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Gas fired plant modeling for monitoring and optimization of electricity and heat production

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Abstract

There has been a marked increase in recent years in the use of gas fired systems characterized by high efficiency and the ability to quickly adapt to changing demand for electricity and heat. To optimize operations for gas fired systems in light of changing demand and changing electricity prices the production process must be planned and monitored with appropriate tools. This paper presents the concept of a tool for monitoring and optimizing heat and electricity production in a gas fired plant. The basic element of the tool is a comprehensive mathematical model of the gas fired plant, verified based on results from on-site tests. The mathematical model is used to perform calculations for defined input data of ambient conditions and heat demand, to determine current heat and electricity production. The paper presents simulation results in the form of changes in the amount of electricity and heat produced during a day, with the aim being to monitor the conditions of the plant and prepare a reliable production plan.

Keywords: Gas fired plant; thermodynamic modeling; optimization; gas turbine; heat demand

1. Introduction

Gas is widely used in the production of electricity and heat [1, 2]. Gas cogeneration systems are highly efficient and able to provide rapid response to variable electricity demand [3, 4]. The use of gas turbines, characterized by its ability to rapidly change load, has a significant impact on electricity production and meeting heat demand, and on the efficiency of the entire system [5, 6]. To enhance efficiency a precise analysis of the operation of the gas fired plant is required, which involves accurately reproducing the parameters of the gas turbine across its full range of operation.

The gas turbine, and the efficiency at which it can operate for the given load, is mainly responsible for the high efficiency of the system and the ability to quickly change load (flexible operation) [5, 6, 7]. In order to determine the amount of electricity and heat produced in the gas system, accurate thermodynamic calculations of the entire system must be carried out. The continuous development of gas cycle modeling tools enables more accurate calculations to be made, both for nominal operating conditions and in the ranges for off-design conditions [7, 8]. Results taken from mathematical modeling are central to optimizing the system, identifying best scenarios [9] and verifying modification gas systems [10, 11].

The paper presents (i) the concept of a tool for monitoring and optimizing electricity and heat production, and (ii) the results of the analysis for the gas system. The calculations were performed using the developed thermodynamic model of the Combined Heat and Power Plant (CHP) using Ebsilon® software [12]. The model, verified based on measurement results, is the basic element of the developed tool and can be used in calculations with variable input data. The results of calculations in the form of daily production of heat and electricity were determined for the forecast heat demand.

2. Gas Fired Plant

The analysis of heat and electricity production presented in the paper was prepared for the gas fired cogeneration plant system presented in Fig. 1. The electricity is produced in two generators connected to two gas turbines supplied with gas and air. Heat production is carried out for the purpose of heating water used to supply the District Heating Network (DHN). This water can be heated in two Heat Recovery Hot Water Boilers (HRHWB) and in four Heat Only Boilers (HOB). The heat energy transferred to the water in HRHWB comes from exhaust gases of the Gas Turbine (GT) and from

