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Analysis of supercritical coal-fired combined heat and power plant integrated with membrane carbon capture and storage installation

In the paper, the results of analysis of integrating chosen supercritical combined heat and power (CHP) unit with a membrane carbon capture and storage (CCS) installation are shown. As a way to improving the operation characteristics of such a system, the use of heat from cooling of permeate compressed in area of carbon capture installation for useful heat production is proposed. An additional source of heat is the cooling of carbon dioxide which is compressed for its preparation for transport to storage place. The considered use of cooling heat to useful heat production of leads to a reduction in steam consumption, and in consequence to an increase of steam turbine power. For two analyzed cases the influence of changing thermal load of unit on gross power and loads of heat exchangers is determined. The study involved the influence of assumed annual operation time of CHP unit on the basic thermodynamic characteristics: annual efficiency of electricity production, annual efficiency of heat production and annual overall efficiency. In conclusions, the paper highlighted the importance of the heat integration of CHP unit with CCS installation.

1 Introduction

For the Polish energy sector, the modernization and construction of new cogeneration units is an important priority [1,2]. Motivation for this is provided by the mechanisms of support created in the European Union, which allow for the growth of competitiveness for high-efficiency and ecological energy sources [3,4]. It is expected that for the areas concerning electricity producers, the motivation to invest here will become increasingly rigorous conditions on emission of pollutants and greenhouse gases. It should also be assumed that, as in the

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biggest Polish power plants (Bełchatów, Pątnów, Łagisza), the movement toward improving ecological characteristics will take the form of investments in supercritical coal-fired units and the long-term integration of such units with carbon capture and storage (CCS) installations [5,6].

Currently, research on different ways of reducing anthropogenic emissions of carbon dioxide into the atmosphere is being conducted worldwide. In this field, there are several opinions regarding the actions that fossil fuel users in the energy sector can take. Due to the great global importance of carbon fuels, methods for capturing carbon dioxide from flue gases leaving the boilers (post-combustion technologies) are actively being developed. Methods for capturing carbon dioxide before the combustion process (pre-combustion technologies) for use in the area of gaseous fuels, including the synthesis of gaseous fuels, are also being developed. In the area of coal technology, there are high hopes for technologies based on burning coal in an oxy-enriched atmosphere (oxy-combustion technology). For these different technologies, different methods of capture are being developed. Among the most mature methods are those using chemical absorption and physical adsorption. At the same time, there are efforts to commercialize methods based on cryogenic distillation and methods using membranes. Fuel cells have also been considered for the reduction of CO_2 emissions [7].

In this paper, the results of calculations are discussed, and the positive attributes of membranes methods for carbon capture are discussed. The main advantage using membranes for combined heat and power (CHP) plants consisting of an extraction-condensing steam turbine is the fact that, unlike absorption and adsorption methods, the technologies based on polymer membranes are not heat-consuming. In the case of condensing units, the required head flow can be supplied with the steam extracted from the steam turbine. In the case of CHP plants, the residual amount of steam, which might be used for this purpose, is limited due to the use of steam for useful heat production. In the case of membrane technology, the partial pressure difference between gases appearing on both sides of the membrane is the driving force for capture. To achieve a suitable pressure difference, vacuum pumps and optional compressors are used. Therefore, the capture process requires a supply of electricity in a CCS installation.

2 Characteristic of the combined heat and power plant

In the analysis, a model of a supercritical CHP plant with a gross power of 320 MW was used. The diagram of such a unit is shown in Fig. 1. The assumed gross power, as well as the characteristic quantities presented in Tab. 1, correspond to a full condensation operation. These conditions were assumed to be the design conditions. In the model, only the district heating heat exchangers are designed for the maximum loads occurring in the operation cycle. The unit consists of a steam coal-fed boiler (SCB); an extraction-condensing steam turbine with a high-pressure component (H), a single-flow intermediate-pressure component (I1), a double-flow asymmetric intermediate-pressure component (I2+I3) and two double-flow low-pressure components (L1+L2 and L3+L4); a condenser (CND); deaerator (DA); four intermediate low-pressure regenerative heat exchangers (LR); three high-pressure regenerative heat exchangers (HR); and a steam cooler (SC). The combined heat and power plant cooperate with water boilers (KW).

