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Thermodynamic and economic analysis of a 900 MW ultra-supercritical power unit

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Abstract The paper presents a thermal-economic analysis of different variants of a hard coal-fired 900 MW ultra-supercritical power unit. The aim of the study was to determine the effect of the parameters of live and reheated steam on the basic thermodynamic and economic indices of the thermal cycle. The subject of the study was the cycle configuration proposed as the "initial thermal cycle structure" during the completion of the project "Advanced Technologies for Energy Generation" with the live and reheated steam parameters of 650/670 °C. At the same time, a new concept of a thermal cycle for ultra-supercritical parameters with live and reheated steam temperature of 700/720 °C was suggested. The analysis of the ultra-supercritical unit concerned a variant with a single and double steam reheat. All solutions presented in the paper were subject to a detailed thermodynamic analysis, as well as an economic one which also included CO_2emissions charges. The conducted economic analysis made it possible to determine the maximum value of investment expenditures at which given solutions are profitable.

Keywords: Ultra-supercritical steam parameters; Steam cycle; Coal-fired power unit; Double reheat

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1 Introduction

Professional power engineering based on hard and brown coal is the principal source of electricity generation. Coal is the primary source of energy both in Poland and in the world. The advantages and disadvantages of the coal technology are well known. Coal-based power engineering is proven and reliable, and the cost of fuel itself is low. The prices of the raw material are stable and supplies are guaranteed. These undoubted benefits are in conflict with ever more stringent ecological requirements. At the moment, this mainly concerns the problem of reduction of carbon dioxide emissions into the atmosphere. And that is why there is such a big pressure on the development of CO_2 capture and storage technologies. At the same time, attempts are made to increase the efficiency of the conversion of the fuel chemical energy into electricity. An increase in the efficiency of electricity generation is possible owing to the application of a series of new solutions to the structure of the thermal power plant, as well as to the use of supercritical live steam parameters. The main factors which could improve the efficiency of a thermal power plant are:

- rise in the temperature of the upper source of heat by increasing the live and reheated steam parameters,
- increase in the live steam pressure which allows an extension of the expansion line,
- reduction in the temperature of the lower source of heat by decreasing the pressure in the condenser,
- optimum configuration of the structure of the thermal cycle (heat recovery from exhaust gases, double steam reheat, etc.),
- reduction of own needs of the thermal power plant.

The present development of supercritical and ultra-supercritical power unit technologies makes it possible to obtain live steam temperatures at the level of 600 °C. At the same time, it is already possible to raise that temperature to the value of 650 °C, and even 700 °C. Additionally, new solutions to the structure of the thermal cycle itself will soon make it possible to reach electricity generation efficiency exceeding 50%. It is noteworthy, however, that all the presented solutions entail the increase in investment expenditures. Therefore, each solution should be subjected to a detailed thermodynamic and economic analysis.

The aim of this paper is to present an initial structure of a cycle for ultra-supercritical parameters together with the analysis of impact of selected factors on the efficiency of the cycle itself. This is mainly related to the concept of the application of a double steam reheat. An economic analysis of the proposed solution will also be conducted for two variants of live steam. Three variants of a 900 MW hard coal-fired power unit for ultra-supercritical parameters were adopted for the calculations.

- variant I: (basic) cycle with a single steam reheat, 650/670 °C;
- variant II: cycle with a single steam reheat, 700/720 °C;
- variant III: cycle with a double steam reheat, 700/720 °C.

Figure 1 presents the diagram of the 900 MW thermal cycle with a single steam reheat. The configuration was adopted as the "initial thermal cycle structure" during the completion of the project “Advanced Technologies for Energy Generation". The cycle consists of four low pressure feed water heaters, three high pressure feed water heaters, a mixing exchanger which fulfils the function of the deaerator and a steam desuperheater, which is the last component of high pressure regeneration. An electric drive of the boiler feed pump was used in the cycle variant under consideration. The solution is becoming more and more popular, mainly due to lower investment expenditures. Table 1 presents the basic values adopted during the cycle analysis. The value of the live and reheated steam temperature is in this case 650/670 °C.

The basic indices of the operation of the cycle together with their definitions are listed in Tab. 2. The cycle efficiency in this case is 50.92%, and the gross electricity generation efficiency for hard coal equals 49.1%. With the own needs index ε taken into account at the level of 7.5%, the net electricity generation efficiency is equal to 45.42%.

