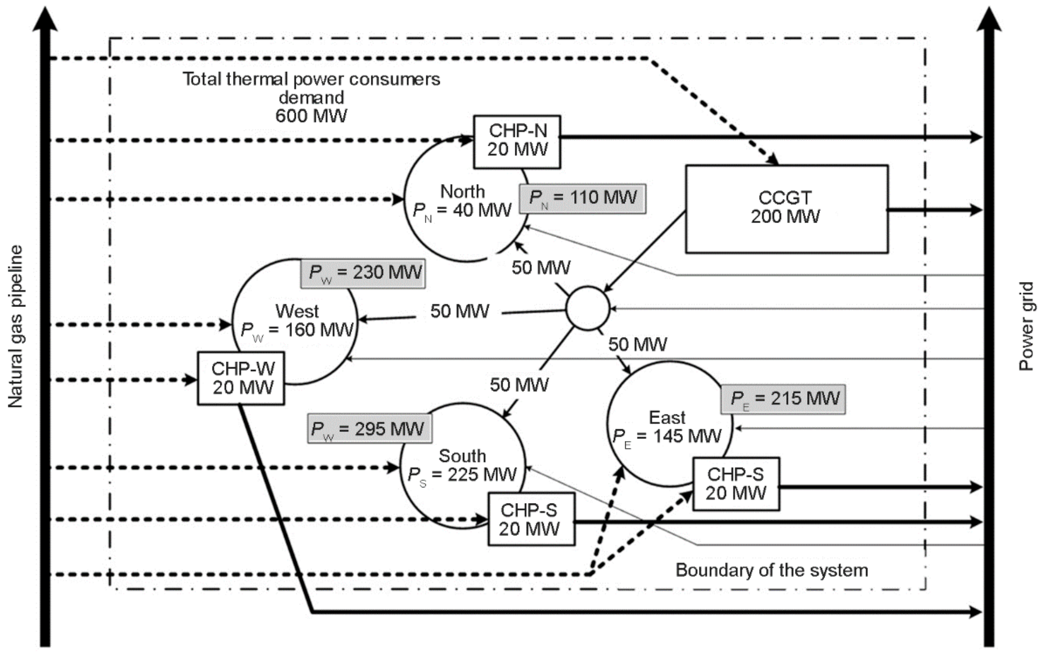

Figure 3. Proposal for the reconstruction of the DHS (Option 2)

The goal function which expresses the total CO_2 emission can be:

$$\Phi = \left(\frac{Q_{N,\text{Bo}}}{\eta_{N,\text{Bo}}} + \frac{Q_{E,\text{Bo}}}{\eta_{E,\text{Bo}}} + \frac{Q_{S,\text{Bo}}}{\eta_{S,\text{Bo}}} + \frac{Q_{W,\text{Bo}}}{\eta_{W,\text{Bo}}}\right)\varepsilon_{\text{ng}} + \left(\frac{Q_{N,\text{CHP}}}{\eta_{N,\text{CHPt}}} + \frac{Q_{E,\text{CHP}}}{\eta_{E,\text{CHPt}}} + \frac{Q_{S,\text{CHP}}}{\eta_{S,\text{CHPt}}} + \frac{Q_{W,\text{CHP}}}{\eta_{W,\text{CHPt}}}\right)\varepsilon_{\text{ng}} -$$

$$- (E_{N,\text{CHP}} + E_{E,\text{CHP}} + E_{S,\text{CHP}} + E_{W,\text{CHP}})\varepsilon_{EE} + \frac{EE_{\text{CCGT}}}{\eta_{\text{CCGT}}}\varepsilon_{\text{ng}} - EE_{\text{CCGT}}\varepsilon_{EE} \tag{8}$$

where $Q_{N,\text{Bo}}$, $Q_{E,\text{Bo}}$, $Q_{S,\text{Bo}}$, and $Q_{W,\text{Bo}}$ are the thermal power of boilers in every part of the DH system, $Q_{N,\text{CHP}}$, $Q_{E,\text{CHP}}$, $Q_{S,\text{CHP}}$, and $Q_{W,\text{CHP}}$ – the thermal power of the CHP gas engine, $E_{N,\text{CHP}}$, $E_{E,\text{CHP}}$, $E_{S,\text{CHP}}$, and $E_{W,\text{CHP}}$ – the electric powers of the CHP gas engine, EE_{CCGT} – the electric power of the CCGT power plant, η_{CCGT} – the power plant efficiency, ε_{ng} – the emission of CO_2 resulting from the combustion of natural gas, and ε_{EE} – the emission of CO_2 for delivered electricity using appropriate energy mix. Optimization should reach the minimum value of total emission Φ. For solving this problem, we have identified 29 limitations and 12 independent variables.