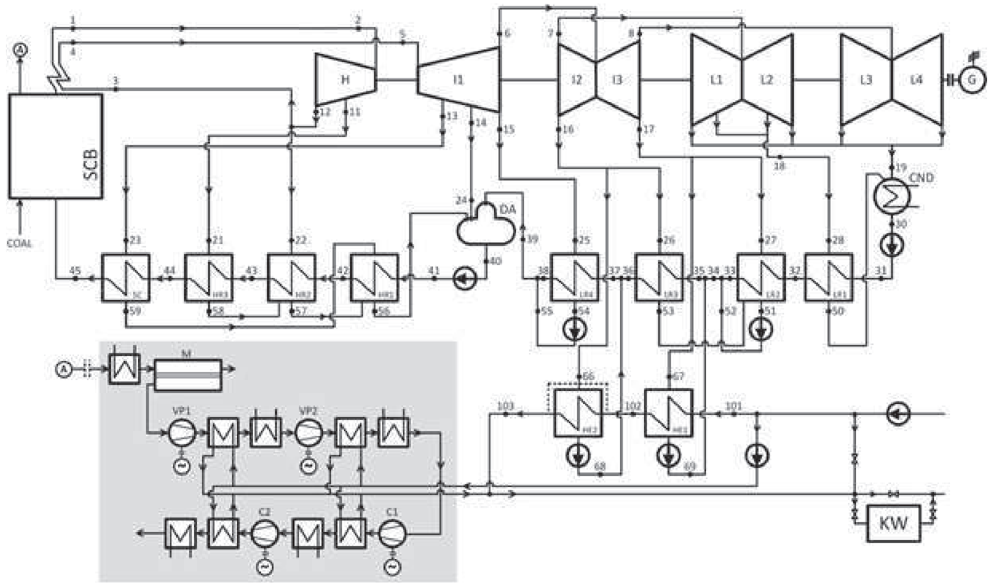

Figure 1. Diagram of the combined heat and power plant.

It was assumed that, in the CHP plant, two district heating heat exchangers are operating. Both exchangers are supplied by individual outlets of the double-flow asymmetric turbine (Fig. 1). The preheaters heat water in accordance with the diagram of heat demand and temperature characteristics of the heating system (Fig. 2). Depending on the needs of the system, the flows and pressures of the steam supplied to the heat exchangers of the heating network and the flow of water can change.

In Fig. 1, the membrane CCS installation is marked on a gray background. The model of the installation is integrated with the CHP plant model. The flue

Table 1. Assumptions for calculations.

Temperature of live steam at the outlet of the boiler	653	°C
Pressure of live steam at the outlet of the boiler	30.3	MPa
Temperature of live steam at the inlet of the steam turbine	650	°C
Pressure of live steam at the inlet of the steam turbine	30	MPa
Temperature of reheated steam at the outlet of the boiler	672	°C
Pressure of reheated steam at the outlet of the boiler	6	MPa
Temperature of reheated steam at inlet of the steam turbine	670	°C
Deaerator operating pressure	1.15	MPa
Condenser operating pressure	0.005	MPa
Pressure at the outlet of condensate pump	2.2	MPa
Temperature of feed water	310	°C
Isentropic efficiency of stages of the H part of steam turbine (ST) points 2–11 (Fig. 1)	87.0	%
Is. eff. of stages the H part of ST – points 11–12	88.0	%
Is. eff. of stages the I1 part of ST – points 5–13–14–15	92.0	%
Is. eff. of stages the I2 and I3 parts of ST – points 6–7 and 6–8	90.0	%
Is. eff. of stages the L1 and L2 parts of ST – points 7–18	90.0	%
Is. eff. of stages the L1 and L2 parts of ST – points 18–19	85.0	%
Is. eff. of stages the L3 and L4 parts of ST – points 8–19	85.0	%
Boiler efficiency (bituminous coal)	94.5	%
Generator efficiency	98.8	%
Steam turbine mechanical losses	0.32	MW
Isentropic efficiency of pumps	85.0	%
Efficiency of regenerative heat exchangers	99.5	%
Efficiency of the steam cooler	99.5	%
Steam flowing losses in the pipeline due to regenerative heat exchangers and the steam cooler	2.0	%
Steam flowing losses in the pipeline from the steam cooler to HR1 regenerative heat exchanger	1.0	%
Water flowing losses through regenerative heat exchangers and the steam cooler	1.0	%
Pressure losses of the working medium in the boiler	4.2	MPa
Pressure losses of steam in the reheater	0.3	MPa
Steam flow losses in reheated steam pipelines	1.7 1.7	%
Condensate temperature rise in low-pressure regenerative heat exchangers	120.7	K
Feed water temperature rise in the HR1 regenerative heat exchanger	41.9	K
Feed water temperature rise in the HR3 regenerative heat exchanger	28.4	K
Feed water temperature rise in the steam cooler	5.0	K
Terminal temperature differences in LR1, LR2, LR3 and LR4 regenerative heat exchangers	3.0	K
Terminal temperature differences in HR1, HR2 and HR3 regenerative heat exchangers	2.0	K
Drain cooling approach temperature in HR1, HR2 and HR3 regenerative heat exchangers	10	K
Gross power	320	MW

