Optimization of the CHP Plant "EL-TO Zagreb" Operation

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Abstract

CHP plant "EL-TO Zagreb" consists of four cogeneration units and three auxiliary boilers that produce heat, process steam and electricity. The primary purpose of the power plant is district heating and supply of steam to industrial consumers, but it also produced a significant amount of electricity in the past. The rise of natural gas prices in recent years decreased the competitiveness of electricity production of this power plant and analyses have shown the possibility for reduction of operating costs by changing the operation regime of the power plant. Due to electricity and gas market price variations, an optimization model of CHP plant has been developed to enable short-term operation planning in order to reduce operating costs.

Electricity market simulation and optimization software PLEXOS® Integrated Energy Model was used to model the power plant. A large amount of input data used includes technical and economic parameters of all units of the power plant, hourly heat and steam load data and market data. Using heat and steam demand projections and market prices, simulations are performed on a detailed hourly basis for one week in advance. Thus the CHP plant operation is optimized according to the current market conditions in order to meet the heat and steam demand at the lowest possible cost. Operation management based on the optimization results showed the possibilities for significant decrease of operating costs and improvement of CHP plant profitability.

Keywords

Power plant operation optimization, market simulation, electricity prices, short-term planning, operating costs.

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I. NOMENCLATURE

CHP – Combined Heat and Power
O&M – Operation and Maintenance

II. INTRODUCTION

CHP plant "EL-TO Zagreb" is one of the two existing CHP plants for district heating in the city of Zagreb. Cogeneration units and auxiliary boilers of the CHP plant "EL-TO Zagreb" produce heat, process steam and electricity. Total installed capacity is around 88.8 MW_e and 439 MW_t with possibility to produce about 160 tons of process steam per hour. Natural gas is used as the main operating fuel, although it can use fuel oil as an alternative fuel. The primary purpose of "EL-TO Zagreb" plant is heat supply to residential and commercial consumers and process steam supply to industrial and public (hospitals) consumers, but CHP plant also produces electricity, depending on the operation regime.

Due to the rise of natural gas prices in recent years, the competitiveness of this power plant has been decreased, and the production efficiency is also affected by electricity prices which have shown decreasing trend in recent years. While the steam and heat production is determined by the local demand, the electricity production can be optimized in the power company's portfolio and on the market. Several previous analyses shown the possibility for reduction of operating costs in "EL-TO Zagreb" CHP plant by changing the operation regime of the power plant, i.e. by reducing electricity production. A development of method for optimizing CHP plant operation according to the movements of market prices was chosen as appropriate solution for reduction of operating costs. Optimization enables more efficient production of heat and steam.

For that purpose, the software package PLEXOS® Integrated Energy Model is used [1]. PLEXOS is a market simulation and optimization tool, based on object model of the electricity market. In this case, PLEXOS was used to develop a simulation model of CHP plant "EL-TO Zagreb" that enables short-term operation planning.

CHP plant operation is optimized according to the market conditions in order to meet the heat and steam demand at the lowest possible cost. Three different outputs (electricity, heat and steam) can be produced by different combination of generating units. Simulations are performed on a detailed hourly basis, meaning that the results show production of each unit of the CHP plant in every hour of the simulated period.

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Based on the simulation results, power plant operators plan unit commitment of the CHP plant "EL-TO Zagreb". Operation management based on the simulation results showed a significant reduction of operating costs.

Two scenarios of electricity price movements are analyzed in this paper in order to examine the impact of prices on unit commitment of the CHP plant. Hourly heat and steam load is equal in both scenarios.

The paper is organized as follows: Chapter III gives general data regarding CHP plant "EL-TO Zagreb". General assumptions of the optimization and simulation model are shown in Chapter IV. Chapter V presents simulation results based on analysis of two scenarios and the conclusions are given afterwards.

III. Basic Data on CHP Plant "EL-TO Zagreb"

Power plant "EL-TO Zagreb" entered into operation in 1907 with capacity of 0.8 MW and coal as operating fuel. Power plant gradually developed with increasing population and increasing demand for electricity and heat in the city of Zagreb. The district heating started to develop in 1954 and process steam supply started in 1961. Today, power plant "EL-TO Zagreb" is one of the two CHP plants in the city of Zagreb used for district heating, steam supply and electricity generation. It consists of several units of different types including thermal, combined cycle and auxiliary boilers. The power plant uses natural gas as the main fuel and fuel oil in smaller quantities. Table I provides basic data on units in CHP plant "EL-TO Zagreb".