2 Analysis of possible structures of the power unit for ultra-supercritical parameters

The continuous increase in the live and reheated steam parameters, and the new solutions to the structure of the thermal cycle itself, on the one hand lead to an improved efficiency of the cycle, but on the other — entail a substantial rise in investment expenditures. Therefore, each solution should be preceded by a detailed thermal-economic analysis. Figure 2

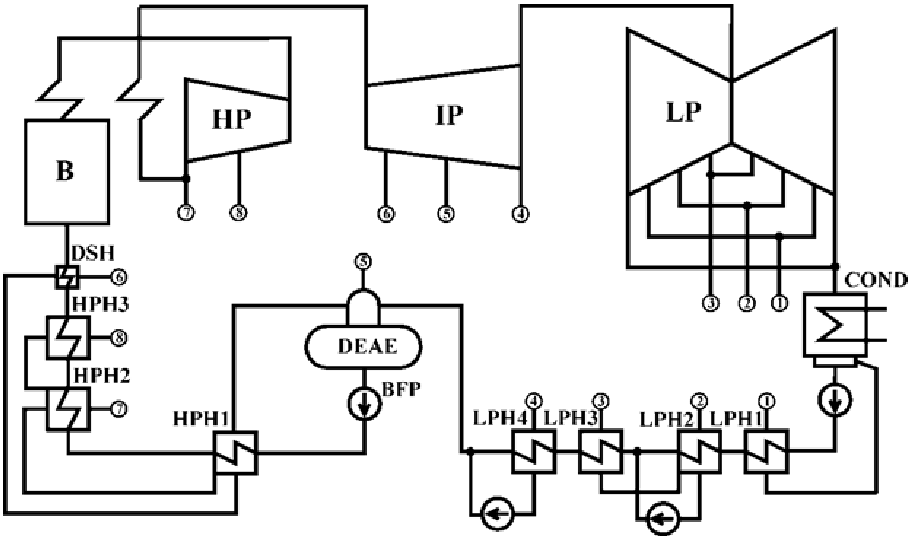

Figure 1. Diagram of the basic cycle (B-boiler, HP-high pressure turbine, IP-intermediate pressure turbine, LP-low pressure turbine, COND-condenser, DEAE-deaerator, BFP-boiler feed pump, LPH-low pressure feed water heater, HPH-high pressure feed water heater, DSH-steam desuperheater).

Table 1. Basic values adopted during the basic cycle analysis.

Live steam parameters before the turbine	p_{LS} t_{LS}	30 MPa, 650 °C,
Reheated steam parameters before the turbine	p_{RS}, t_{RS}	6 MPa, 670 °C
Gross electric power of the unit	N_{elG}	900 MW
Feed water temperature	t_{FW}	310 °C
Pressure in the condenser	p_{cond}	5 kPa
Boiler efficiency	η_B	• hard coal – 94.5% (exhaust gas temperature: 115(120) °C) • brown coal – 90% (exhaust gas temperature: 170 °C)
Internal efficiency of stage groups	η_{iHP}	90.0
	η_{iIP}	92.0
	η_{iLP}	85.0
	η_{iLP1}	80.0

Table 2. Basic indices of the power unit operation.

Gross electric power (at the generator terminals)	N_{elG}	900.0 MW
Net electric power (own needs index: ε=7.5%)	N_{elN}	832.5 MW
Cycle efficiency	$\eta_c = \frac{Q_{in}-Q_{out}}{Q_{in}}$	50.92%
Fuel chemical energy	Q_{en_ch}	1833 MW
Gross electricity generation efficiency (for hard coal)	$\eta_{elG} = \frac{N_{elG}}{Q_{en_ch}}$	49.1%
Net electricity generation efficiency	$\eta_{elN} == \frac{N_{elG}(1-\varepsilon)}{Q_{en_ch}}$	45.42%
Internal power of the feed water pump	N_{BFP}	28.8 MW
Unit consumption of the fuel chemical energy (for hard coal)	$q_{en_ch} = 3600\frac{Q_{en_ch}}{N_{elG}}$	7322 kJ/kWh

presents a proposed structure of an ultra-supercritical power unit with the live steam parameters of 700 °C/35 MPa, and reheated steam parameters of 720 °C/7.5 MPa. The assumed cycle configurations and the basic steam parameters are based on [2] and [3]. The basic data for the steam boiler calculations were taken from [7]. The efficiency of individual stage groups of the turbine, the pressure values in the condenser and the value of the own needs index were assumed as identical to those in the basic cycle (Tab. 1). The presented cycle has a structure similar to that of the basic cycle. One of the major differences is the application of an additional mixing exchanger in the low-pressure regenerative system. Therefore, there is also a need for the use of an additional condensate pump. There is no additional steam desuperheater in the high-pressure feed water heaters system under consideration. The feed water temperature is 330 °C. An electric drive of the main pump was used for the presented cycle. At the same time, a booster pump was used before the main pump. Such a solution prevents cavitation, a phenomenon which may occur in the main pump itself.