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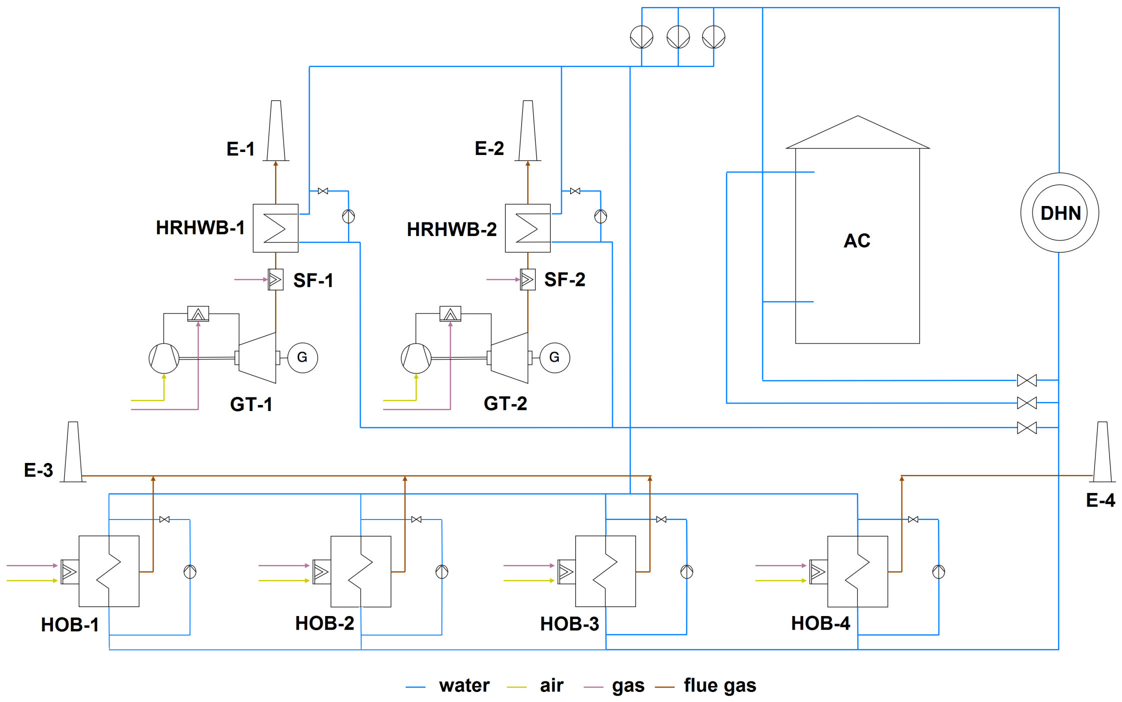

Figure 1: Schematic diagram of the gas fired cogeneration plant

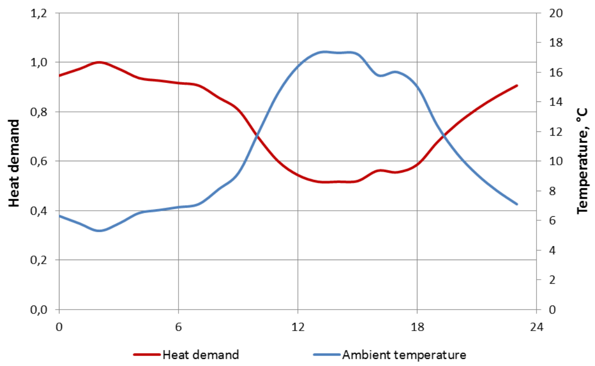

Figure 2: Graph showing an example of changing heat demand and ambient temperature during the day

exhaust gases produced in the Supplementary Firing (SF) system. If the gas turbines are out of action or heat demand is higher than heat output of two HRHWB, the district heating water can be heated in HOBs, which are powered by gas. Produced heat can also be stored in the Hot Water Accumulator (AC).

The presented CHP plant has several possible operating configurations, depending on the availability of equipment and current heat demand, which strongly depends on ambient temperature. An example of heat demand changing during one day together with ambient temperature is presented in Fig. 2.

Heat and electricity production as well as gas consumption by individual system components can be calculated using a complex thermodynamic model of the gas fired plant. Based on the calculation results, several scenarios of plant operation can be created taking into account heat demand which varies with ambient conditions.

3. Thermodynamic model of gas fired plant

A model consisting of all the described components was developed to calculate heat and electricity production in the analyzed gas fired plant, (Fig. 3).

The calculations of gas turbine operation were conducted using the characteristics utilizing vendor information in the form of correction curves (Fig. 4). Based on a data set in specified reference conditions the following parameters were determined by linear interpolation between characteristic lines:

- net output (power at generator terminals),
- heat rate,
- exhaust gas flow,
- exhaust gas temperature,
- cooling duty (of gas turbine compressor intercooler, if applicable),
- water or steam injection flow (to combustion chamber, if applicable).