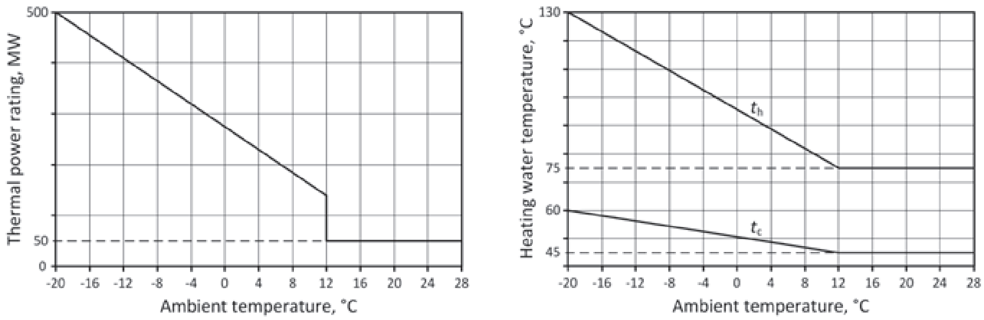

Figure 2. Diagram of the heat demand the temperature characteristics of the heating system.

gases generated in steam boiler are purified before entering the CCS installation. Additionally, before entering the membrane modules, the flue gases are cooled to the membrane temperature (40 °C). The flue gas flow generated in the boiler is 301.3 kg/s, and the gas produced has the following composition: (CO_2)=0.1416, (SO_2)=0.0009, (O_2)=0.0329, (N_2)=0.7378, (H_2O)=0.0780, (Ar)=0.0088. Before entering the membranes (M), the flue gases are dried. There is a pressure difference across the membrane, and thus, the gas with a high concentration of CO2 permeates through the membrane. It was assumed that pressure on the permeate side is 3 kPa. The vacuum is caused by the work of two vacuum pumps (VP1 and VP2). The use of two pumps and interstage cooling makes it possible to decrease the energy consumption of these machines. The calculations for membranes were performed in the AspenPlus program. The membranes were assumed to have a selectivity of 200. The membrane surface was chosen to achieve a recovery rate of 0.9. A permeate flow equal of 62.96 kg/s was calculated, and the following composition was determined for the permeate: (CO_2)=0.8575, (SO_2)=0.0013, (O_2)=0.0159, (N_2)=0.1238, (Ar)=0.0015. The pressure at the outlet of the VP2 vacuum pump is 100 kPa. For the analysis, it was assumed that the two vacuum pumps have the same pressure ratios. In the next step after cooling, the permeate is fed to the compressor station, where it is prepared for transport and storage. In the compressor station, the gas is compressed to a pressure of 20 MPa. Here, as in the case of the vacuum pumps, the same pressure ratios are assumed. The heat exchangers are installed after the machines, and the cooling medium used the heating water taken from before the low-pressure heating network heat exchanger (HE1). In each heat exchanger, water is preheated to the same temperature according to the assumed temperature characteristics of the heating system. The heat exchangers allow a reduced flow of steam to be used for heating the water. After the permeate/heating water heat exchangers, the permeate is cooled in additional heat exchangers. The cooling heat obtained in these heat exchangers is dissipated into the atmosphere. It is assumed that the heat exchangers cool the gas to 40 °C.