Figure 3 presents a diagram of an ultra-supercritical power unit with an additional use of a double steam reheat. The live steam parameters are 700 °C/37.5 MPa, for reheated steam – 720 °C/12.5 MPa and 720 °C/3 MPa. The assumed cycle configuration and the basic steam parameters are based on [2] and [6]. The high-pressure turbine in this case does not have any

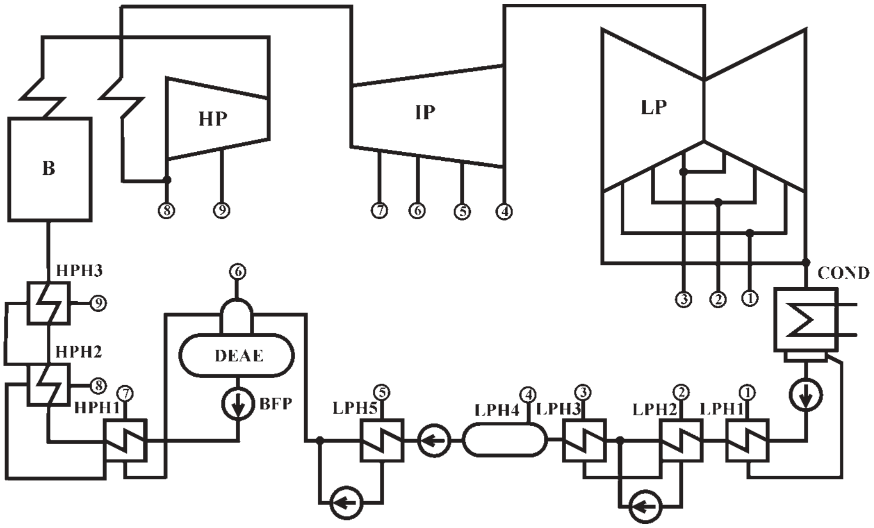

Figure 2. Diagram of a 900 MW ultra-supercritical power unit with a single steam reheat.

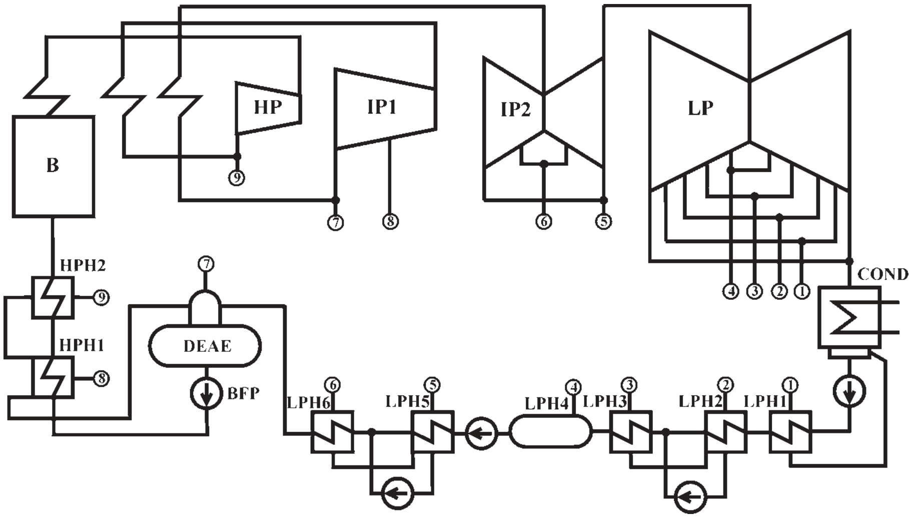

Figure 3. Diagram of a 900 MW ultra-supercritical power unit with a double steam reheat.

