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The effect of parallel hot windbox repowering on 387 MW fossil fuel power plant

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Abstract

The paper presents the concept of repowering in existing power plant. Among technologies for existing steam power plants, the hot windbox repowering is the fastest way to respond to the energy demand, improve efficiency and reduce the pollutants emissions. Thermodynamic analysis of power plant model with fossil boiler before and after hot windbox repowering, has been investigated using commercial software. The purpose of this work is to understand and analyze the effect of hot windbox repowering on 387 MW fossil fuel power plant as well as the effect of additional heat exchangers, which have been installed parallel with regeneration system to use the heat of boiler exhaust gases. In this way, after repowering the summary power of power plant in base load is 615 MW, which has been reached adding gas turbine (176.9 MW). To analyze the model, calculations were performed in 3 stages: 1) calculation and comparison of the thermodynamic parameters as well as carbon dioxide emissions of power plant model before and after repowering, 2) analysis of the optimal value of feed water mass flow through heat exchangers installed after economizer, 3) calculation of thermodynamic parameters in values 100%, 90%, 80% and 75% of fossil boiler heat loads.

Keywords: Combined cycle power plant; Fossil boiler; Hot windbox repowering; CO_2 emissions

1 Introduction

1.1 Combined cycle power plants

The concept of a steam and gas turbine (GT) cooperating in a common system essentially arises directly from a review of the main advantages and disadvantages

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of steam and gas systems treated separately. The advantage of the steam turbine is its very low ratio of compression work to expansion work (due to water condensation which runs at a constant temperature, only slightly higher, 5–7 °C, than ambient temperature). The disadvantage of this system is the process of heat supply, implemented through a metal wall, mechanically and thermal loaded. Substantial heat transfer surfaces are needed, forcing a reduction in the temperature used in the live steam to below about 570 °C. The most efficient solution from the viewpoint of the efficiency of the system is the classical gas turbine combined cycle (GTCC) [1,2].

1.2 Repowering of steam power plants

According to remarkable increase in global electricity consumption especially in developing countries, due to increasing population and industrialization, rise of using fossil fuels and consequent environmental pollution, global warming and exhaustibility of nonrenewable resources makes it necessary to analyze methods of enhancing power and efficiency of electricity generation using these fuels and methods of decreasing pollutants emissions from such power plants [3]. In that case one of the most suitable solving method is repowering.

Repowering (RP) is broadly defined as an addition to or replacement of existing power plant equipment, retaining serviceable permitted components to improve generation economics, extend life, improve environmental performance, enhance operability and maintainability, and more effectively use an existing site [4].

Repowering is the way to make it possible to continue using at least parts of older steam power plants that have become uneconomical. Moreover, repowering to a combined cycle can improve the efficiency of an existing plant to a level relatively close to that of new combined-cycle plants [5].

1.3 Repowering methods

There are several alternatives to combine and integrate a gas turbine into an existing steam power plant. Repowering methods have two categories which are applicable in fossil fuel power plants

1) repowering of nonsolid fuel power plants,
2) repowering of solid fuel power plants.

These methods can be divided into two main categories:

1) complete repowering,
2) partial repowering (PR),

and partial repowering (PR) includes the following methods [6]:

1) hot windbox repowering (HWBR),
2) feed water heating repowering (FWHR),
3) supplementary boiler repowering (SBR).

1.4 Hot windbox repowering

Hot windbox repowering (HWBR) can be applied using 3 methods.

1. In the first one, the exhaust gas from a gas turbine is fed into the original boiler, and oxygen (O_2) content of the exhaust gas is generally enough to fire the fuel particles. However, due to the high temperature of the exhaust gas, the burner section has to be upgraded with high-temperature–resistant materials (Fig. 1). This method is called direct hot windbox repowering.