The deviation between the rating in reference conditions and the current operating point is calculated as a function of the following parameters:

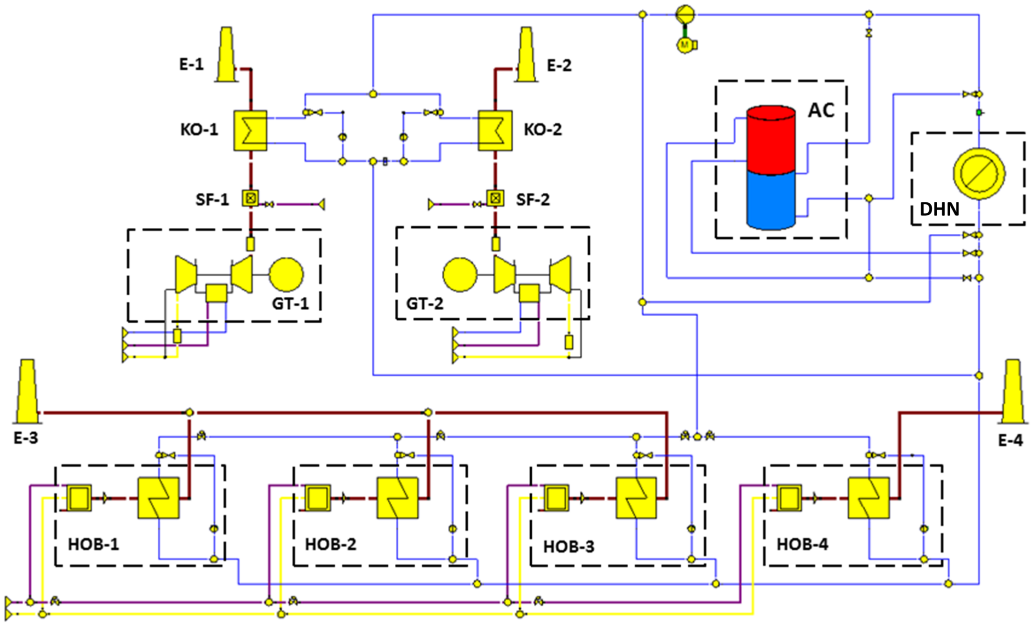

Figure 3: Schematic diagram of the mathematical model of gas fired plant: AC—Hot Water Accumulator, E—Emitter, GT—Gas Turbine, HOB—Heat Only Boiler, HRHWB—Heat Recovery Hot Water Boiler, DHN—District Heating Network, SF—Supplementary Firing System

