FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 20, Nº 1, 2022, pp. 53 - 72
https://doi.org/10.22190/FUME200218017M

Original scientific paper

ENERGY ANALYSIS OF REPOWERING STEAM POWER PLANTS BY FEED WATER HEATING

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Abstract. *Modern society and economic development are completely dependent on various forms of energy while the ever-increasing demand for energy, in combination with significant environmental topics, has resulted in state-of-the-art ideas and solutions for fulfilling these often-contradictory goals, i.e. increasing efficiency or environmental protection and economic goal. The efficiency of the existing operating units for electricity production based on the usage of low-quality coal does not go hand in hand with the requirements of this new concept.*
One of the most efficient ways to reduce specific energy consumption is using Combined Heat and Power plants. In comparison to classical, separate heat and power plants, the advantage for CHP plants comes from their high efficiency. The result of higher efficiency is lower primary energy consumption and lower environmental pollution due to low values of CO2 emissions.
Several revitalization configurations can be applied in order to fit the existing thermal power plants into combined cycles. The idea is to install, at the existing location, one gas turbine to increase the overall efficiency. This paper analyzes the potential of a combined gas-steam facility in the situation where the gas facility is used for heating feed water, which enters the heat recovery steam generator.
A comparison of energy efficiency for various operating regimes, with and without heat production, is performed for this option.

Key Words: *Repowering Power Plants, Steam Power Plant, Gas Turbine, Energy Analysis, Efficiency*

Received February 18, 2020 / Accepted May 13, 2020
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1. INTRODUCTION

With the increasing global population, and a rise in the living standard, energy consumption rises as well, exhausting energy resources and threatening the environment. A rapid increase in energy consumption could be expected in currently undeveloped economies, due to the industrialization or re-industrialization. The previous statement is particularly true considering the demand for electricity, since 1/3 of energy resources are being utilized (used, consumed) for electricity production [1]. The limits of energy reserves, the necessity of their further usage and the constraints of the atmosphere potential, have led to shifts in energy policies in numerous developed countries with regard to sustainable development. The strategic goal of these revised energy policies is to achieve maximum energy efficiency by using advanced and state-of-the art energy technologies, which provide maximum efficiency and minimum losses during energy conversion. Maximum environmental protection during energy production is achieved through minimization of pollutants acting on the atmosphere, soil and water, while preserving flora and fauna. Since classically constructed steam blocks have reached their peak considering further improvements and efficiency increase, while gas blocks operate with high specific heat consumption, special attention is given to the construction of combined steam-gas power plants.

Repowering the old, existing steam power plants is an appropriate method for reducing thermal losses and increasing their overall efficiency. Repowering decreases the operation costs of energy production and minimizes environmental pollutions. In addition, repowering enables an increase in the capacity of power plants to a significant extent. Therefore, electricity production companies are giving more attention to this issue [1–3]. The reduction in environmental effects and investment expenses is the most important advantage of repowering a steam power plant [4]. Repowering a steam power plant may increase the net output power by 200% and may improve the efficiency of the power plant by 30% [5]. Methods of repowering steam power plants can be categorized as: full repowering or partial repowering. The most used methods of partial repowering are the feed water heating method, hot wind box method, and supplemental boiler method [6]. In the feed water heating method, the gas turbine exhaust gas is used to heat the current boiler feed water. Power plants suitable for the application of this method are relatively new and modern. The method is particularly suitable for large power plants [7]. Techno-economical characteristics (simplicity and flexibility of feasible designs, low investment cost and lower specific cost of generated electricity) in comparison to other repowering methods are the main advantages of feed water heating in comparison to other methods of partial repowering [8]. The efficiency of the power plant increases with this type of partial repowering [9, 10].

The importance of repowering power plants is well documented in the literature. In [2], general techniques for the conversion of steam cycles to combined cycles by full recovery are given with a few practical cases described. The technically evaluated integration of gas turbines into steam cycles by one of the partial repowering methods is shown and compared with the combined cycle in [11]. The authors found that the partial repowering methods could improve the quality of power production and reduce emissions in steam power plants. Bracco and Siri used a mathematical model to optimize a single pressure heat recovery boiler for a combined cycle using the first and second laws of thermodynamics [12]. There are many published papers in which the combined cycles are techno-economically analyzed or optimized. Some of these studies examine the effect of each of the main components of the cycle on the economic and technical characteristics of the system. Bassily studied the influence of parameters on the quality of power generation in a three-pressure combined plant based on the cycle efficiency [13]. The presented papers on repowering are almost always focused on the effects of different methods of full and partial repowering on target functions.

Feed water is mainly heated in the power plant boiler, but the system feed water is preheated indirectly (via heat exchanger) before entering the boiler. In repowering by feed water heating, part of the heat needed to preheat the feed water is added in heat exchangers; this heat is released by gas turbine(s) hot exhaust gases.

This paper analyzes the possibility of repowering a power plant by heating system feed water in a heat recovery steam generator, with an option to keep the steam boiler as part of the power plant. Repowering the power plant produces heating energy in addition to electricity production. The developed mathematical model allows for varying heat load on the plant, depending on the actual consumer heat demand. The impact of selected parameters of the CHP plant on energy efficiency is analyzed as well.

2. Repowering Options of Steam Power Plants

In the Republic of Serbia, electricity is dominantly (to a larger extent compared to other sources) produced in steam power plants, most of which have already surpassed their initial operation lifetime. Experiences from other countries considering the repowering of steam power plants show that there is an acceptable solution for improvements in power plants and the whole electricity system, in the sense of increasing capacity and overall efficiency, reducing fuel consumption, investment (capital), maintenance and operation costs and reducing environmental impact (footprint).

2.1. Options for facility improvements

Options for modernizing power plants, which include gas turbines, with the largest possibilities are:

- Using the existing location,
- Adding a gas turbine with the existing steam boiler modification,
- Heating feed water with gas turbine exhaust gases, and,
- Replacing the steam boiler with a gas turbine and heat recovery steam generator.