Results and discussion

In fig. 4, the results of the calculation of emissions for all 16 periods (the first interval corresponds to the highest load and the 16$^{\text{th}}$ to the lowest) and for three analyzed options are given. For each of technological configurations of the DH system, the optimum distribution of loads by individual sources of heat is found (as the requirement, the aim is set to satisfy thermal energy needs of consumers) while meeting conditions of the goal function (minimum CO_2 emissions). The negative sign of CO_2 emissions indicates that at the national level, CO_2 emissions are reduced due to cogenerated electricity production. This is very significant in all options with the CHP. A specific load corresponds to each of periods.

For each option, the total consumption of natural gas for all plants in operation is calculated. This consumption corresponds to the load by the period. The combustion of the total amount of natural gas also leads to adequate CO_2 emissions. However, in addition to heat, corresponding electricity is produced for which corresponding CO_2 emissions are estimated as being generated in the national system. The difference between these values is the reduction of CO_2 emissions and this value is shown in fig. 4 by periods. The reduction of CO_2 emissions is shown for the medium strength of the load in each of the periods. The total effect of the reduction of CO_2 emissions is shown separately for each option at the annual level (tCO_2/a).

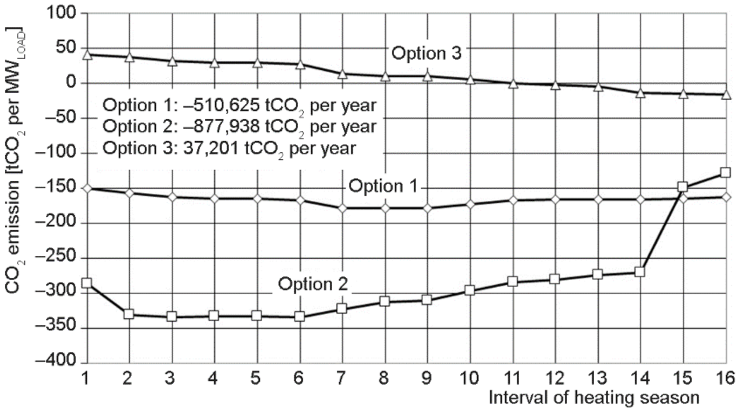

Figure 4. The CO_2 emissions *vs.* time for analyzed options

In the Option 3, there is the lowest reduction of CO_2 emissions compared to other options. Since the introduction of CCGT is not considered in this option, there is no production of electricity, except for a smaller amount in CHP. It is necessary to have in mind the way in which the goal function has been defined, eq. (8). In the Option 2, at intervals 15 and 16, when the heat load is the lowest, there is a sharp decrease in the production of electricity in CHP and especially in the CCGT plant. In this option, the power of the CCGT plant is the largest compared to other two options and at lowered demand load, there is also significant reduction of electricity production. In the Option 1, there is lower share of CCGT than in the Option 2 and the whole demand load is equally distributed to all capacities on the supply side.

Each of these options can be economically justified depending on the national energy policy and regulatory incentives or restrictions. The presentation of these three options actualy shows possibilities of the proposed method for complex analyzes of different options for operations of complex energy plants.

Another criterion that is important for assessing the quality of the technical solution is PES. Its calculation for the selected cogeneration plant is based on the annual production of heat and electricity and on the consumption of primary fuel. PES is defined:

$$\text{PES} = \left(1 - \frac{1}{\dfrac{\eta_{\text{CHP-H}}}{\eta_{\text{ref-H}}} + \dfrac{\eta_{\text{CHP-E}}}{\eta_{\text{ref-E}}}} \right) 100\% \tag{9}$$

where PES is the primary energy savings, $\eta_{\text{CHP-H}}$ – the heat efficiency of the CHP production defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration, and $\eta_{\text{ref-H}}$ – the efficiency reference value for separate heat production. It is adopted that: $\eta_{\text{ref-H}} = 0.85$. The $\eta_{\text{CHP-E}}$ is electrical efficiency of the CHP production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration. The $\eta_{\text{ref-E}}$ is the efficiency reference value for separate electricity production. Here, it is adopted that $\eta_{\text{ref-E}} = 0.3074$, which is the efficiency for a corresponding national energy mix.