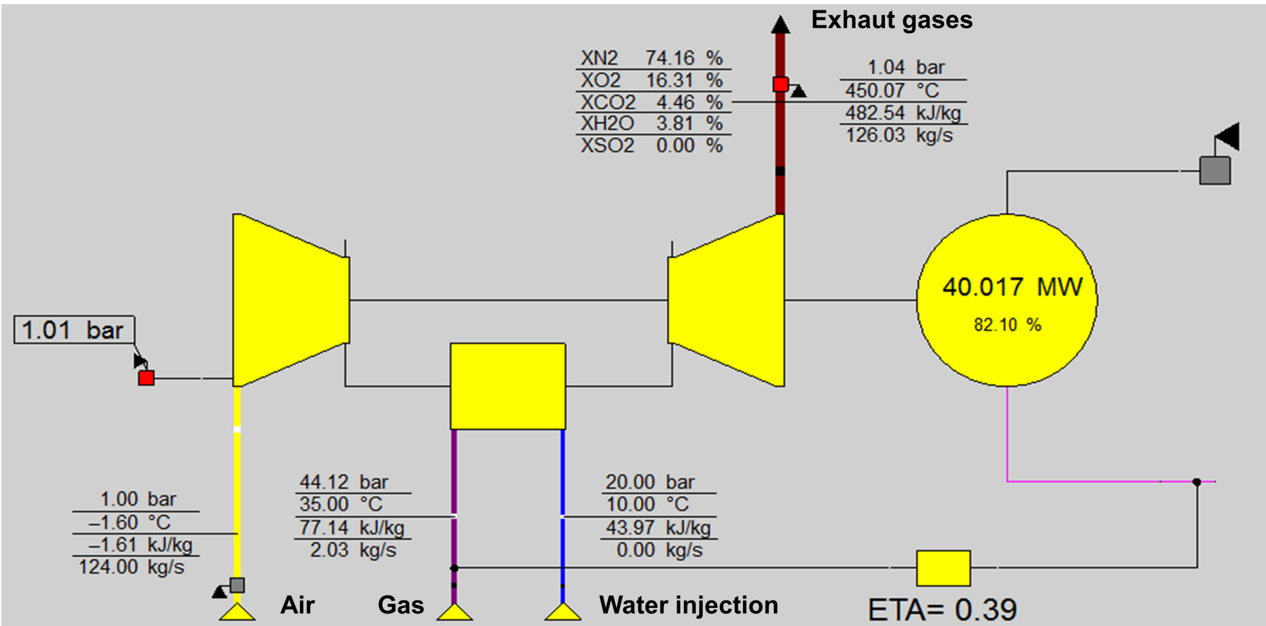

Figure 4: Gas turbine model using the characteristics utilizing vendor information in the form of correction curves

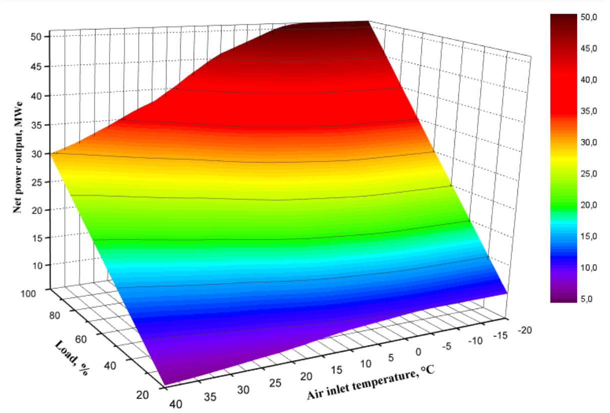

Figure 5: Net power output (N_{elGT}) as a function of the gas turbine load (Q_{GT}) and air inlet temperature (t_{am})

Table 1: Nominal gas turbine parameters in specified reference conditions

Parameter	Unit	Value
Net Power Output (N_{el-GT})	MWe	42.136
Heat Rate (q_p)	kJ/kWh	8875
Exhaust gas flow rate (m_{sp-GT})	kg/s	125.16
Exhaust Gas Temperature (t_{sp-GT})	°C	463.1

- air inlet temperature,
- air inlet pressure,
- air inlet relative humidity,
- inlet pressure drop between ambient and compressor inlet,
- outlet pressure drop between turbine exit and ambient,
- lower heating value of fuel,
- gas turbine load.

The nominal parameters of the analyzed gas turbine are presented in Table 1. The values were calculated for specified reference conditions: ambient temperature $t_{am} = 15°$C, ambient pressure $p_{am} = 101325$ Pa, and relative humidity $\varphi_{rel} = 84.6$.

The characteristics developed for the dedicated gas turbine type were used to calculate and determine gas turbine parameters across its full range of operation. Fig. 5 shows a graph presenting electric power as a function of gas turbine load and air inlet temperature. Calculations were performed across the full range of turbine load (20–100%) and for the air inlet temperature range from $-15°$C to $+40°$C. Electric power production in the gas turbine for a given load depends very strongly on air temperature, and the highest value can be achieved for low air temperatures.

The model of the supplementary firing system is based on an assumption of complete combustion between fuel and primary air and subsequent mixing with a secondary air mass flow. The composition of the flue gas in the combustion calculation is based on the composition of the incoming gases and the fuel composition. The outlet enthalpy of the hot gas results from a balance principle which factors in combustion efficiency and adiabatic conditions. The outlet pressure results from inlet pressure and pressure loss.

The part of the model consisting of the boiler with the water recirculation system is presented in Fig. 6. The return water from the district heating network is transported to the heat recovery hot water boiler, where it is heated. The water is heated to 135°C and then leaves the boiler.

The exhaust gases leaving the gas turbine are directed to the heat recovery boiler hot water, where heat production occurs and the water is heated. Exhaust gases at the inlet to the boiler may have different parameters depending on whether or not the supplementary firing system is active. The amount of heat transferred in the HRHWB is determined by the exhaust gas parameters at the outlet of the boiler. The permissible exhaust gas temperature at the HRHWB outlet is in the range of 70–115°C, and the exhaust gases produced are directed to the emitter and leave the system.