2.1.1. Modernizing by using the existing location

This modernizing process encompasses the disassembly of the existing facility on the location and the construction of a new combined gas-steam facility (new parts are a gas turbine, heat recovery steam generator and steam turbo-facility). In this option, the existing cooling system, connections to the grid, buildings, reservoirs and other objects could be kept. Often called the “brown field” investment, this option's main advantage is in applying new, state-of-the-art equipment for the combined cycle, without any technological compromises during the assembly and connection to the existing equipment. Compared to the “green field” investment, this option has the following advantages: there are no costs for land acquisition and administrative and legal barriers that can occur, the time saved in administrative procedures and socio-economic analysis is significant, and the technical performances of the new power plant are practically the same as in the case of repowering the existing power plant.

2.1.2. Modernizing by installing gas turbine(s)

In this type of modernizing, exhaust gases of one or several gas turbines are connected to the fresh air supply of the existing steam boiler, operating on the same primary fuel. This option can increase the nominal capacity by 10-25% and the efficiency by 10-20% while improving the operation on partial load and reducing NO_X emissions. This option has good results if applied to larger and relatively newer blocks based on liquid or gas fuel. Capacity and efficiency increases are the main advantage, and since the gas turbine has a small share in total power and thus has a small impact on the overall efficiency, larger power plants are good candidates for applying this option.

2.1.3. Preheating feed water with gas turbine exhaust gases

In this option, the exhaust gases from the gas turbine are used for preheating feed water entering the steam boiler. The steam, usually taken from the turbine for this purpose, can produce additional work and give more power, if the steam turbine and generator have the capacity for this additional power. Another solution is to inject this steam in the gas turbine and increase its capacity. The existing regenerative heaters can be used when the gas turbine is off. This configuration of a combined facility should be taken into consideration when the goal is to obtain additional capacity for electricity production. The existing steam turbine is then used for base load while the gas turbine operates in order to get additional power and improve efficiency during maximum peak loads.

2.1.4. Modernizing by replacing the steam boiler with a gas block and heat recovery steam generator

The most used option for modernizing the existing power plants is to disassemble the existing steam boiler and to replace it with a gas turbine and heat recovery steam generator while keeping the existing steam turbine. This approach leads to the capacity increase of up to 150-200% compared to the classical steam block. Heat consumption is reduced by 30-40% and NO_X emissions are reduced as well. Due to a significant capacity increase, this approach is usually applied for older units, with the capacities of up to 250MW. The biggest concern is to optimize the cycle of the existing steam turbine with a new equipment of the combined cycle.

2.2. Selected model of the power plant facility

The schematic flow diagram of a combined cycle power plant is given in Fig. 1. The scheme is of flexible configuration since it allows, depending on the component selection and operation parameters, the analysis of:

- Operation of the condensing type steam block,
- Operation of the steam block for combined heat and power production,
- Operation of the combined gas-steam plant only for the production of power, and,
- Operation of the combined gas-steam plant for the combined heat and power production.

The reason for selecting this model is the flexibility for plant configuration. Depending on the heat demand, the condensing type steam block operation analysis (power production only) or the operation of the combined heat and power production are enabled. During the combined heat and power operation, the heat output represents an input for the numerical simulation of plant operation. In the case of the gas turbine operation, the plant becomes a combined gas-steam plant with possibilities to analyze both only power production and combined heat and power production. There is also a possibility to adjust the scheme to represent the option of replacing the existing regenerative heaters (steam boiler remains) with a gas turbine, and to represent the option of replacing the existing regenerative heaters and steam boiler with a gas turbine.

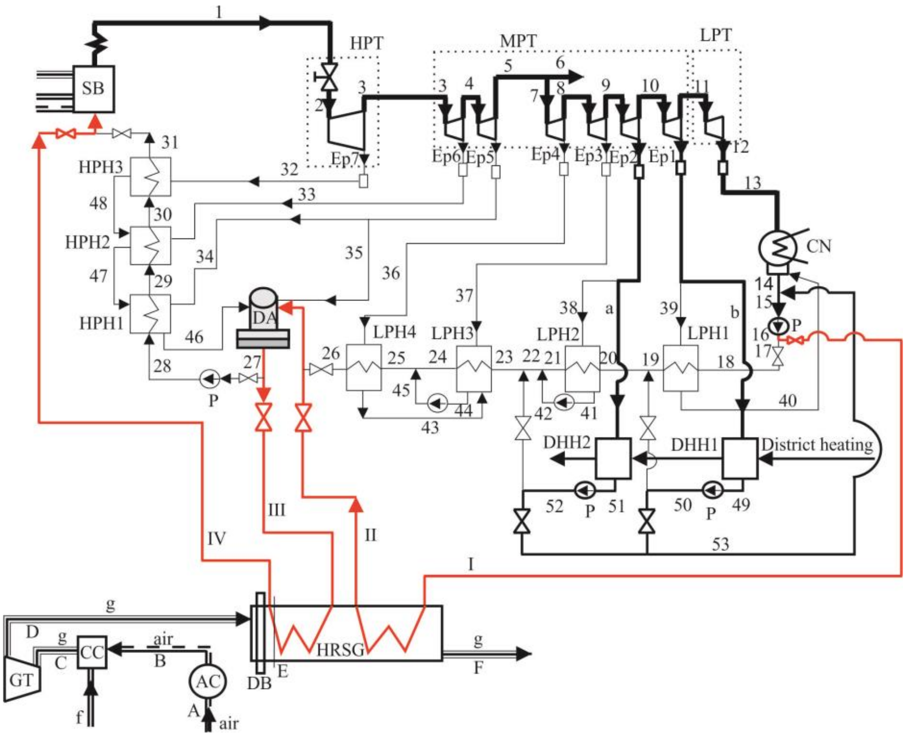

Fig. 1 Schematic flow diagram of a combined cycle power plant

3. Steam Power Plant Cycle Description

Turbines include a high-pressure turbine (*HPT*), a medium-pressure turbine (*MPT*) and two low-pressure turbines (*LPT*). The steam turbine set is equipped with seven extraction ports. Preheating of the condensed steam is done in the low-pressure preheaters of the plant which include four low-pressure heaters (*LPH4*, *LPH5*, *LPH6*, *LPH7*). Heating up the boiler (*SB*) feed water to the final stage at the input of the boiler is done by three high-pressure regenerative heaters (*HPH1*, *HPH2*, *HPH3*). These heaters are supplied with steam from the extraction ports (Ep_1, Ep_2, ...). Part of the steam from the high-pressure turbine is extracted for the high-pressure regenerative heater (HPH3), while the other regenerative heaters and deaerator are supplied with steam extracted from the medium and low-pressure turbines. The deaerator (*DA*) removes the non-condensable gases from the steam cycle. Used steam from the low-pressure turbine is completely condensed in the surface condenser (*CN*). For satisfying the heat demand, two heaters are defined (*DHH1* and *DHH2*, for heat output between 0 MW and 170 MW) with controlled steam extraction from the medium-pressure turbine (Ep_1 and E_{p2}). The plant uses natural gas as a primary fuel with the lower heating value of this fuel mostly above 50020 kJ/kg [14]. The gas turbine facility is of classical configuration with a compressor, burning chamber, gas turbine and heat recovery steam generator. The central place in the heat-flow scheme of the combined gas-steam facility belongs to the heat recovery steam generator, which is used for preheating feed water or for the production of superheated steam. Additional combustion in the heat recovery steam generator is provided as well.