TABLE I
Basic Data on Units in CHP Plant "EL-TO Zagreb"

Unit	Capacity	Type	Year of construction
A	11 MW_e	thermal unit	1970
B	30 MW_e	thermal unit	1980
H&J	2 x 23,9 MW_e	combined-cycle cogeneration unit with two gas turbines	1998
K-7	64 MW_t	auxiliary steam boiler	1971
VK-3	116 MW_t	auxiliary hot water boiler	1991
VK-4	116 MW_t	auxiliary hot water boiler	2010

Total installed capacity is 88.8 MW_e and 439 MW_t with possibility to produce about 160 tons of steam per hour. CHP plant "EL-TO Zagreb" produces about 340 GWh of electricity, 615 GWh of heat and 320,000 tons of steam per year. Electricity production in 2014 was about 260 GWh, which is significantly less compared to the average annual production from 2010 to 2013 amounting about 360 GWh [2].

Decreased economic efficiency of the CHP plant in the past few years is the result of an increase in natural gas prices and a decrease in electricity prices. In order to decrease operating costs and improve CHP plant profitability, it is necessary to optimize operation on a short-term basis taking into account all influencing factors. A developed simulation model of the CHP plant shows possibilities for significant cost reduction and increase in economic efficiency.

IV. The Optimization Model

CHP plant "EL-TO Zagreb" is modeled using PLEXOS® Integrated Energy Model tool. This is a simulation and optimization tool based on an object model of the electricity market. A set of classes and their hierarchy is defined by the object model. During the setup of the input data, the user creates individual objects and their relations that represent the individual elements of network and market. In general, a well-designed object model provides a wide range of possibilities for defining structure of the market.

In this case PLEXOS is used to create a simulation model of the CHP plant "EL-TO Zagreb" and to optimize its operation in order to reduce operating costs. CHP plant operation regime depends on numerous factors, such as heat load, market data (prices of fuel, emission allowances and electricity) and operating constraints. The optimization algorithm primarily takes into account the requirement to meet the heat and steam demand. In other words, satisfying the heat and steam demand is the main constraint of the optimization problem. The objective function of the optimization is to maximize operating profit, which is determined by variable costs of operation and revenues from sales of electricity, heat and steam. The objective function is shown by equation (1).

$$\max \sum_{h=1}^{168} \sum_{u=1}^{n} P_{E,h} \times Q_{E,h,u} + P_H \times Q_{H,h,u} + P_S \times Q_{S,h,u} - P_G \times Q_{G,h,u} - P_A \times Q_{EM,h,u} \quad (1)$$

where P_E is the price of electricity, P_H price of heat, P_S price of steam, P_G price of natural gas, P_A price of emission allowances, Q_E quantity of electricity, Q_H quantity of heat, Q_S quantity of steam, Q_G quantity of natural gas, Q_{EM} quantity of emissions, *h* hour and *u* unit of the power plant.

This model specific requirements for heat and process steam delivery are modelled with two equality constraints per each hour. These constraints coupled with the heat and process steam output from the units condition the model so that the resulting operation complies with heat and steam demand, as follows:

$$\sum_{u} Q_{H,h,u} = D_{H,h}, \forall h \in [0,168] \quad (2)$$

$$\sum_{u} Q_{S,h,u} = D_{S,h} \; \forall h \in [0,168] \quad (3)$$

where D_H is the demanded quantity of heat, and D_S is the demanded quantity of steam.

The algorithm also includes technical operation constraints such as minimum up time, minimum down time, ramping constraints. The formulation of these constraints is standard for unit commitment formulations and further details on the formulation of UC problem can be found in [3]. The following parameters are defined for each unit in the CHP plant "EL-TO Zagreb":

- Technical minimum (minimum operating power) (MW),
- Maximum power (MW),
- Ramp up and ramp down rates (MW/min),
- Heat load at minimum and maximum power (GJ/MWh),

- Specific heat rate in CHP mode (GJ/MWh),
- Boiler efficiency (%),
- Scheduled outages (-),
- Minimum operation time (h),
- Start cost (€/start).