The analyzed gas fired plant is equipped with four water Heat Only Boilers (Fig. 7). The main function of their work is to cover peak demand for heat, where the heat demand exceeds the capacity of the gas turbine system with HRHWBs. Due to their construction and the system of connections in the plant system, they can also be used as basic equipment. The basic fuel for HOBs is high methane natural gas.

Water from the district heating network is heated up to 135°C in the boiler, which is the nominal hot water temperature at the boiler outlet. Part of the hot water can be directed to the recirculation circuit to ensure constant operation of the HOB boiler. The maximum heat power of the boiler is 30 MWt and the nominal efficiency of the boiler is 95.5% (for gas fuel).

4. Analysis of gas fired plant operation

The developed simulation model of the gas fired CHP plant was used to perform the thermodynamic analysis. Calculations were conducted for the mid-hour values for one day of CHP plant operation. The assumptions used in the analysis are presented in Table 2. Columns no. 2 and 3 in Table 2 show the predicted values of outdoor air temperature and heat demand in the district heating network. Based on the flow chart of the district heating network, the water supply and return temperatures were determined (columns no. 4 and 5). The heat accumulator is assumed to be fully charged at the start of the day. The total heat capacity of the hot water accumulator is 600 MWh for the first operation hour. The presented model includes a procedure that indicates the order of use of individual units.

The results of the thermodynamic analysis are presented in Table 3. Columns no. 2, 3 and 4 of Table 3 present the values of heat produced in heat recovery boilers, heat only boilers and hot water accumulator for the analyzed CHP unit. The total fuel consumption for the CHP plant is presented in columns no. 6 and 7. The energy utilization factors (EUF)