Technical specifications are presented in Table 1.

Table 1 Total properties of the existing steam power plant

Nominal electrical power of the facility (MW)	121
Nominal heat power of the facility (MW)	170
Boiler steam production (kg/s)	121
Steam pressure in point 1 (MPa)	12.1
Steam temperature in point 1 (ºC)	555
Interheated steam pressure (MPa)	2.6
Interheated steam temperature (ºC)	363
Low/high pressure pre-heater number	4/3
Heater number	2
Condensing pressure (MPa)	0.0065
Natural gas lower heating value (kJ/kg)	50020
Extraction port pressure Ep7 (MPa)	2.6
Extraction port pressure Ep6 (MPa)	1.84
Extraction port pressure Ep5 (MPa)	1.02
Extraction port pressure Ep4 (MPa)	0.42
Extraction port pressure Ep3 (MPa)	0.23
Extraction port pressure Ep2 (MPa)	0.069
Extraction port pressure Ep1 (MPa)	0.0067

4. Thermodynamic Analysis - Modeling the Repowered Cycle

The mathematical model of the analyzed plant is a group of nonlinear algebraic equations. For solving these equations, a sequential simulation approach of the facility is adopted in this paper. Custom software is developed for solving the mathematical model and performing the simulation of combined heat and power production. Selecting the operation parameters allows switching the heat-flow scheme to various options (section 2.2) and simulating nominal and other plant operating regimes.

Plant operation simulation enables one to check the performances of the analyzed option and to perform diagnosis for increasing energy efficiency. Plant simulation is merely the first step toward its optimization. The algorithm that the software follows is shown in Fig. 2.

The model is defined as the network of inter-connected modules: turbines, heat exchangers, pumps, compressor, combustion chamber, gas turbine and heat recovery steam generator. The model has a modular structure, so that it quickly adopts various operating regimes. The mathematical model on the proposed flow sheeting problem formulation is created as a type of steady state simulation. Numerical integration was done using the Microsoft Excel programming platform and the *Visual Basic* programming language. The thermodynamic properties of water and steam can be calculated by a group of functions using the equations from the IAPWS-IF97 formulae for industrial applications [15]. The independent variables of the simulation model are defined as mass flow rate, pressure and specific enthalpy. By combining the IAPWS-IF97 formulae with an iterative procedure, the dependent variables of the model can be calculated as a function of pressure and specific enthalpy. Thus, using the three variables, the properties of each flow for the different regions can be determined.

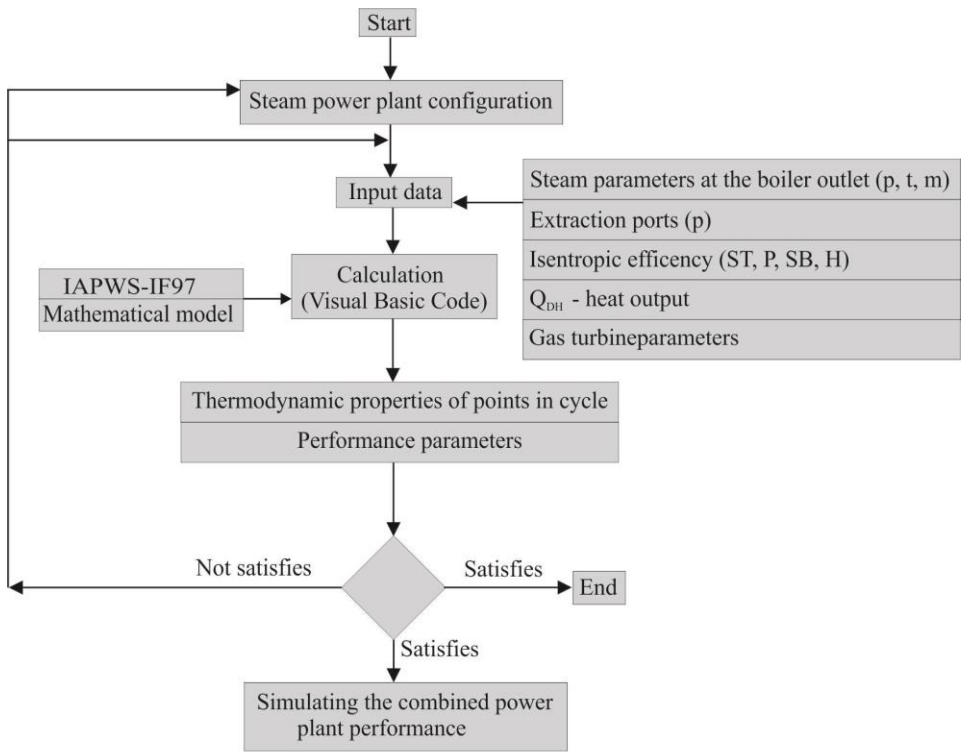

Fig. 2 Methodological framework

The repowered cycle is separately modeled for each section. The governing equations of each section are as follows.

4.1. Steam Turbine (ST)

The steam turbines effective efficiencies are evaluated using the *Spencer, Cotton and Cannon* model [16]. The basic efficiency of the turbine, which is a function of the load, is corrected by factors, considering volume flow, pressure ratio, initial pressure and temperature:

basic efficiency × correction factors = effective efficiency

The most detailed approach is given by *Spencer, Cotton and Cannon* [16]. The turbine internal efficiency for any operating regime is calculated by correction factors:

$$\eta_{ST,new} = \eta_{i0}^{*} \prod_{j=1}^{n} (1+\varepsilon_j) \,, \tag{1}$$

where: η_{i0}^{*} - the "zero" or weighted internal efficiency without a correction for the influential parameters deviation, ε_j - the efficiency deviation for the impact of the j-th influential parameter, n – the number of correction coefficients.