The complete model formulation includes system-specific configuration constraints – these consider the power plant heat exchanger configuration and ensure feasible concurrent operation of units.

Based on the estimated demand of heat and process steam and short-term economic indicators (wholesale prices of electricity, emission allowances, natural gas, etc.), the mixed-integer optimization problem result are hourly productions of all units in CHP plant "EL-TO Zagreb". A simplified chart-flow of the optimization process is shown in Figure 1.

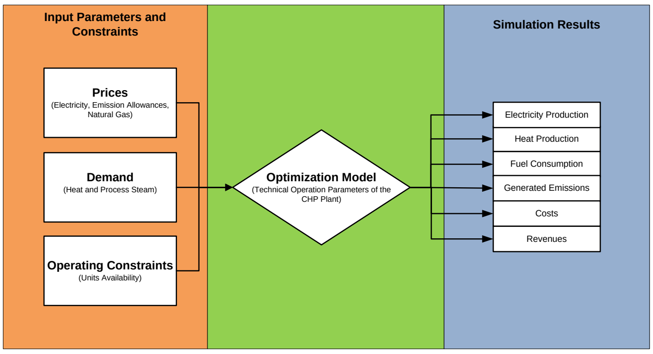

Fig. 1. Chart-flow of the optimization process

The optimization model requires a large amount of input data: technical and economic parameters for each unit, data on hourly heat and steam load as well as market data (prices of electricity, fuels and emission allowances).

Variable costs of operation include fuel costs and emission allowances costs. These are determined by unit engagement, specific fuel consumption per unit, fuel price (€/GJ), CO_2 emission factor of fuel (kgCO_2/GJ) and the price of emission allowances (€/tCO_2). Natural gas price depends on the gas purchase contract between the power producer and the gas supplier and were included in the model. Prices of emission allowances are taken from EEX power exchange [4].

Further input data include hourly heat and steam load for CHP plant "EL-TO Zagreb" and electricity prices. Hourly electricity prices are determined on a weekly basis according to data from regional power exchanges and developed methodology. A special methodology is also developed for heat and steam load forecast, both described below.

A. Heat and Steam Load Forecast

Heat load is a key input variable for determining optimal unit dispatch and shows a significant correlation with weather conditions, in particular with air temperature. Therefore, hourly temperature forecasts for each day in the following week are used to create heat and steam load forecast. Besides the forecasted temperatures, historical data on heat and steam production in CHP plant "EL-TO Zagreb" are used for load forecast. Historical data provide correlation between hourly air temperatures and production of heat and process steam for the past three years (2012, 2013 and 2014). By using the three-year period one ensures various environmental conditions (e.g. during hotter or colder winters) are covered in the input dataset. The forecasted temperatures for the week ahead are obtained from several sources including a national meteorological institute. Afterwards, a technique equivalent to similar-day electric load forecasting is combined with a time series approach to smooth the non-realistic peaks: the technique firstly chooses the days from the past where a recorded temperature profile is the most similar to the forecasted temperature profile, and then a smoothing filter is applied. From this forecast, the hourly heat and process steam production of selected days are used as forecasted demands for heat and process steam [5], [6].

The final result for each simulation period is determined load at the hourly level, both for heat and process steam.

Figure 2 shows forecasted hourly heat load in one week on the basis of the above described methodology, compared to the realized heat load.

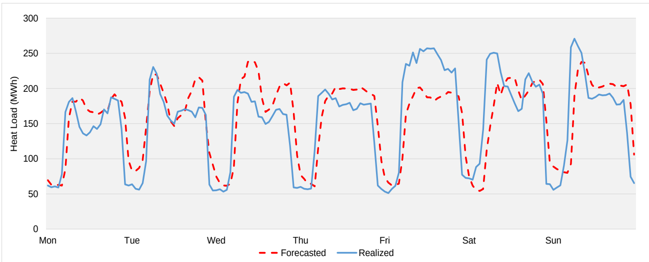

Fig. 2. Forecasted and realized heat load for one week

This method shows that it is not possible to accurately predict heat load for each hour so there are differences between forecasted and realized load for every day in the particular week. The greatest difference between projected and realized heat load can be seen on Friday when CHP plant "EL-TO Zagreb" had to produce more heat because of the sudden outage of the other CHP plant in the city of Zagreb. Such cases can not be anticipated in the projections of future heat load.