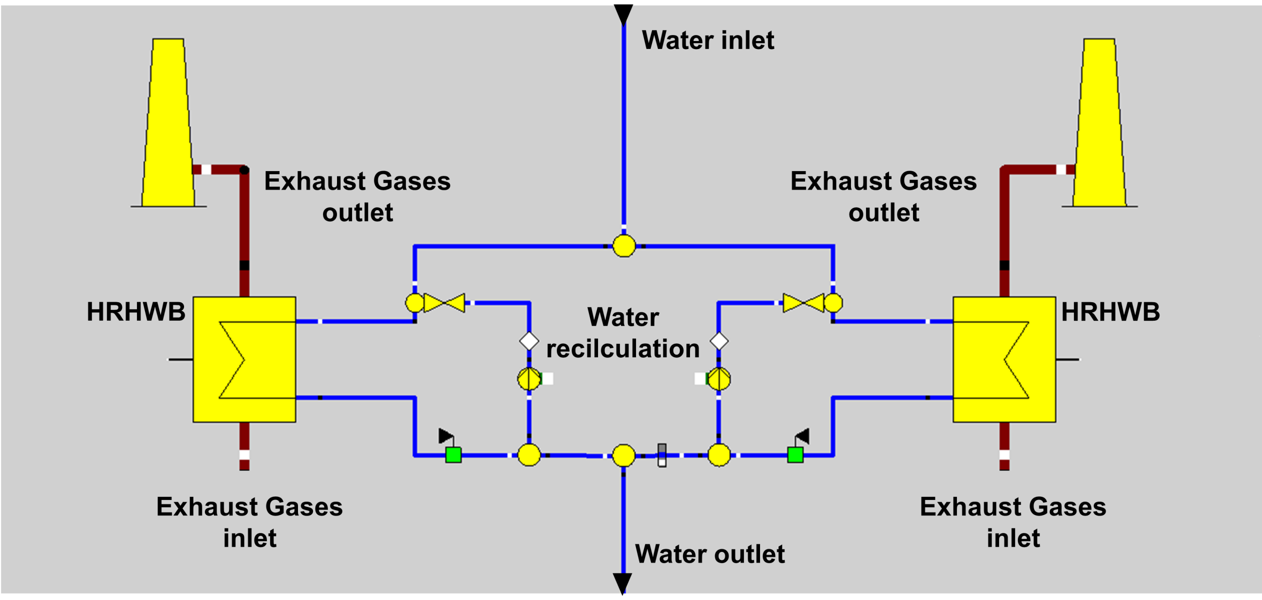

Figure 6: Part of the model with Heat Recovery Hot Water Boilers (HRHWB) system

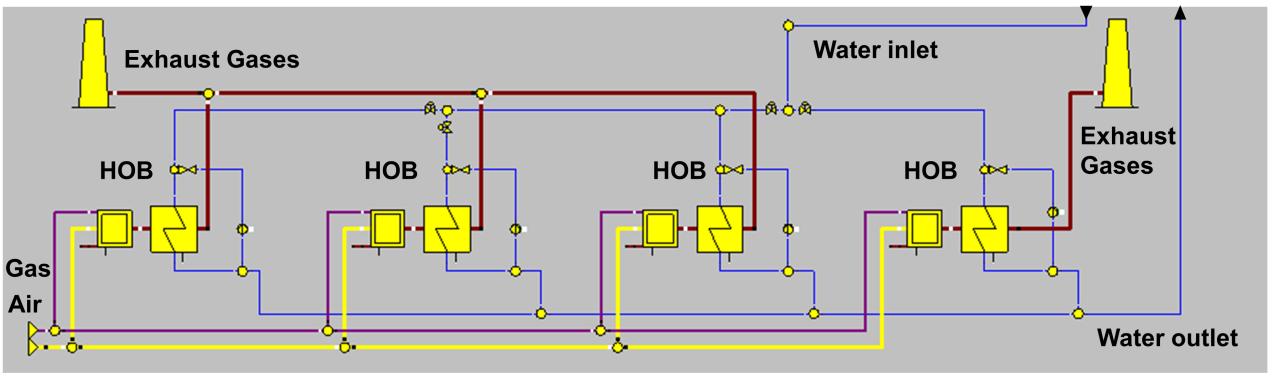

Figure 7: Part of the model presenting four Heat Only Boilers system (HOB)

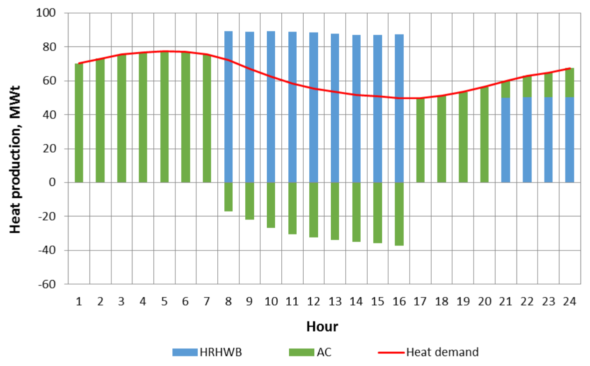

Figure 8: Results of hourly heat production in CHP plant

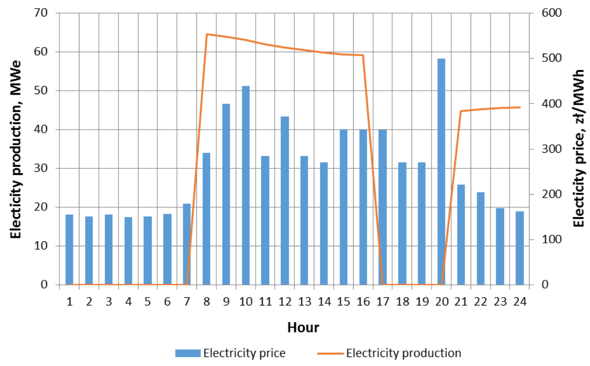

Figure 9: Results of hourly electricity production in CHP plant and electricity price changing during one day [13]

were determined based on the calculation results. The EUF indicator for the cogeneration heat-and-power plant (CHP) is defined as follows:

$$(EUF)_{CHP} = \frac{E_{el} + Q_h}{E_{f\,CHP}} \qquad (1)$$

where:

E_{el}—electricity production in the CHP unit, MWh

Q_h—heat production in the CHP unit, MWh

$E_{f\,CHP}$—consumption of fuel chemical energy, MWh

The gross values of energy utilization factor (EUF) for the analyzed CHP unit are presented in Table 3 (column no. 8). The average value of the EUF indicator for the whole day of CHP plant operation was 85.0%. Total heat production in the CHP plant during one day (using HRHWB) was 3584.2 GJ (995.6 MWh), electricity production 734.8 MWh and total gas consumption $m_{f\,CHP} = 153.3$ Mg. The rest of the heat, according to the calculated daily demand, was transferred to the district heating network using heat from the hot water accumulator. The amount of energy stored in the accumulator varies during the day, and the amount of accumulated heat decreases from 2160 GJ (600 MWh) to 282.96 GJ (78.6 MWh). About 65% of the total daily heat demand of 5318.65 GJ was covered by heat generated by HRHWB, with the rest coming from heat from the accumulator.