Different correction factors are evaluated in each turbine section, i.e. from one extraction point to the next extraction point. Thus, a different effective efficiency is calculated for every section. Exhaust losses, mechanical losses and generator losses are considered as well.

When the extractions of the steam turbines are closed, the flow rate and state of steam will change at each section. Therefore, the steam turbines will no longer work at the designed condition. There are three steam turbines with different operating pressures, and each turbine should be separately analyzed. The following equation is called the Stodela equation and it relates to mass flow rates, temperatures and pressures for the first and the new cycles [17-19]:

$$\frac{\dot{m}_{new}}{\dot{m}_{first}} = \frac{p_{out,new}}{p_{out,first}} \sqrt{\frac{T_{in,new}}{T_{in,first}}} \sqrt{\frac{1-\left(\dfrac{p_{in,new}}{p_{out,new}}\right)^2}{1-\left(\dfrac{p_{in,first}}{p_{out,first}}\right)^2}} \,, \tag{2}$$

The net steam turbine power is given as below:

$$\dot{W}_{ST} = \dot{m}_{steam} (h_{steam,in} - h_{steam,out}) \,, \tag{3}$$

where: $\dot{m}_{steam}$ - mass flow rate of steam (kg/s), h – specific enthalpy (kJ/kg).

4.2. Heat exchangers

The heat exchangers are modeled using the TTD and TDCA parameters and pressure losses provided by the manufacturers. TTD is the difference between the temperature of the outlet cold flow and the saturated steam temperature of the inlet hot stream. TDCA is the temperature difference of the outlet hot flow, which is subcooled, and the inlet cold flow [20, 21].

4.3. Pump

The pumps (P) are simulated with regard to their efficiency as a function of the mass flow, evaluated from the experimental data. The condensate pump is neglected in the simulator, because its consumption is very small. The condenser, the boiler and the reheater are not simulated, only matter and energy balances are used to evaluate the properties of the unknown streams. In the case of the boiler and reheater, energy efficiency is evaluated from the real plant data.

4.4. Compressor (AC)

The outlet temperature is obtained assuming an adiabatic process [22].

$$T_{out} = T_{in}\left(1 + \frac{r_{p,AC}^{\frac{k_{air}-1}{k_{air}}} - 1}{\eta_{ise,AC}}\right), \tag{4}$$

$$r_{p,AC} = \frac{p_{out,AC}}{p_{in,AC}} \text{ - pressure ratio,} \tag{5}$$

where $k_{air} = \frac{c_{p_{air}}}{c_{v_{air}}}$ for air, c_p - specific heat capacity at constant pressure (kJ/kgK) and c_v - heat capacity at constant volume (kJ/kgK).

The required power for the compressor is given by:

$$\dot{W}_{AC} = \dot{m}_{air}\left(\frac{c_{p,air}(T_{out,AC} - T_{in,AC})}{\eta_{ise,AC}}\right), \tag{6}$$

4.5. Combustion Chamber (CC)

For this component the following balance equation applies:
Mass and energy balance equations are written as bellow:

$$\dot{m}_{air} + \dot{m}_{f,CC} = \dot{m}_g \,. \tag{7}$$

$$\dot{m}_{air}\, c_{p_{air,B}} T_{air,B} + \dot{m}_{f,CC}\, LHV \eta_{CC} = \dot{m}_{g,C}\, c_{p_{g,C}} T_{g,C} \,, \tag{8}$$

In the chamber there is a pressure loss, which is given as an input database parameter, based on which the leaving pressure can be calculated as:

$$p_{g,C} = (1 - \varepsilon_{CC})\, p_{air,B} \,. \tag{9}$$

where ε_{CC} - pressure loss (%).

The boundary condition is given as the exhaust gas temperature leaving the chamber. Based on this temperature, the composition and thermophysical properties of exhaust gases are determined.

4.6. Gas turbine

For this component, the following balance equation applies [23]:
The temperature of steam leaving the turbine:

$$T_{iout,GT} = T_{in,GT}\left(1-\eta_{ise,GT}(1-r_{p,GT}^{-\frac{k_g-1}{k_g}})\right). \tag{10}$$

$$k_g = \frac{c_{p_g}}{c_{v_g}} \quad \text{for exhaust gases} \tag{11}$$

$$r_{p,GT} = \frac{p_{in.GT}}{p_{out,GT}} \quad \text{pressure ratio,} \tag{12}$$

where ε_{CC} - pressure loss (%)

The net gas turbine power is related to the turbine and compressor power as below:

$$\dot{W}_{net,GT} = \dot{W}_{GT} - \dot{W}_{AC}\ , \tag{13}$$

4.7. Heat recovery steam generator (HRSG)

This section is based on the heat exchange between two fluids: the water coming from the condenser and the exhaust gases of the gas turbine(s) combined with the gases produced in the duct burner. The thermodynamic properties at different sections of a double pressure reheating HRSG are obtained by:

$$\dot{m}_{water/steam}(h_{out,water/steam} - h_{in,water/steam}) = \dot{m}_g\, c_{p,g}\,(T_{in,g} - T_{out,g})(1-E_1)\ . \tag{14}$$

where E_1 is the percentage of heat loss in each section, which is taken as 5%. This equation can yield the heat exchanged in every component as well as temperatures in characteristic points of HRSG [24].