The PES indicates savings of primary energy that are achieved by cogeneration. The PES should be higher than 10% for systems that are larger than 1 MW_e and for smaller systems, PES should be positive. The CHP system that fulfils PES criterion is called a *high efficient cogeneration* and can either obtain or retain the status of a privileged producer. The PES is directly proportional to the reduction of harmful CO_2 emission. Figure 5 shows the change of the PES indicator for individual periods for three options and their total PES for the entire heating season. The average PES is the highest for the Option 2 and it is 43.7%. For the Option 1, it is 40.5% and for the Option 3, it is 19.1%.

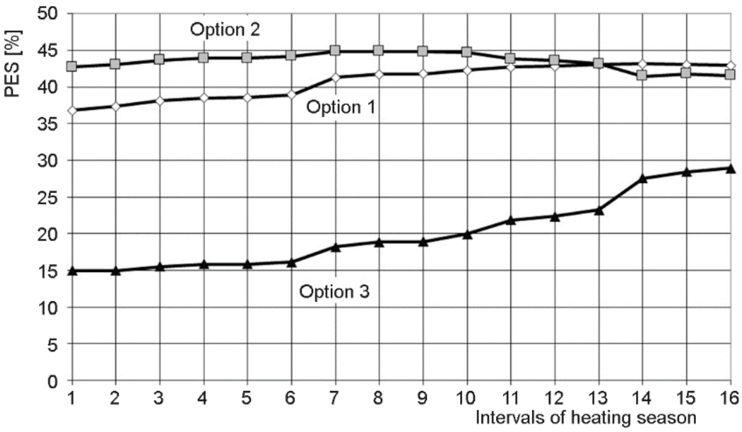

Figure 5. Primary energy saving for analyzed options

The presentation of results obtained from the goal function and energy production is given in tab. 2. All three considered options satisfy the heating needs. From presented results and given that the basic criterion is the minimum CO_2 emissions, the Option 2 is optimum. The goal function, eq. (8), is at the minimum.

Table 2. Production of electricity, thermal energy, fuel consumption and CO_2 emissions (for heating season only)

	Units	Option 1	Option 2	Option 3
Duration of heating season	[hours per year]	4,608	4,608	4,608
Working hours of the plant	[hours per year]	3,072	3,072	3,072
Generated heat	[MWh]	725,376	725,376	725,376
Produced electricity	[MWh]	869,299	1,357,781	161,617
Natural gas consumption	[MWh]	2,128,592	2,824,906	1,067,722
Emission of CO_2	[tCO_2]	–528,567	–879,164	+35,929

Based on the results of the performed optimization and on operations of several possible DH system options with reference to the adopted optimization criterion, it can be concluded that CHP technologies have explicit advantage over conventional boiler systems. All analyzed options with CHP technologies for peak loads predict the use of boilers, but here, above all, it refers mainly to existing boilers.

In the previous analysis, the main criterion is the reduction of CO_2 emissions and PES as additional criterion. Cogeneration technologies have fully demonstrated the advantage over conventional ones. In the Option 2, boilers have operated only at low outside temperatures, while in the Option 3, they have operated throughout the whole heating season.

Conclusions

If the negative impact on climate change is accepted as an indisputable criterion in the decision-making process then, national and global economies will have to adjust gradually to it without much reliance on the profitability of the DH system reconstruction. Such approach imposes serious changes in the global economic system, but it seems as the only way to reduce GHG emissions substantially. The presented method of analysis of complex energy systems allows a very reliable estimation of their parameters and gives the opportunity to evaluate the influence of different assumptions on their efficiency. The number of independent variables and the number of constraints is practically unlimited. Therefore, the flexibility of the model is great. This can be of great benefit to energy policy makers as energy policy determines directions and goals of energy development, whether in companies, countries, or regions.

The model has been successfully tested on the DH system with the capacity of 600 MW. This system has been designed primarily for the use natural gas boilers and for occasional use of the capacity of the existing CCGT plant. A possible direction for the development of the DH system is gradual replacement of boiler capacities with smaller CHP plants with phase engines. Three options for this concept have been considered and one of them is suggested on the basis the criterion that it provides the largest reductions of CO_2 emissions at the national level. This means that produced electricity is valued taking into account the national energy mix.

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