3 Assumptions for analysis and results of calculations

The primary aim of the analysis was to determine whether cooling heat obtained from the CCS installation could be used for the production of useful hot water and to determine the effects of such an integration on the following annual effectiveness indicators:

- annual efficiency of electricity production:

$$\eta_{el_R} = \frac{E_{el_R}}{m_{c_R} LHV_c} = \frac{\int_0^{\tau_R} N_{el,b} d\tau}{LHV_c \int_0^{\tau_R} \dot{m}_c d\tau} , \tag{1}$$

where:

E_{el_R}	–	gross annual production of electricity, MJ
m_{c_R}	–	annual consumption of coal, kg
LHV_c	–	lower heating value of coal, MJ kg^{-1}
$N_{el,b}$	–	gross power, MW
$\dot{m}_c$	–	flow of coal, kg s^{-1}
τ	–	time, s
τ_R	–	annual time, s

- annual efficiency of useful heat production:

$$\eta_{q_R} = \frac{Q_R}{m_{c_R} LHV_c} = \frac{\int_0^{\tau_R} \dot{Q}\, d\tau}{LHV_c \int_0^{\tau_R} \dot{m}_c d\tau} , \tag{2}$$

where:

Q_R	–	annual production of useful heat, MJ
$\dot{Q}$	–	thermal power of CHP, MW

- annual overall efficiency

$$\eta_{el+q_R} = \eta_{e_R} + \eta_{q_R} . \tag{3}$$

To determine the quantities defined by Eqs. (1)–(3), knowledge of the ambient temperature distribution within the calendar year is required. The ordered diagram of ambient temperature as a function of time was adopted based on [8]. It was assumed that the chosen temperature diagram is representative, but it should be noted that the shapes of characteristics can undergo major changes over the period of CHP plant operation [9]. This will undoubtedly affect the values of annual efficiency measures.

The results shown in Figs. 3–5 concern two cases of operation of the CHP plant integrated with CCS installation:

- **case A:** operation without the use of cooling heat obtained from the CCS installation for the preheating of useful heating water,
- **case B** operation with the use of cooling heat obtained from the CCS installation for the preheating of useful heating water.

In the first step, the calculations were performed for a predetermined range of ambient temperatures t_a (from -20 °C to 28 °C with step of 1 K), which, according to the heat demand diagram (Fig. 2), determined the required level of heat production. This stage of the calculations was performed separately for the two cases, and the aim of this stage was to determine the gross power and thermal power (which is the sum of the thermal power of the basic district heating heat exchanger (HE1), the thermal power of peak district heating heat exchanger (HE2) and, for case B, the additional cooling heat flux occurring in the CCS installation). The results are shown in Fig. 3. In the next step, based on the obtained characteristics and with the use of the assumed ordered diagram of ambient temperature as a function of time, the values of characteristics were transformed to obtain the distributions of gross power and thermal power as functions of time. The results of the transformation are shown in Fig. 4. With the characteristics of gross power, thermal power and coal flow (constant load of boiler was assumed) as a function of time, it is possible to calculate the quantity defined by relationships (1)–(3). In Fig. 5, the characteristics of annual efficiencies as a function of operation time are shown.

4 Conclusions

The use of cooling heat from the CCS installation for preheating district heating water makes it possible to:

- reduce steam consumption at ambient temperatures above -8 °C and consequently increase steam turbine power,

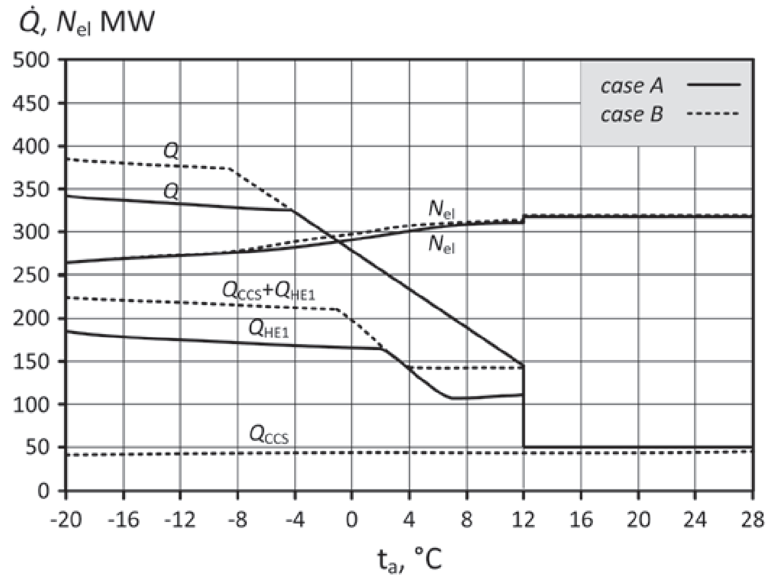

Figure 3. Characteristics of gross power and thermal power as a function of ambient temperature.