4.8. Duct burner (DB)

Applying the energy balance equation to calculate the mass flow rate of the fuel added in the duct burner:

$$\dot{m}_{g,D}\, c_{p_{g,D}} T_{g,D} + \dot{m}_{f,DB}\, LHV \eta_{DB} = \dot{m}_{g,E}\, c_{p_{g,E}} T_{g,E}\ . \tag{15}$$

The mass balance equation is written as bellow

$$\dot{m}_{g,D} + \dot{m}_{f,DB} = \dot{m}_{g,E}\ . \tag{16}$$

4.9. Exhaust gases

For the mixture of ideal gases (g - flue gases can be treated as such), the specific heat capacity was calculated by the Rosario-Messina method [25]:

$$c_p(T) = \sum_{i=0}^{5} a_i (\ln T^*)^i \qquad [J / molK], \tag{17}$$

where a_i are the coefficients from [25] and

$$T^* = \frac{T}{T_0}. \tag{18}$$

4.10. Thermal efficiency

The thermal efficiency of the combined cycle (CCPP) is given by [26]:

$$\eta_{th,CCPP} = \frac{\dot{W}_{net,CCPP} + \dot{Q}_{DH}}{\dot{Q}_{f,CCPP}}, \tag{19}$$

where the net power of the combined cycle equals the sum of the net power of the gas cycle and the net power of the steam cycle:

$$\dot{W}_{net,CCPP} = \dot{W}_{net,GT} + \dot{W}_{net,ST}. \tag{20}$$

The total fuel consumption equals the sum of the fuel consumption in the gas cycle, the fuel consumption in the steam cycle and, if necessary, the fuel consumption in the heat recovery steam generator:

$$\dot{Q}_{f,CCPP} = \dot{Q}_{f,CC} + \dot{Q}_{f,DB} + \dot{Q}_{f,SB}. \tag{20}$$

5. RESULTS AND DISCUSSION

The developed software provided numerical simulations of the combined gas-steam cycle for different configurations. In this paper, the simulation of the combined facility is shown in Fig. 1. The presented scheme is one of the potential repowering methods for the existing thermal power plants, with the gas-block replacing the regenerative feed water and condensing steam heaters, while keeping the steam boiler in operation. In both cases the plant operates without steam interheating. The steam part of the combined cycle represents the scheme applied in the CHP plant Novi Sad, which uses natural gas as a primary fuel and has been in operation for more than 25 years.

The model inputs are given in Table 1, representing the design conditions for the CHP plant Novi Sad. Based on these parameters and the described mathematical model of the facility, a numerical simulation of the intermittent operation was performed.

The simulation was performed by considering the parameters from Table 1 and varying some parameters for the intermittent operation as:

- Steam production ranges from 60 to 110% compared to the nominal value (i.e. 90-130 kg/s),
- The plant operates in the condensing regime (Q_{DH}=0 MW) or in the regime with a controlled extraction of steam (Q_{DH}=170 MW),
- The compression ratio of the compressor ranges from 10 to 30, and,
- The temperature of exhaust gases entering the gas turbine ranges from 1200 to 1600K.

5.1. Impact of the compression ratio and the entering temperature in the gas turbine on the energy efficiency of the plant

Figs. 3-11 represent the impact of the compression ratio and the temperature of exhaust gases entering the gas turbine on the thermal efficiency of the plant for the configuration with the steam boiler. The dependency is drawn for three different cases of heat output and maximum, average and minimum steam production in the boiler, and for four different temperatures of exhaust gases entering the gas turbine.

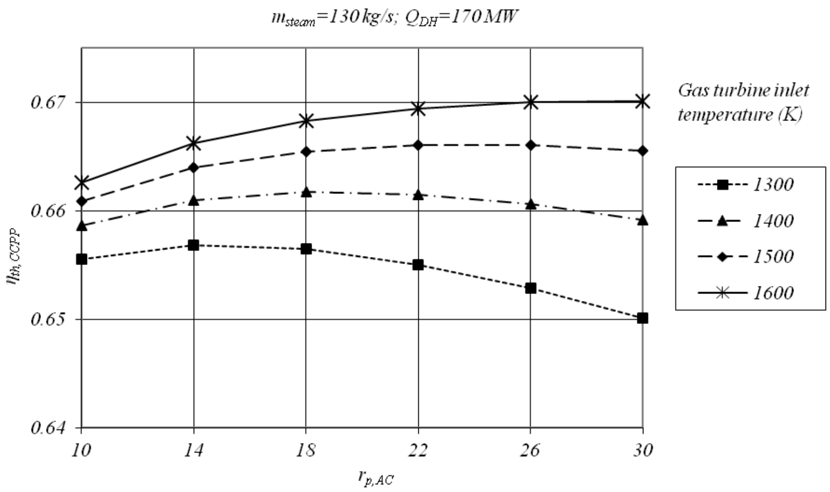

Fig. 3 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 130 kg/s steam production and 170 MW heat output

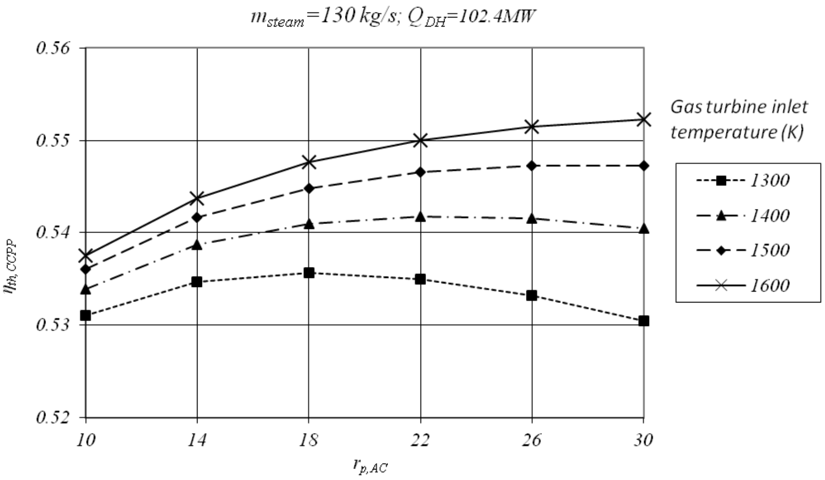

Fig. 4 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 130 kg/s steam production and 102.4 MW heat output

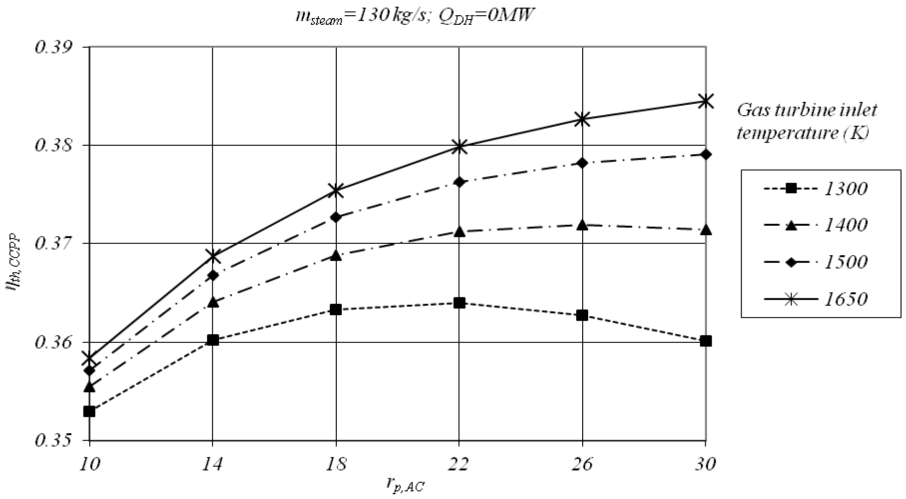

Fig. 5 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 130 kg/s steam production and no heat output