steam bleeds. From the HP turbine a part of steam is directed for high-pressure feed water heaters and the rest – for first reheat. Then the superheated steam goes to the intermediate part of the turbine IP1, and from there it is directed for the second reheat. Table 3 illustrates the basic operation indices of the presented variants of the ultra-supercritical power unit with a single (variant II) and double (variant III) steam reheat. The application of the second reheat produces a net increase in the electricity generation efficiency of 0.89%. It should be noted that the calculations were made assuming the average annual pressure in the condenser at 5 kPa. With lower pressure values the profits gained from the use of the second steam reheat rise significantly. The advantages of the improvement in the steam dryness factor in the low-pressure part of the turbine were also taken into account in the calculations. A higher dryness factor translates in this case into a better efficiency of the last stages of the LP part of the turbine, and prevents many operation-related problems. The loss resulting from steam moisture content was taken into consideration according to Baumann equation [4]:

$$\begin{gathered}\eta_x = \bar{X}\eta \\ \bar{X} = \frac{X_1 + X_2}{2}\end{gathered} \tag{1}$$

where:

η_x – efficiency of the turbine stage group taking account of the impact of the steam dryness factor,

η – efficiency of the turbine stage groups working in the area of superheated steam,

$\bar{X}$ – average dryness factor in the stage group,

X_1 – dryness factor at the inlet to the stage group,

X_2 – dryness factor at the outlet of the stage group.

For the presented variants (Fig. 2 and Fig. 3) the net electricity generation efficiency was 47.3% and 48.1%, respectively. The own needs index was in this case assumed at 7.5%. This rather high value of the own needs index was adopted due to the use of an electric drive of the main pump.

3 Economic analysis

The economic analysis of the ultra-supercritical power unit variants under consideration was based on the net present value – *NPV* – method according

Table 3. Basic indices of the operation of the presented variants of an ultra-supercritical power unit.

Variant	II	III	
Cycle efficiency	52.91	53.92	%
Gross electric power (at the generator terminals)	900	900	MW
Gross electricity generation efficiency	51.14	52.03	%
Net electricity generation efficiency	47.3	48.13	%
Internal power of the booster feed water pump	1.53	1.43	MW
Internal power of the main feed water pump	28.76	27.02	MW
Internal power of all condensate pumps	1.54	1.96	MW
Unit heat consumption	6652	6539	kJ/kWh
Unit consumption of the fuel chemical energy	7039	6919	kJ/kWh

to [1]. NPV is defined by the following dependence:

$$NPV = \sum_{t=1}^{t=N} \frac{CF_t}{(1+r)^t} , \tag{2}$$

where:

CF_t – cash flows in time t,

r – discount rate,

t – next year of consideration from the commencement of the cycle construction ($t = 1$ the year when the construction was started).

Discount rate r is calculated from the following dependence:

$$r = r_k(1 - p_d)u_k + r_w(1 - u_k) , \tag{3}$$

where:

r_k – commercial credit rate,

p_d – income tax,

u_k – share of credit in the investment financing,

r_w – return on equity (e.g. in treasury bonds).

Cash flows in time t are defined by the following dependence:

$$CF_\tau = [-J + S_{el} - (K_{op} + P_d + K_{cwc}) + A + L]_\tau , \tag{4}$$

where:

J – investment expenditures,
S_{el} – revenues from the sale of electricity,
K_{op} – operating costs,
P_d – income tax,
K_{cwc} – change in the working capital,
A – depreciation,
L – liquidation value.

The determination of the total investment expenditures was based on unit investment expenditures necessary to build 1 kW of electric power:

$$J = i_X N_{el} \ , \tag{5}$$

where:
J – investment expenditures,
i_X – unit investment expenditures,
N_{el} – the power unit gross electric power.

Revenues from the sale of electricity:

$$S_{el} = \int_0^{\tau_el} (1 - \varepsilon_c) N_{el} d\tau_{el} \ , \tag{6}$$

N_{el} – the power unit gross electric power
C_{el} – average selling price of electricity,
τ_{el} – total annual operation time of the power unit
ε – the power unit own needs index.

Operating costs:

$$K_{op} = K_f + K_o + K_{ps} + K_e + K_r + K_u + A_k + A \ , \tag{7}$$

where:
K_f – fuel costs,
K_o, K_r – servicing, maintenance and repair costs,
K_{ps} – costs related to other raw materials,
K_e – other operating costs (including environmental charges),
A_k – excise tax cost.

The subject of the economic analysis was the presented variant of an ultra-supercritical power unit with a single reheat of steam with parameters of 650/670 °C. Table 4 presents the basic data assumed during the economic analysis. The adopted discount rate was determined from dependence (3). It was assumed that the service life of the power unit was 20 years. The construction of the power unit was spread over 4 years, and the involvement of investment means in each year was 10%, 25%, 35% and 30%, respectively. Additionally, the liquidation value of the investment was omitted in the calculations of the *NPV*. Excise tax costs were not taken into consideration, either, due to the new laws which require that excise tax be paid not by electricity manufacturers but by its suppliers.