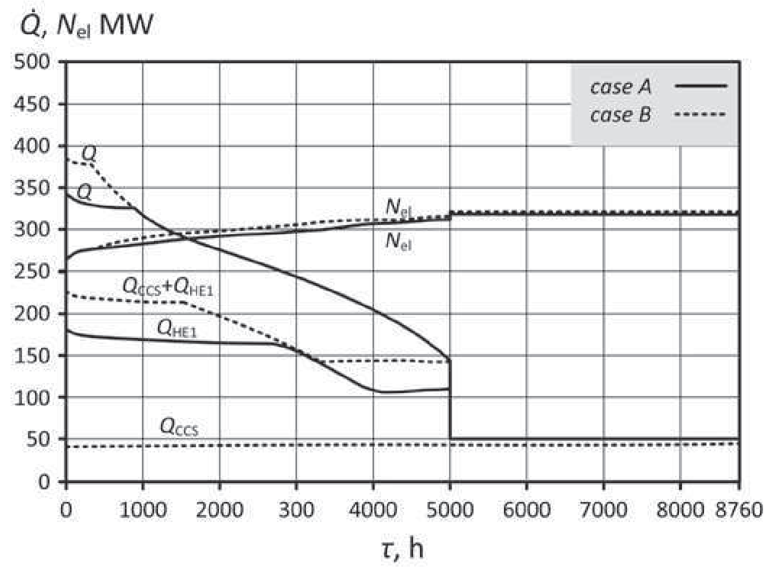

Figure 4. Characteristics of gross power and thermal powers as a function of time.

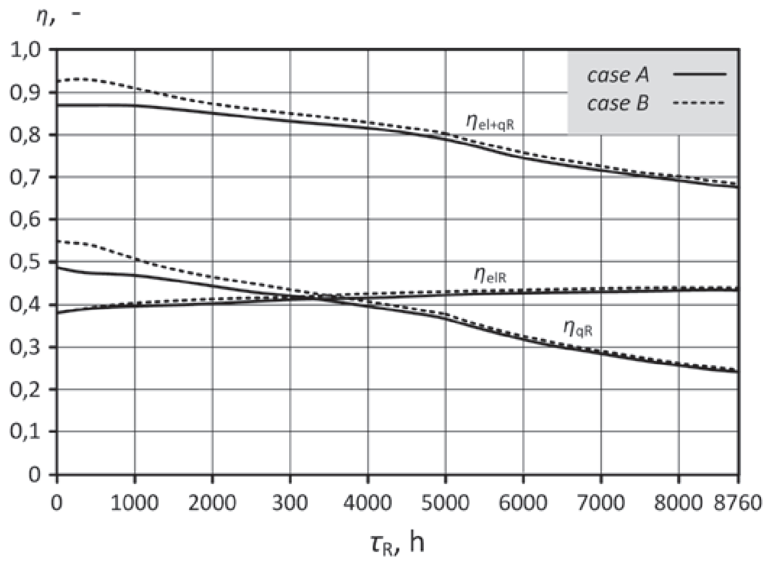

Figure 5. Characteristics of annual efficiency of electricity production, annual efficiency of useful heat production and annual overall efficiency as a function of annual time of operation of CHP plant.

- almost fully cover heat demand during the summer (for ambient temperatures above 12 °C),
- reduce annual operation times of peak heating devices from approximately 800 h to approximately 300 h,
- increase annual efficiency regardless of the annual time of operation of the CHP plant.

For the real annual time of operation of the CHP plant, e.g., 8000 h/a, the annual efficiencies of electricity production for the two cases were as follows: 0.4336 for case A and 0.4397 for case B. Respectively, the annual efficiencies of useful heat production are 0.2575 and 0.2624, while the annual overall efficiencies are 0.7914 and 0.8002.