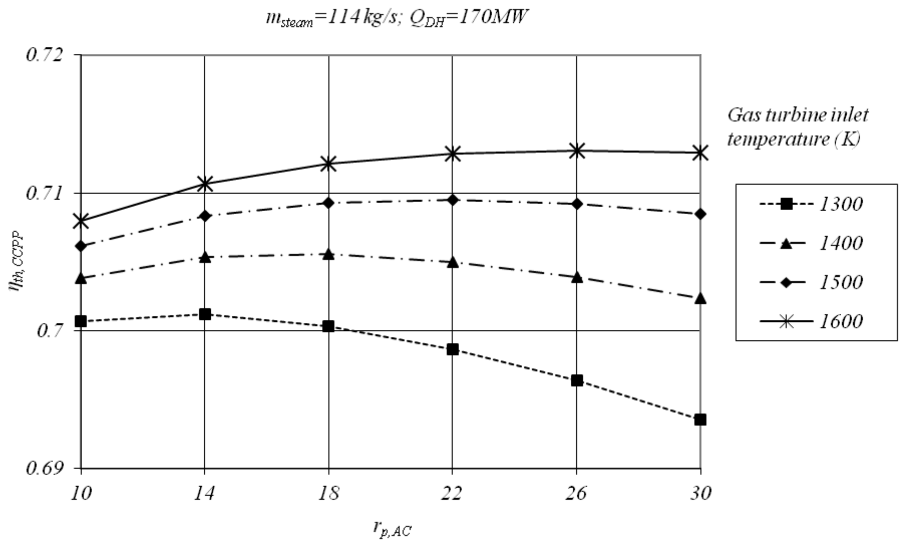

Fig. 6 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 114 kg/s steam production and 170 MW heat output

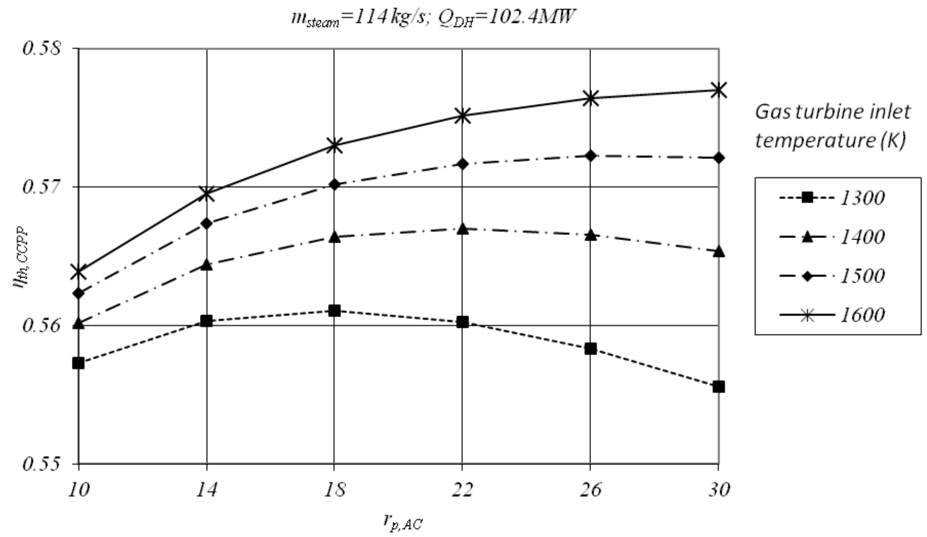

Fig. 7 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 114 kg/s steam production and 102.4 MW heat output

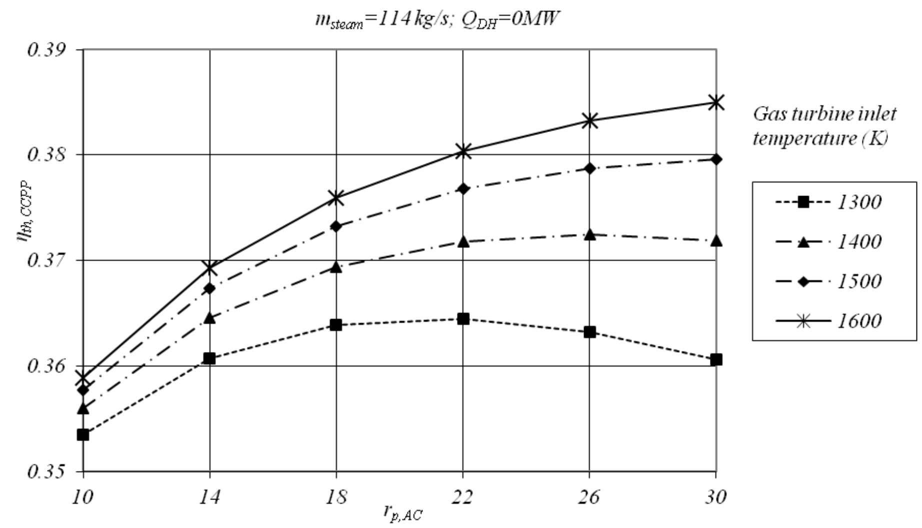

Fig. 8 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 114 kg/s steam production and no heat output