Table 4. Basic data adopted for the economic analysis.

The power unit rated power	900 MW
Annual operation time of a coal-fired power unit	8000 h,
Average price of fuel (hard coal – 23 MJ/kg)	270 PLN/tonne
Price of electricity	220/320 PLN/MWh
Employment	0.4 person/MW
Unit payroll cost	6000
Depreciation rate	6%
Income tax rate	19%
Share of equity	20%
Own means interest rate	5.75%
Discount rate	6.33%
Commercial credit interest rate	8%
Commercial credit repayment period	10 years
Power unit service life	20 years
CO_2 emissions charge price	150 PLN/tonne

It was additionally assumed that the costs of repairs and insurance are constant and each year they are equal to 1% of the investment expenditures. For all variants under consideration the own needs index was assumed as $\delta = 7.5\%$. In order to determine the investment expenditures, the average exchange rate of 1 US dollar in the previous three months was assumed at 2.89 PLN.

The economic analysis also included the costs of emissions of sulphur and nitrogen oxides, and carbon dioxide. Moreover, many extra fixed and variable costs were taken into account, such as the costs of disposal of solid products, lime suspension costs or the cost of demineralised water. Within the economic analysis, the minimum selling price of electricity was used, which is defined by dependence (8):

$$NPV(c_{el_min}) = 0\ . \tag{8}$$

Figure 4 presents the characteristics of the dependence of the minimum selling price of electricity c_{el_min} and the net present value NPV on the fuel price. The conducted calculations concerned two variants in which the carbon dioxide emissions charges were either taken into consideration or omitted. It was assumed that the price of carbon dioxide emissions was 150 PLN/t$_{CO2}$. The fuel price varied within the range of 220–320 PLN/t, with initial price assumed at 270 PLN/t. The presented characteristics were obtained assuming three different values of unit investment expenditures. For the initial fuel price at 270 PLN/t, the minimum selling price of electricity is approx. 208 PLN/MWh with investment expenditures of 1900 USD/kW. If, in this case, the carbon dioxide emissions charges are taken into consideration, the minimum selling price of electricity rises to as much as 320 PLN/MWh.

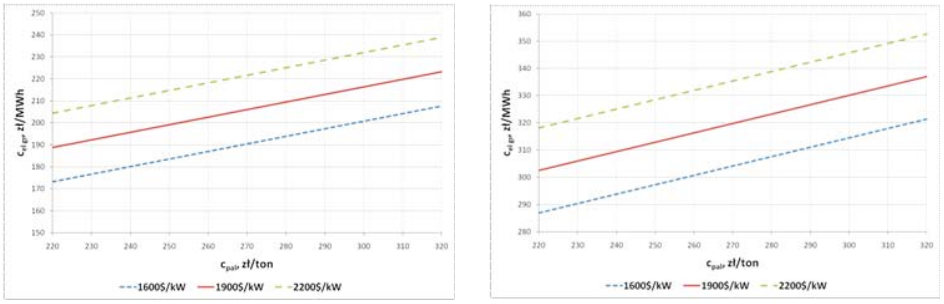

Figure 4. The impact of the hard coal price on the minimum selling price of electricity for the considered values of unit investment expenditures.

The dependence of the change in the net present value NPV on the hard coal price was also considered (Fig. 5). In the case where CO_2 emissions charges were omitted, the selling price of electricity was assumed at 220 PLN/MWh. If they were taken into consideration, the assumed price was 320 PLN/MWh. For the considered range of variety in the fuel price and for the assumed selling price of electricity, the net present value NPV remains positive only for the lowest value of investment expenditures of 1600 USD/kW. An increase in the considered investment expenditures and a simultaneous rise in the prices of fuel may render the investment unprofitable.

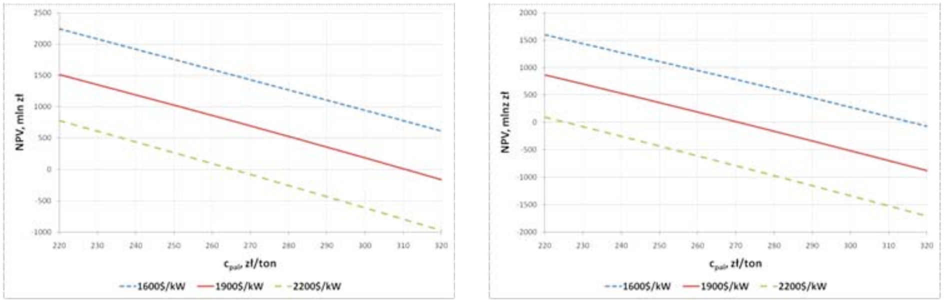

Figure 5. The impact of the hard coal price on the NPV for the considered values of unit investment expenditures.