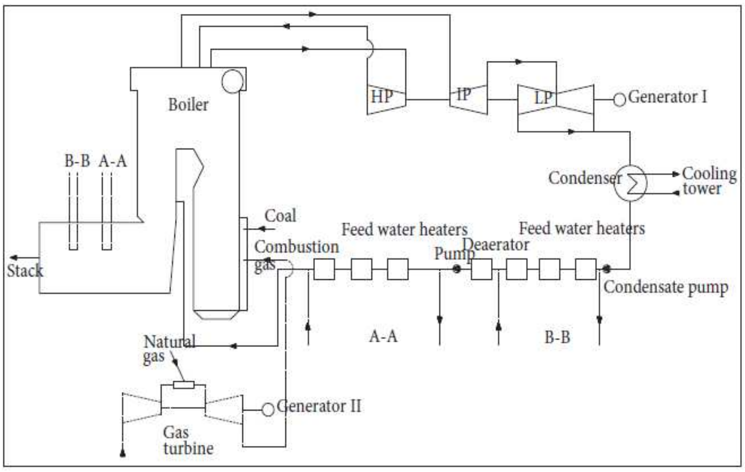

Figure 1: Direct hot windbox repowering: HP – high-, IP – intermediate-, LP – low-pressure part of steam turbine [7].

2. In the second method, the exhaust gas can be diluted by fresh air to decrease the temperature of the combustion gases and to increase oxygen content of the gas stream (Fig. 2).
3. In the third option, the exhaust gas can be diluted by fresh air like in the second method. After gas turbine the economizer is installed from which feedwater heating is obtained (Fig. 3) [7].

In comparison to simple combined-cycle installations hot windbox repowering has some advantages:

- coal can be burned in the steam generator,

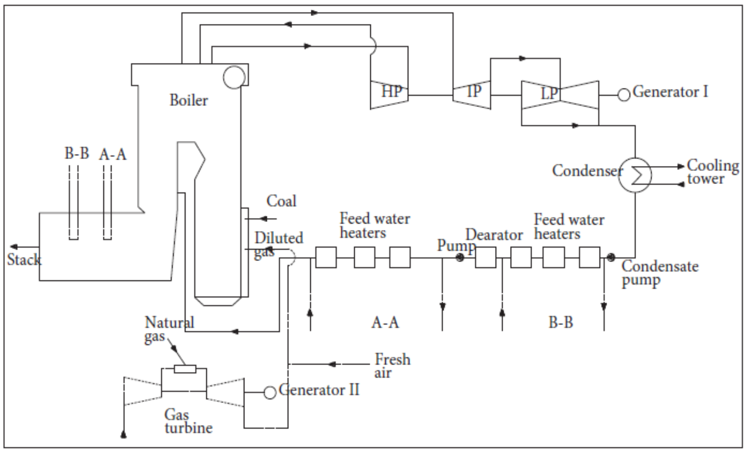

Figure 2: Fresh air dilution hot windbox repowering [7].

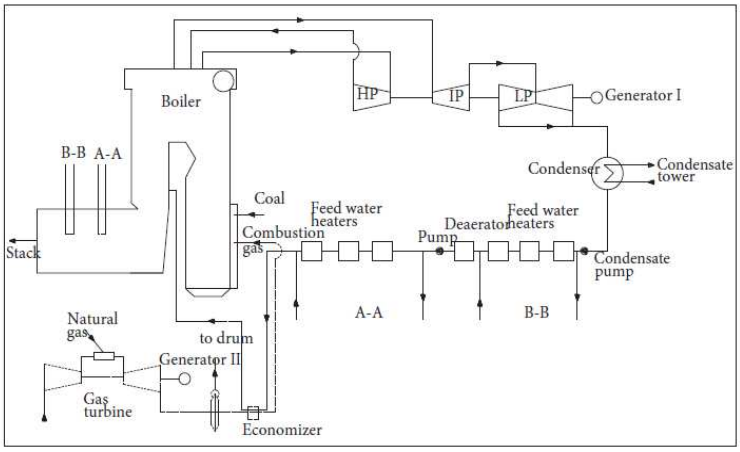

Figure 3: Precooling hot windbox application [7].

- part load efficiency is very good,

and the disadvantages:

- lower efficiency,
- higher investment costs,
- more complex installations, more difficult to operate and maintain, especially if the steam generator is coal-fired [8].

In this paper the first method of boiler hot windbox repowering has been researched, i.e., direct hot windbox repowering without fresh air dilution.