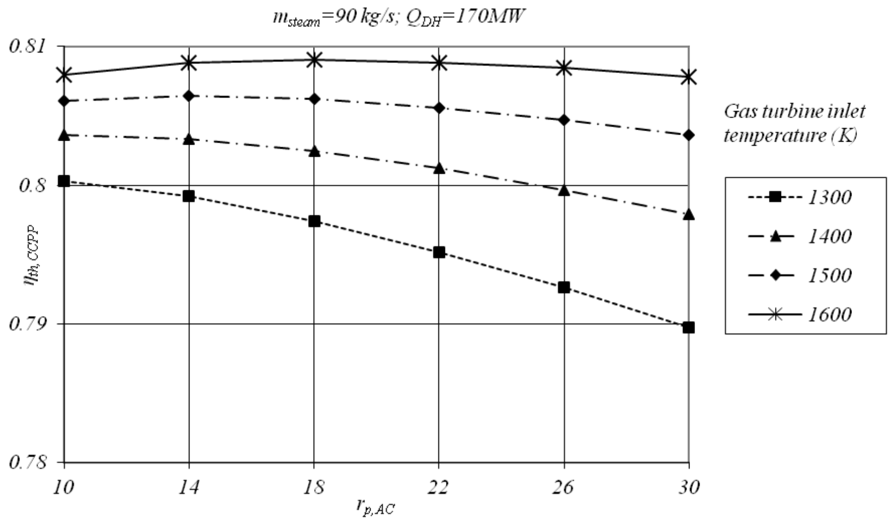

Fig. 9 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 90 kg/s steam production and 170 MW heat output

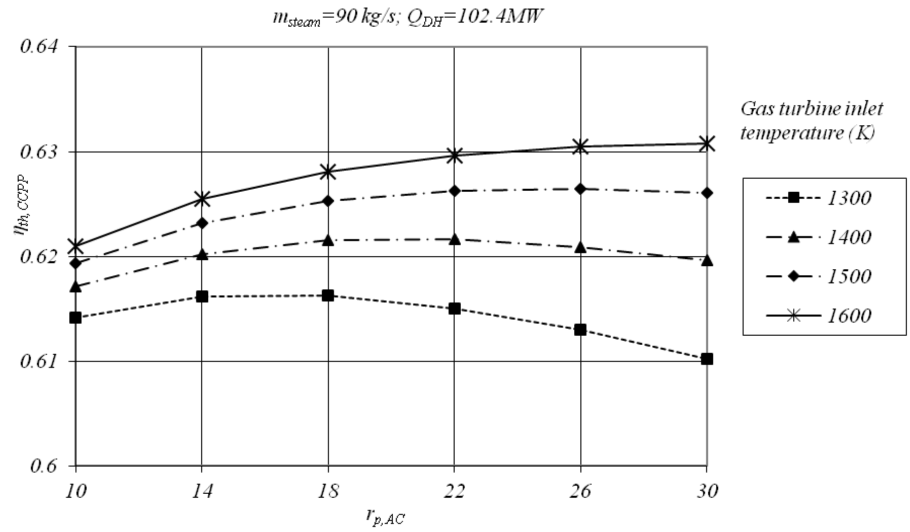

Fig. 10 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 90 kg/s steam production and 102.4 MW heat output

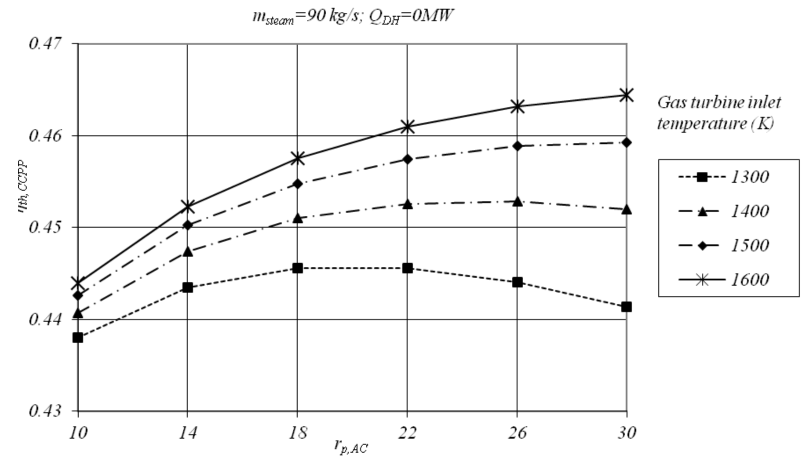

Fig. 11 Thermal efficiency as a function of the compression ratio (r) and the temperature of exhaust gases entering the gas turbine for 90 kg/s steam production and no heat output

In general, for the same compression ratio, thermal efficiency increases with the increasing temperature of exhaust gases entering the gas turbine (Figs. 3-11). For a constant temperature of exhaust gases entering the gas turbine, thermal efficiency increases to the maximum value with an increase in the compression ratio, and then decreases. Thermal efficiency also depends on the operating regime of the facilities. With a constant heat output it decreases if the steam production increases, and vice versa, for a constant steam production it decreases if the heat output decreases. Depending on the heat output, thermal efficiency varies from 35% (condensing operation) to 81% (heat production operation).

Compared to the results from different authors [27] (Fig. 12), the same trend of thermal efficiency occurs.

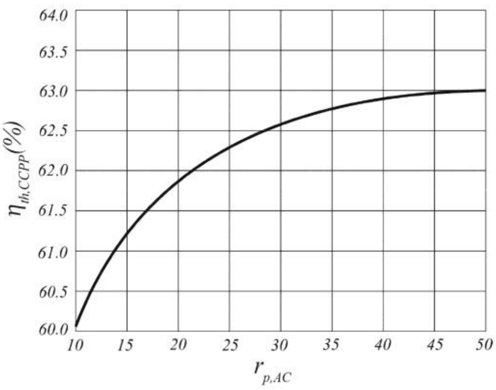

Fig. 12 CHP thermal efficiency as a function of the compression ratio (r) [27]

5.2. Influence of the temperature of exhaust gases entering the gas turbine on fuel consumption

Fuel consumption dependency on the temperature of exhaust gases entering the gas turbine, for the combined gas-steam cycle with the steam boiler, is shown in Fig. 13. Fuel consumption is given for the average steam production and nominal heat output, but for different compression ratios.

Fuel consumption slightly increases with an increase in temperature, due to the fact that the total consumption matches the consumption of the gas and steam part of the plant.