Apart from the basic variant of the ultra-supercritical power unit, two other variants of the power unit with the live and reheated steam parameters of 700/720 °C were the subject of the economic analysis. The calculations were made for both the variant with a single (Variant II) and a double (Variant III) steam reheat. Table 5 shows the results of the economic analysis which was based on the input values listed in Tab. 4.

Table 5. Comparison of the discussed variants of the ultra-supercritical power units.

Case under consideration	η_{elG} %	Investment expenditures for $NPV = 0$			
		CO_2 emissions charges omitted Assumed selling price of electricity 220 PLN/kWh		CO_2 emissions charges taken into consideration Assumed selling price of electricity 320 PLN/kWh	
		per unit	total	per unit	total
		USD/kW / PLN/kW	billion USD / billion PLN	USD/kW / PLN/kW	billion USD / billion PLN
Variant I (basic)	49.1	2169 / 6267	1.95 / 5.64	1905 / 5505	1.71 / 4.96
Variant II	51.14	2243 / 6483	2.02 / 5.83	2066.9 / 5973	1.86 / 5.38
Variant III	52.03	2274 / 6572	2.05 / 5.91	2133.6 / 6166	1.92 / 5.55

For the purposes of the analysis of the variants under consideration, it was assumed that the net present value NPV in each case equalled zero, which made it possible to determine the maximum values of the unit and total investment expenditures that will ensure a return on investment. The calculations were made for the carbon dioxide emissions charges both omitted and taken into consideration. For both cases, two different values of the selling price of electricity were assumed: 220 and 320 PLN/KWh. The economic analysis which was conducted with omitted emissions charges showed that the maximum value of investment expenditures, with the temperature values of the live and reheated steam at 650/670 °C, was 2169 USD/kW (6267 PLN/kW). The use of the ultra-supercritical steam parameters of 700/720 °C increases the value of the unit maximum investment expenditures to 2243 USD/kW (6483 PLN/kW), and the introduction of the second steam reheat gives the amount of 2274 USD/kW (6572 PLN/kW). The difference in the total investment expenditures between the basic variant and Variant III was approx. 100 million USD (280 million PLN). If, additionally, the CO_2 emissions charges are taken into account, the differences in the maximum unit investment expenditures between the variants under consideration increase substantially. In this case, the use of high steam parameters results in a profitable rise in the unit investment expenditures by more than 9% compared to the basic variant. The application of the second reheat increases the value by another 3%. Summarising, it gives the potential increase in the total investment expenditures by approx. 210 million USD (600 million PLN). The presented results show that the inclusion of the CO_2 emissions charges in the economic analysis leads to a more than twofold increase in profitable investment expenditures which result from raising the live steam parameters and the application of the double steam reheat.

4 Conclusions

The aim of the analysis was to determine the basic thermodynamic and economic indices of different variants of the ultra-supercritical power units. The conducted calculations included the "initial thermal cycle structure" with a capacity of 900 MW proposed within the completion of the project “Advanced Technologies for Energy Generation” with the live and reheated steam parameters of 650/670 °C. Additionally, two other configurations of the thermal cycle with the steam parameters of 700/720 °C were considered, both with a single and double steam reheat. The performed calculations show that the rise in the live and reheated steam parameters results in the improvement in the efficiency of electricity generation by more than 2%, and the extra use of a double steam reheat increases the value to over 2.9%. The economic analysis proved that the proposed basic configuration of the ultra-supercritical power unit showed a positive net present value. Within the study, the impact of investment expenditures on the minimum selling price of electricity and on the net present value was also defined. It appears that the increase in the live and reheated steam parameters to the value of 700/720 °C can entail a rise in investment expenditures by over 70 million USD (202 million PLN), which constitutes approx. 5% of the total investment expenditures. The investment expenditures on the second steam reheat can additionally increase the value of the investment itself by another 30 million USD (87 million PLN). At the same time, the inclusion of the CO_2 emissions charges in the economic analysis can produce a more than a twofold rise in the value of profitable total investment expenditures. In total, investment expenditures can rise by more than 12% and reach the value of 1.92 billion USD (5.55 billion PLN).

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