For the repowering analysis, gas turbine leverage, λ_{GT}, and repowering efficiency, η_{RP}, are very important parameters. Repowering efficiency can be defind as the rate of increment in the electricity generation to the increment in the heat added to the cycle, given in

$$\eta_{RP} = \frac{P_{AR} - P_{BR}}{Q_{in\ AR} - Q_{in\ BR}} , \tag{1}$$

where P and Q_{in} are the electric power and heat energy added to the cycle. Gas turbine leverage can be defined as the rate of increment in the electricity generation to gas turbine installed capacity, $P_{el,\ GT}$

$$\lambda_{GT} = \frac{\Delta P_{el}}{P_{el,\ GT}} = \frac{P_{AR} - P_{BR}}{P_{el,\ GT}} . \tag{2}$$

The subscripts AR and BR stand for after repowering and before repowering, respectively [7].

2 Software used for simulation

Mathematical modeling is the perfect way to establish the characteristics of the object, as well as to evaluate the technical optimization. For this purpose commercial General Electric software GateCycle [9] is used for design and performance evaluation of thermal power plant systems at both design and off-design points. There is library with more than 100 gas turbines along with saved correction curves. This allows mathematical modeling of the power plant (gas turbine) to determine the performance for conditions other than ISO or for variable load without the need for detailed data from vendor. In this paper the chosen Alstom GT13E2 gas turbine is applied using the GateCycle library.

3 Description of the model (design point)

Presented here simulated power plant is an example of combined cycle power plant (CCPP) with 615 MW summary net electric power output, which is result of boiler hot windbox repowering. It contains one Alstom production GT13E2 gas turbine (175 MW), one fossil boiler with 1 GW heat load and 345 kg/s steam generating capacity and one 450 MW condensing steam turbine. Based on the fraction of oxygen within exhaust gases, the gas turbine was chosen from GT Library – Alstom GT13E2 50 Hz SC (GTW 2009) GT. The volume of oxygen within exhaust gases must be correspond oxygen consumption by fossil boiler. In Tab. 1 are shown ambient and performance parameters of that GT.

Table 1: Reference values for gas turbine.

	Unit	Value
Ambient conditions		
Relative humidity	%	60
Inlet pressure	kPa	101.32
Inlet temperature	°C	15
Performance parameters		
Exhaust gases mass flow	kg/s	560
Exhaust gases temperature	°C	513
Heat rate (LHV)/Effect	kJ/kW s	2.7386
Net electric power	MW	176.9
Efficiency	%	36.51
Oxygen (O_2) mole fraction	–	0.1398

Boiler part was developed by modeling fossil boiler and heat exchangers separately. The equipment was used as follows: fossil boiler, high pressure super heater (HPSH), intermediate pressure super heater (IPSH), economizer (ECON), high pressure water gas heat exchanger (HP WGHE) and low pressure water gas heat exchanger (LP WGHE). There were also installed drum, splitters, pipes and temperature control mixers, which control steam temperature after HPSH and IPSH. The GT exhaust gas duct was connected to the boiler burners and supply oxygen for burning process. In steam cycle regime air is supplied to the boiler through two ducts: primary air duct and secondary air duct. But in combined cycle regime those ducts were closed, because the oxygen quantity within GT exhaust gas is enough for burning process in the boiler. The parameters of the considered fossil boiler were chosen from the library example model. In the Tab. 2 were shown the design parameters of fossil boiler. In order to be better represented the steam turbine (ST) was divided into three parts: high-pressure part (HPST), intermediate-pressure part (IPST) and low-pressure part (LPST). The efficiency of particular parts was calculated using the Design Efficiency Method and the Isentropic Expansion Efficiency was equal to 0.9 for all parts. The inlet steam pressure for all parts of steam turbine was calculated using the Design Pressure Method. For high pressure part the inlet pressure was fixed 10 MPa but for

Table 2: Design parameters of fossil boiler.

Parameter	Unit	Value
Heat load	GJ/s	1.00
Live steam pressure	MPa	10
Live steam temperature	°C	527
Steam generating capacity	kg/s	345
Secondary steam pressure	MPa	2.91
Secondary steam temperature	°C	527
Total fuel flow	kg/s	21.07

next two parts was calculated automatically. These all calculation methods are available in GateCycle software. Steam turbine part was equipped with regeneration system, which consists of five feed water heaters (FWH) and deaerator (DA). Two FWH from five were installed in the high pressure part of feed water and three of them – in the low pressure part. After repowering in the boiler section, after economizer, there was installed additional water gas heat exchangers (with high and low pressure) parallel with steam turbine regeneration system to use the temperature of boiler exhaust gas.