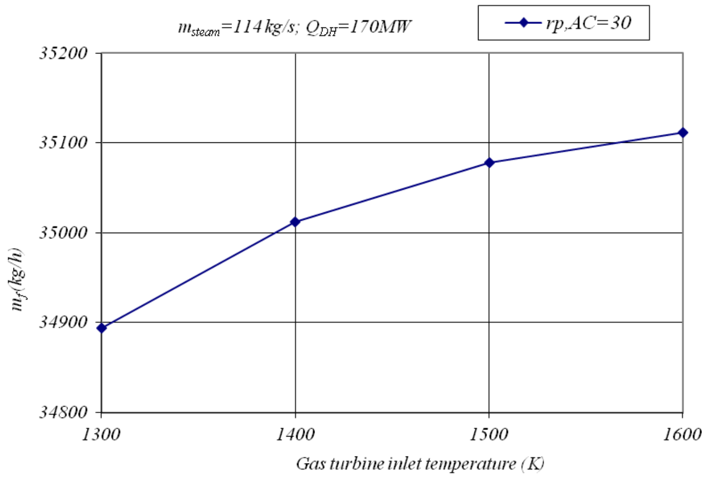

Fig. 13 Fuel consumption as a function of the temperature of exhaust gases entering the gas turbine, for steam production of 114 kg/s and heat output of 170 MW

5.3. Influence of the temperature of exhaust gases entering the gas turbine and steam production on the electrical power of the plant

The influence of the temperature of exhaust gases entering the gas turbine and steam production on the electrical power of the plant, for the nominal heat output and compression ratio, is given in Fig. 14. Electric power increases with an increase in temperature and steam production.

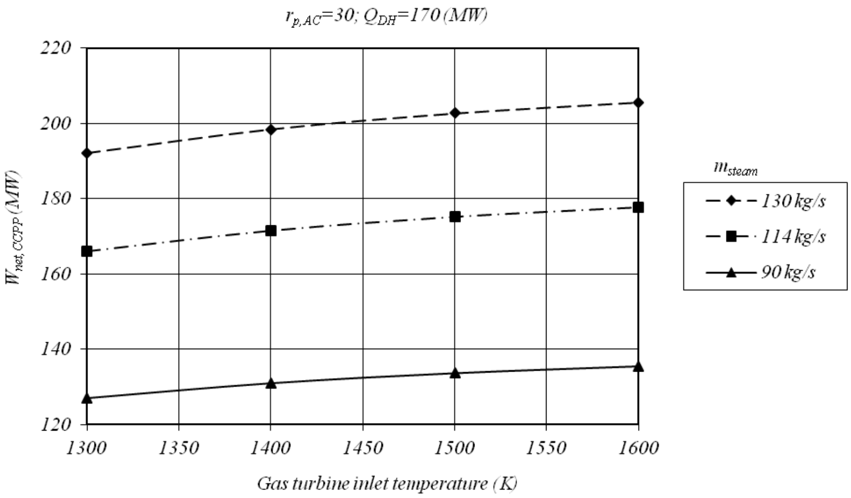

Fig. 14 Electric power as a function of the temperature of exhaust gases entering the gas turbine, for the nominal heat output 170MW and compression ratio of r_{pAC}=30

5.4. Influence of the compression ratio on electrical power

Fig. 15 show the dependency of the electrical power output on different compression ratios, for a constant steam production and temperature of exhaust gases entering the gas turbine. The same figure represents the change of thermal efficiency for the same conditions. The electrical power output rises with the lowering heat output, since less steam is extracted for satisfying the heat output. At the same time, thermal efficiency of the plant decreases with the lower heat output. The electrical power output increases with an increase in the compression ratio.

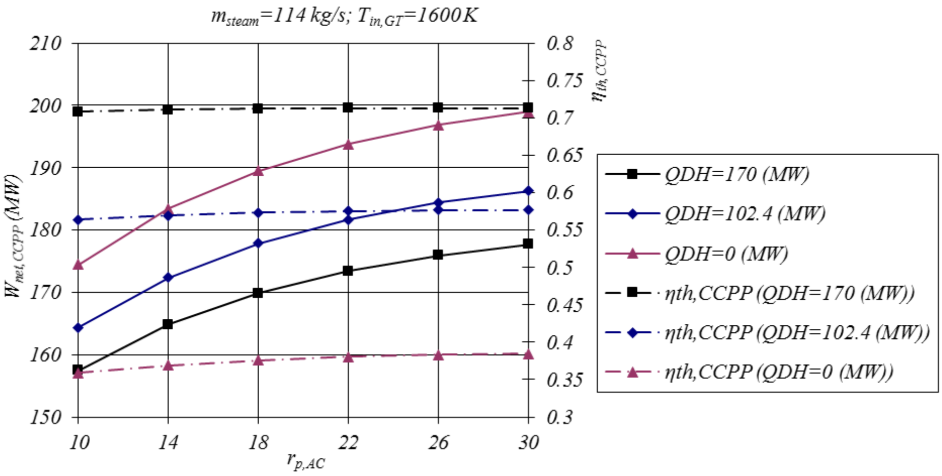

Fig. 15 Electrical power output and thermal efficiency as a function of the compression ratio for steam production of 114 kg/s and entering temperature of 1600 K

6. CONCLUSION

Repowering is an effective method for improving the efficiency and increasing the productive lifespan of an old steam power plant. Using the energy analysis method, the repowering of a power plant was investigated in this paper. The partial repowering option with feed water heating in the heat recovery steam generator was analyzed. The repowered power plant was analyzed for several operating regimes. Energy efficiency of the repowered cycle was selected as the target function. The best repowering mode at which the maximum energy efficiency was achieved is for steam production of 114 kg/s and nominal heat output of 170 MW. In these conditions, energy efficiency reaches the value of 71%, for the compression ratio of 30. For the same conditions, fuel consumption slightly increases with an increase in the temperature of exhaust gases entering the gas turbine, and ranges from 9.69 to 9.75 kg/s. The electrical power output increases with a temperature increase and with stream production increase, for the nominal heat output. For parameters which lead to maximum energy efficiency, electrical power rises from 166 MW (temperature of 1300K) to 178 MW (temperature of 1600K). Electrical power increases with the heat output decrease (less steam is extracted from turbines), but energy efficiency decreases. For the compression ratio of 30, the electrical power output varies from 177 MW to 199 MW, with the heat output reduced from the nominal (170 MW) to zero. Energy efficiency varies in the range of 0.38 (slightly higher compared to the steam power plant) to 0.72. These values show that the repowering option with the combined gas-steam cycle is very attractive regardless of the type of operation, i.e. whether only power or both heat and power are being produced.

Acknowledgments: *This research was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.*

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