5 Summary

The integration of a supercritical CHP plant with a membrane CCS installation is a solution that enables the capture of carbon dioxide without the need to supply heat to the capture process. In CHP plants, this solution is appropriate because extracted steam can be used for the production of useful heat. However, the technology is still immature and cannot be easily implemented commercially.

In this paper, we have analyzed the increase of power in a steam turbine obtained by recycling heat from the CCS compressed permeate cooling process. However, the increase in gross power does not compensate for the decrease of net power in the system that results from high-energy consumption in the CO_2 separation process. During the analysis, the auxiliary power of the CHP plant was not determined. However, the power needed to drive compressors and vacuum pumps is estimated to be approximately two times higher than the total remaining auxiliary power. Therefore, in case A (without use of cooling heat), the decrease in net efficiency is equal to approximately 6 percentage points, whereas the decrease in case B is approximately 5 percentage points. Similar relationships were obtained by the authors of [10] when considering a condensing unit in which cooling heat was used to replace regenerative heat exchangers. Issues concerning the CCS membrane installation energy consumption, as well as the possibility of reducing the net efficiency drop by optimizing the method of integration, will be the subjects of work performed in the next stages of our research.

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References

[1] *Energy Policy of Poland until 2030.* Ministry of Economy. Warsaw, 10 November 2009 (in Polish).

[2] Zaporowski B.: *Energy and cost effectiveness analysis of steam and gas-steam combined heat and power plants.* Rynek Energii **5**(78), 2008, 41–44 (in Polish).

[3] Budzianowski W.: *Critical evaluation of low-carbon electricity production technologies.* Rynek Energii **4**(95), 2011, 127–133 (in Polish).

[4] *Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/94/EEC.*

[5] Chmielniak T., Kosman G., Łukowicz H.: *Carbon dioxide capture system integration with condensing power units.* Rynek Energii **6**(79), 2008, 75–81 (in Polish).

[6] Chmielniak T.: *The role of various technologies in achieving emissions objectives in the perspective of the years up to 2050.* Rynek Energii **1**(92), 2011, 3–9 (in Polish).

[7] Milewski J., Świercz T., Badyda K., Miller A., Dmowski A., Biczel P.: *The control strategy for a molten carbonate fuel cell hybrid system.* Int. J. Hydrogen Energy **35**(2010), 7, 2997–3000 (in Polish).

[8] Szargut J., Ziębik A.: *Fundamentals of thermal engineering.* PWN, Warszawa 1998.

[9] Sekret R., Wilczyński J.: *The effect of variations in ambient air temperature and heating season length on the number of degree-days on the example of the city of Częstochowa.* Rynek Energii **4**(95), 2011, 58–63 (in Polish).

[10] Kotowicz J., Janusz-Szymańska K.: *Influence of CO_2 separation on the efficiency of the supercritical coal fired power plant.* Rynek Energii **2**(93), 2011, 8–12 (in Polish).

Analiza nadkrytycznej elektrociepłowni węglowej zintegrowanej z membranową instalacją CCS

S t r e s z c z e n i e

W artykule przedstawiono rezultaty analizy dotyczącej integracji wybranego nadkrytycznego bloku CHP z membranową instalacją CCS. Zaproponowano sposób na poprawę charakterystyk pracy takiego układu polegający na wykorzystaniu ciepła chłodzenia permeatu sprężanego w obrębie instalacji wychwytu dwutlenku węgla do produkcji ciepła użytkowego. Dodatkowym źródłem ciepła jest chłodzenie dwutlenku węgla sprężanego celem jego przygotowania do transportu do miejsca składowania. Rozpatrywane wykorzystanie ciepła chłodzenia jako ciepła grzewczego prowadzi do zmniejszenia poboru pary upustowej i w rezultacie do wzrostu mocy turbiny parowej. Dla dwóch analizowanych przypadków określono wpływ zmiany obciążeń cieplnych bloku na moc brutto oraz obciążenia poszczególnych wymienników ciepłowniczych. Badaniom poddano wpływ przyjętego czasu pracy elektrociepłowni w roku na podstawowe charakterystyki efektywności średniorocznej: średniorocznej sprawności wytwarzania energii elektrycznej, średniorocznej sprawności wytwarzania ciepła oraz średniorocznej sprawności ogólnej układu. W podsumowaniu pracy podkreślono duże znaczenie samej integracji bloku CHP z instalacją CCS po stronie cieplnej.