B. Electricity Price Forecast

Hourly electricity prices have significant influence on unit engagement in CHP plant "EL-TO Zagreb" taking that heat can be produced from different units including cogeneration units and steam boilers. When electricity prices are low, it is often more profitable to produce heat and process steam using auxiliary boilers. On the contrary, in periods of higher electricity prices it is more profitable to produce heat using cogeneration units. Therefore, along with heat and steam load, electricity prices are one of the basic input data for the optimization of the CHP plant. PLEXOS offers several different possibilities to model hourly electricity prices.

Wholesale prices of electricity are not possible to accurately predict, however operationally acceptable results can be achieved for short-term forecasts. A methodology for hourly electricity prices prediction in the following week is developed combining historical hourly prices and forward electricity prices. Data on hourly prices on HUPX [7] and

BSP [8] power exchanges in the last three years (2012, 2013 and 2014) were collected. Based on the prices on these exchanges in the three-year period, a price movement was modeled taking into account hourly, daily and seasonal movements of prices resulting in calculation of hourly and monthly coefficients for weekdays and weekends.

Calculated hourly and monthly coefficients represent the relationship between prices in a particular period of time compared to the average annual price. Since the model of CHP plant is used for short-term optimization (daily, weekly), only hourly coefficients are considered in modeling electricity price movements (Figure 3).

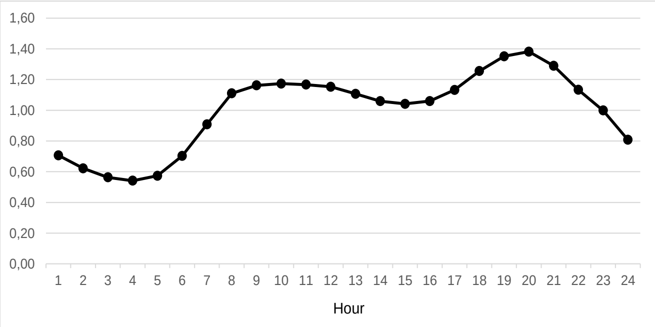

Fig. 3. Typical movement of electricity prices during the day (hourly coefficients)

In addition to hourly coefficients, hourly electricity prices in current week and forward price for base energy for the following week are used to determine price movements for one week in advance. Electricity prices in current week are determined based on hourly electricity prices from HUPX and BSP power exchanges, and forward base price for next week is available at HUPX power exchange.

Prices in the current week are used to determine relations between average prices on weekend (Saturday and Sunday) compared to average price on weekdays. Determined relations and forward base price for next week are used to determine average daily prices in the next week, taking into account difference between weekend and weekdays. To obtain hourly prices for each day in next week, average daily prices are multiplied by hourly coefficients. Prices are corrected if necessary for certain specific cases (e.g. the days of public holiday).

Figure 4 shows forecasted hourly electricity prices according to the described methodology compared to realized prices on HUPX and BSP power exchanges in one week.

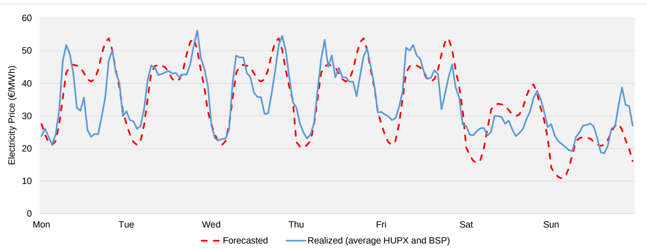

Fig. 4. Forecasted and realized electricity price movement in one week

By modeling prices using hourly coefficients, the impact of extraordinary price fluctuations that may occur on power exchanges is avoided.

V. Simulation Results

Simulation results include hourly production of electricity, heat and process steam, natural gas consumption and emissions generated by each unit within the power plant, cost of fuel and cost of emission allowances, and revenues generated from sales of electricity, heat and process steam.