The amount of heat produced was determined based on

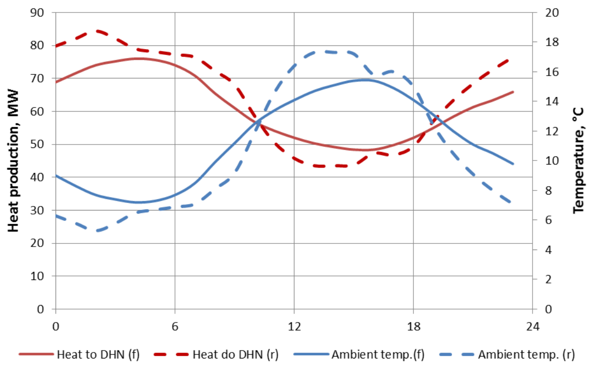

Figure 10: Comparison of forecast (f) and real (r) ambient temperature and heat demand for the analyzed day of CHP operation

Table 2: Input data used in gas fired plant analysis

Time, h	Ambient temperature, °C	Heat demand, MWt	Supply water temperature, °C	Return water temperature, °C
1	2	3	4	5
0	9.0	68.9	69.6	44.1
1	8.3	71.6	70.7	42.7
2	7.7	74.0	71.8	42.0
3	7.4	75.2	71.8	42.0
4	7.2	76.0	71.8	42.0
5	7.3	75.6	71.8	42.0
6	7.7	74.0	71.8	42.0
7	8.5	70.8	70.8	42.7
8	9.9	65.5	69.6	44.1
9	11.2	61.0	69.5	47.0
10	12.5	56.8	69.5	48.1
11	13.4	54.1	69.5	48.1
12	14.1	52.0	69.5	48.1
13	14.7	50.3	69.5	48.1
14	15.1	49.2	69.5	48.1
15	15.4	48.4	69.5	48.1
16	15.4	48.4	69.5	48.1
17	14.9	49.8	69.5	48.1
18	14.1	52.0	69.5	48.1
19	13.1	55.0	69.5	48.1
20	12.0	58.4	69.5	48.1
21	11.1	61.3	69.5	47.0
22	10.5	63.4	69.6	45.3
23	9.8	65.9	69.6	44.1

the calculated heat demand for each hour during the day. Heat energy stored in the hot water accumulator covered demand for 6 hours of the day (Fig. 8). Next, the gas turbine and heat recovery hot water boilers were used to produce heat, and the excess heat produced was stored in the accumulator. Electricity was generated alongside commissioning the gas turbines to cover heat demand.

Heat demand in the first period of the day can be covered using hot water stored in the accumulator (AC). This CHP operation mode means the gas turbines (GT) can be launched when electricity prices reach peak values, as is shown in Fig. 9. The boiler can be kept in continuous operation during the day at constant load, with the excess heat produced being directed to the accumulator.

Calculations of whole day CHP plant operation can be conducted in advance and the accuracy of the results will depend mainly on the accuracy of the ambient temperature forecasting. To demonstrate the differences, Fig. 10