Optimization is carried out for one week and two scenarios of electricity prices – HIGH and LOW scenario. Average weekly electricity price in HIGH scenario is set to 55 €/MWh, while average weekly electricity price in LOW scenario is set to 35 €/MWh. Hourly price movement in both scenarios obtained on the basis of described methodology using hourly coefficients is shown in Figure 5.

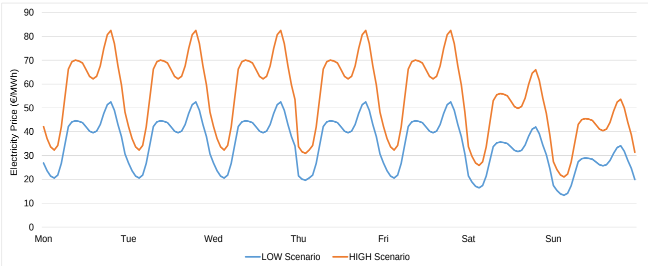

Fig. 5. Electricity price movement in scenarios LOW and HIGH

All other input data are equal in both scenarios. Natural gas price is set to 40 €/MWh, while the price of emission allowances is set to 7.5 €/tCO_2.

The primary objective in both scenarios is to meet the given demand of heat and steam at lowest possible cost, taking into account all the technical constraints of the power plant. Hourly heat and steam load is equal in both scenarios meaning that total production of heat and steam is equal in both scenarios, but the commitment of units that produce heat and steam is different due to different levels of electricity prices. The total heat and steam demand in both scenarios is shown in Figure 6.

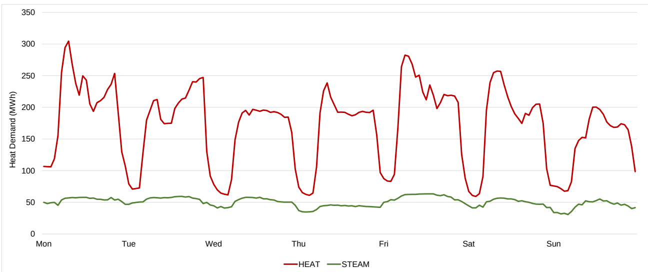

Fig. 6. Heat and steam demand in scenarios LOW and HIGH

Due to the difference in electricity prices, unit commitment is significantly different in two scenarios. Figure 7 shows electricity generation of cogeneration units in CHP plant "EL-TO Zagreb" for both scenarios.

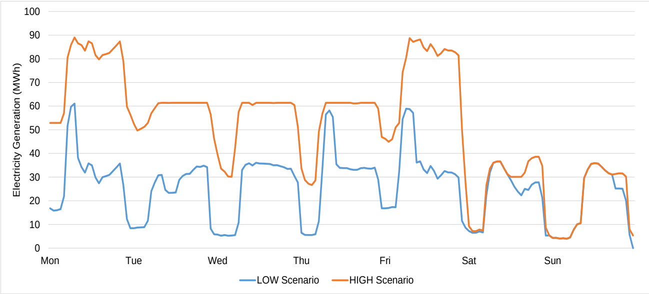

Fig. 7. Electricity generation in scenarios LOW and HIGH

Total electricity generation in LOW scenario amounts 4.37 GWh, while total electricity generation in HIGH scenario amounts 8.65 GWh in the particular week. Greater engagement of cogeneration units in HIGH scenario is the result of higher electricity prices at which use of cogeneration units is more profitable for the production of heat and steam. This is the case on weekdays. Because of lower electricity prices on weekends, electricity generation in both scenarios is almost equal.

Due to grater engagement of cogeneration units, heat production of auxiliary boilers is smaller in HIGH scenario compared to LOW scenario. Figure 8 shows heat production of auxiliary boilers in both scenarios.

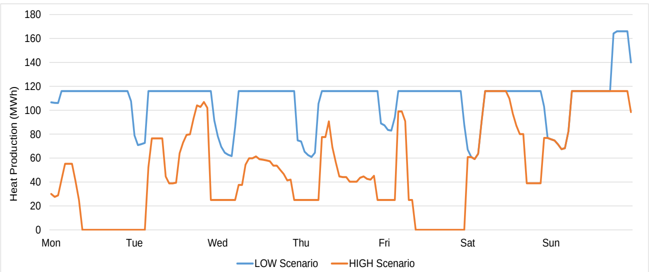

Fig 8. Heat production of auxiliary boilers in scenarios LOW and HIGH

Total heat production of auxiliary boilers in LOW scenario amounts 18.2 GWh, while total heat production of auxiliary boilers in HIGH scenario amounts 8.7 GWh. The remaining heat demand in both scenarios is satisfied by cogeneration units.

Simulation results show that greater use of cogeneration units means greater fuel consumption, which results in greater fuel costs. Total natural gas consumption amounts 191.6 TJ in HIGH scenario and 172.3 TJ in LOW scenario, resulting in 10% higher fuel costs in HIGH scenario. Structure of fuel consumption by units in both scenarios is shown in Figures 9 and 10. Cogeneration units are dominant fuel consumers in HIGH scenario, while auxiliary hot water boiler VK-4 is the greatest fuel consumer in LOW scenario.

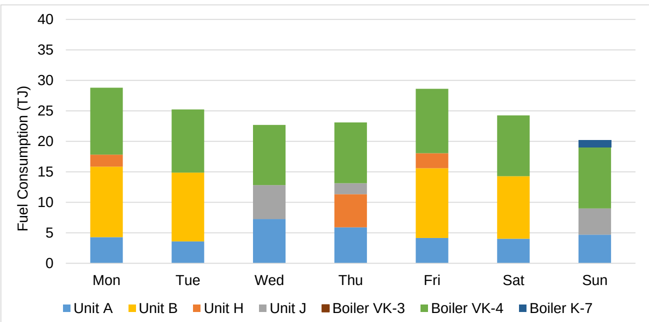

Fig. 9. Fuel consumption by units in LOW scenario

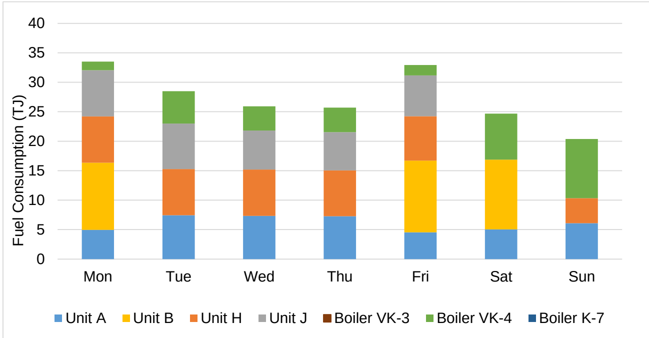

Fig. 10. Fuel consumption by units in HIGH scenario

Comparison of the economic profitability of two scenarios is based on profit comparison. Operating profit is determined as the difference between total revenues and total operating costs. Total revenues are determined by sales of electricity, heat and process steam, while total operating costs include fuel costs, cost of emission allowances and other O&M costs. Figure 11 shows total revenues and costs for both scenarios.

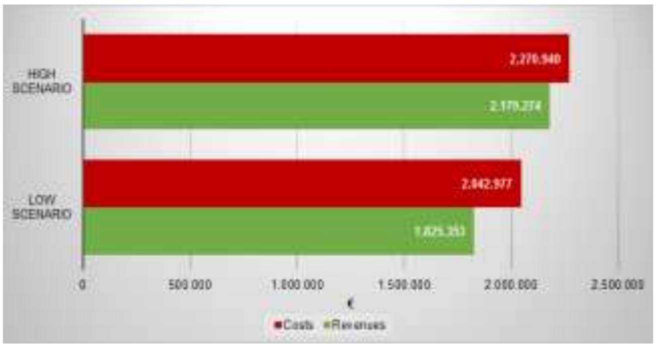

Fig. 11. Total costs and revenues in LOW and HIGH scenario

Both scenarios have higher costs than revenues that is mostly due to low regulated prices of heat. Total revenues and total costs are higher in HIGH scenario. Since revenues from sales of heat and process steam are equal in both scenarios, the difference in revenues refers to difference in revenues from electricity sales. Greater electricity generation in HIGH scenario means greater revenue for about 354,000 euros in comparison to LOW scenario. Total costs are higher in HIGH scenario for about 228,000 euros compared to LOW scenario.