Table 3: Results of thermodynamic analysis

Time	Heat			Electricity	Gas consumption		EUF
h	MWt			MWe	MWh	kg	-
	HRHWB	HOB	AC	GT	-	-	
1	2	3	4	5	6	7	8
0	0.0	0.0	70.4	0.0	0.0	0.0	0.00%
1	0.0	0.0	73.1	0.0	0.0	0.0	0.00%
2	0.0	0.0	75.5	0.0	0.0	0.0	0.00%
3	0.0	0.0	76.7	0.0	0.0	0.0	0.00%
4	0.0	0.0	77.5	0.0	0.0	0.0	0.00%
5	0.0	0.0	77.1	0.0	0.0	0.0	0.00%
6	0.0	0.0	75.5	0.0	0.0	0.0	0.00%
7	89.3	0.0	-16.9	64.6	182.3	13730.4	84.42%
8	89.1	0.0	-21.9	63.9	180.7	13612.7	84.61%
9	89.3	0.0	-26.6	63.1	179.7	13531.6	84.81%
10	89.0	0.0	-30.4	62.0	177.6	13379.5	85.00%
11	88.4	0.0	-32.6	61.2	175.7	13235.9	85.12%
12	87.8	0.0	-34.0	60.5	174.1	13110.7	85.21%
13	87.2	0.0	-35.0	59.8	172.3	12979.6	85.29%
14	87.0	0.0	-35.9	59.4	171.5	12919.3	85.36%
15	87.6	0.0	-37.3	59.1	171.6	12925.3	85.50%
16	0.0	0.0	49.9	0.0	0.0	0.0	0.00%
17	0.0	0.0	51.3	0.0	0.0	0.0	0.00%
18	0.0	0.0	53.5	0.0	0.0	0.0	0.00%
19	0.0	0.0	56.5	0.0	0.0	0.0	0.00%
20	49.9	0.0	10.2	44.7	111.0	8359.3	85.25%
21	50.2	0.0	12.8	45.3	112.2	8449.7	85.11%
22	50.3	0.0	14.8	45.5	112.7	8489.6	85.02%
23	50.4	0.0	17.2	45.8	113.3	8530.5	84.92%

shows the ambient temperature for the selected day based on the available forecast and actual recorded values. Differences in ambient temperatures affect the results of calculated heat demand, which in turn impacts on the amount of heat and electricity production. Despite differences, the trends of change in heat production are very close to real and forecast values. Tools developed, based on the detailed thermodynamic model, can be used in technical-commercial analyses and in determining optimum operating scenarios for the selected CHP.

5. Conclusions

The paper presents an analysis of the results of gas fired plant operations for heat demand changing during one day. The calculations were performed using a tool developed for the purpose of monitoring and optimizing heat and electricity production. The tool was based on a detailed thermodynamic model that contains all basic elements of the analyzed plant. The mathematical model performed calculations for variable input data in terms of ambient conditions and heat demand and to determine the current production of heat and electricity. The results of the modeling are values of heat and electricity produced using individual components of the analyzed CHP.

Heat production in the CHP depends on factors such as heat demand and the availability of individual components, and can be executed in several ways. The simulation results presented in this paper show one of the possible scenarios of heat and electricity production during a selected day for defined input data in the form of ambient temperature and heat demand. The tool was developed based on the detailed thermodynamic model and can be used in technical-commercial analyses and in indicating optimum operating scenarios of the selected CHP. The tool can be used to select the optimum solution and schedule production within one hour, taking into account the most important external factors.

The modeling results can be used to determine the amount of gas consumption and the electricity produced in gas turbines. The monitoring system based on the thermodynamic modeling can be insightful in decision-making, monitoring of the production process and drawing up a reliable production plan. The calculated results of gas consumption and generated electricity, and current information about the prices of gas and electricity, can be used to determine total costs and profits of CHP with high accuracy.

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Nomenclature

ϕ_{rel} relative humidity,

AC hot water accumulator

CHP combined heat and power plant

DHN district heating network

E emitter

E_{el} electricity production in the CHP unit, MWh

E_{fCHP} consumption of fuel chemical energy, MWh

EUF energy utilization factor

G generator

GT gas turbine

HOB heat only boiler

HRHWB heat recovery hot water boiler

m_{fCHP} the mass of the fuel consumed in the CHP unit, kg

m_{sp-GT} Exhasut gas flow rate, kg/s

N_{el-GT} Net Power Output, MW

p_{am} ambient pressure, Pa

Q_h heat production in the CHP unit, MWh

q_p Heat Rate, kJ/kWh

SF supplementary firing system

t_{am} ambient temperature, °C

t_{sp-GT} Exhaust Gas Temperature, °C