Despite the higher costs compared to revenues in both scenarios, simulation results show more profitability in HIGH scenario due to higher earnings from electricity sales and lower operating losses. As expected, optimization results show that the operation of cogeneration power plants is more profitable in case of higher market prices of electricity.

VI. Conclusions

Rise of natural gas prices and decrease of electricity prices in recent years decreased the competitiveness of electricity production in CHP plant "EL-TO Zagreb", as well as other gas fired CHP plants. In order to optimize power plant operation according to variable market conditions, electricity market simulation and optimization tool was used to model the power plant. Using heat and steam load forecast and market data, simulations are performed on a detailed hourly basis.

Optimization was made for two scenarios of electricity prices. The simulations were carried out with the assumption that all other input data remain the same in both cases, including natural gas price. Simulation results for two scenarios showed significant correlation between CHP plant operation and electricity prices. In scenario with higher electricity prices, cogeneration units are mostly used to cover heat and steam demand. Greater engagement of cogeneration units compared to auxiliary boilers means greater electricity production and greater revenues from electricity sales. Electricity prices on markets in the region are currently very unfavorable for electricity generation in power plants which use natural gas and "EL-TO Zagreb" operation should be optimized according to current situation.

In addition to electricity prices, optimization model enables various analyzes by changing different input data and thus more efficient operation planning. In the long term, the adjustment of the operating regime to simulation results will reduce operating costs of the power plant and improve CHP plant profitability.

Finally, it is important to emphasize that the developed model can be adjusted to any cogeneration plant, using appropriate modifications. This allows wider application of the optimization model meaning that operation of plants that have different technical characteristics and operating constraints or use different fuels compared to CHP plant "EL-TO Zagreb" can also be optimized.

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VIII. Biographies

Mladen Zeljko is a Head of Energy Generation and Transformation department at the Energy Institute Hrvoje Požar. He obtained BS degree from Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia, in 1979, and MS and PhD degrees from Faculty of Electrical Engineering, University of Zagreb, Croatia in 1984 and 2003, respectively. Before joining Energy Institute Hrvoje Požar in 1994 he was with Power Sector Institute, Zagreb, Croatia.

His scope of work and research activities comprises the areas of power system operation and expansion planning, hydro power plants operation planning, electricity consumption analysis, energy sector costs and financing and energy sector organization and management. On the behalf of IAEA he participated as a lecturer in several training courses in the fields of long term generation expansion planning and options for sustainable energy development. He was lieder of many projects and studies in Croatia, and also consultant in some international projects financed by WB, EU and EBRD. He is member of CIGRE, Paris, member of Croatian Energy Council (HED) and he was the president of Group C1 of Croatian CIGRE Committee since for the period 1999 – 2007. He is Assistant Professor on University of Rijeka (Croatia) and University of Osijek (Croatia).

Krešimir Komljenović graduated from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia in 1999. He is employed at CHP plant "EL-TO Zagreb" since 2000. His first position was an engineer in maintenance department and in 2007 he became the Head of production department. From 2012 he holds the position of executive director at CHP plant "EL-TO Zagreb".

In 2011 he received a MS degree from Faculty of Electrical Engineering and Computing of the University of Zagreb. He is author and co-author of several scientific papers, mainly in the field of energy efficiency, the impact of the power system to environment and the application of new technologies in cogeneration units.

Dražen Jakšić graduated from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia in 1999 in the field of electrical power engineering (dipl.ing). He is with Energy Institute Hrvoje Požar, Zagreb, from 2006 and currently holds the position of Deputy Head of Department for Energy Generation and Transformation. His interests include power system planning, electricity and gas markets design, modeling and simulations of power system and market operation.

Ivana Milinković Turalija graduated at Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia in 2011 in the field of electrical power engineering (M.Sc.E.E.). She is with Energy Institute Hrvoje Požar, Zagreb from September 2011 as a researcher at Department for Energy Generation and Transformation. Her interests include power system planning and analysis, modeling and simulations of power system and market operation, renewable energy sources. She is also interested in power sector economics and currently is a student of postgraduate study program in Energy Economics at University of Rijeka.

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