Considering experience of choosing optimal design parameters of combined cycle power plants close to this plant, here was chosen the optimal distribution of feedwater mass flow through feed water heaters and gas water heat exchangers. According to that 70% of feed water mass flow is directed to the gas water heat exchangers (GWHE) and 30% is directed to the regeneration system. The same situation is for both (high pressure and low pressure) parts. In the next section (description of the model, off-design) the optimal value of mass flow distribution through aforementioned heat exchangers was recalculated.

In Figs. 4 and 5 accordingly model diagram before repowering (BR) and after repowering (AR) are shown respectively.

4 Results of calculations and analyzes (off-design)

In this section are presented analyzes and calculation results of thermodynamic parameters of the model with hot windbox repowering in off-design mode. The off design model is used mostly to simulate the behavior of a particular system in conditions different from the designed in order to access crucial parameters of that system in variable conditions. The simulations were performed with three stages:

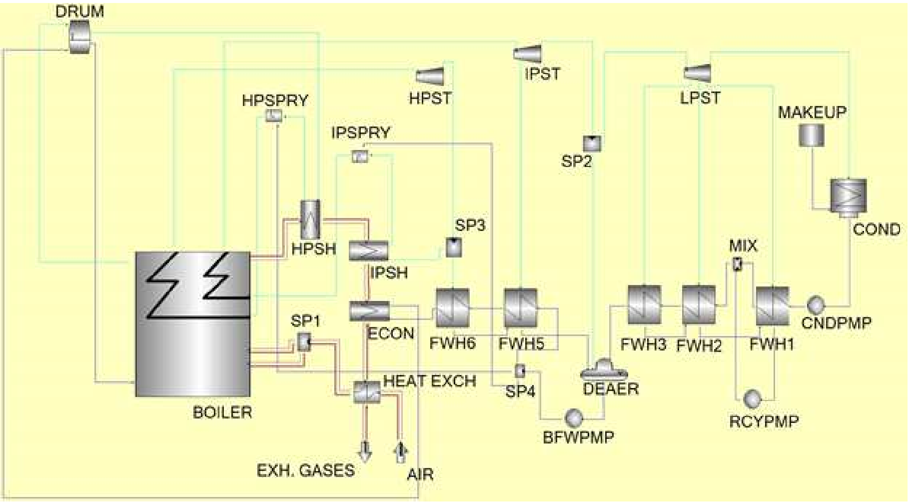

Figure 4: Model diagram of simulated power plant before repowering (BR); HPST – high pressure steam turbine, IPST – intermediate pressure steam turbine, LPST – low pressure steam turbine, COND – condenser, CNDPMP – condensate pump, RCYPMP – recirculation pump, MIX – mixer, FWH1,2,3,5,6 – feed water heaters No. 1,2,3,5,6, DEAER – deaerator, BFWPMP – boiler feed water pump, SP1,2,3,4 – splitter No. 1,2,3,4, HEAT EXCH – heat exchanger, ECON – economizer, HPSH – high pressure super heater, IPSH – intermediate pressure super heater, EXH. GASES – exhaust gases.

1. Analyzes of thermodynamic parameters as well as carbon dioxide (CO_2) emissions of the power plant model of the before and after repowering and then comparison the results.
2. Calculations of the optimal value of distribution of feed water mass flow trough gas water heat exchangers and regeneration system.
3. Calculations of thermodynamic parameters in values 100%, 90%, 80%, 75% of fossil boiler heat load to show the advantage of hot windbox repowering in part loads.

Ad. 1. In the first part thermodynamic parameters of the power plant model before and after repowering were analyzed and then as a result were made charts, which describe the effect of hot windbox repowering. Also carbon dioxide (CO_2) emissions were calculated before and after repowering.

In the Fig. 6, are shown values of electrical power of gas turbine, steam turbine and CCPP before repowering and after repowering. So according to these charts, after repowering, it means after adding 176.9 MW gas turbine, steam turbine

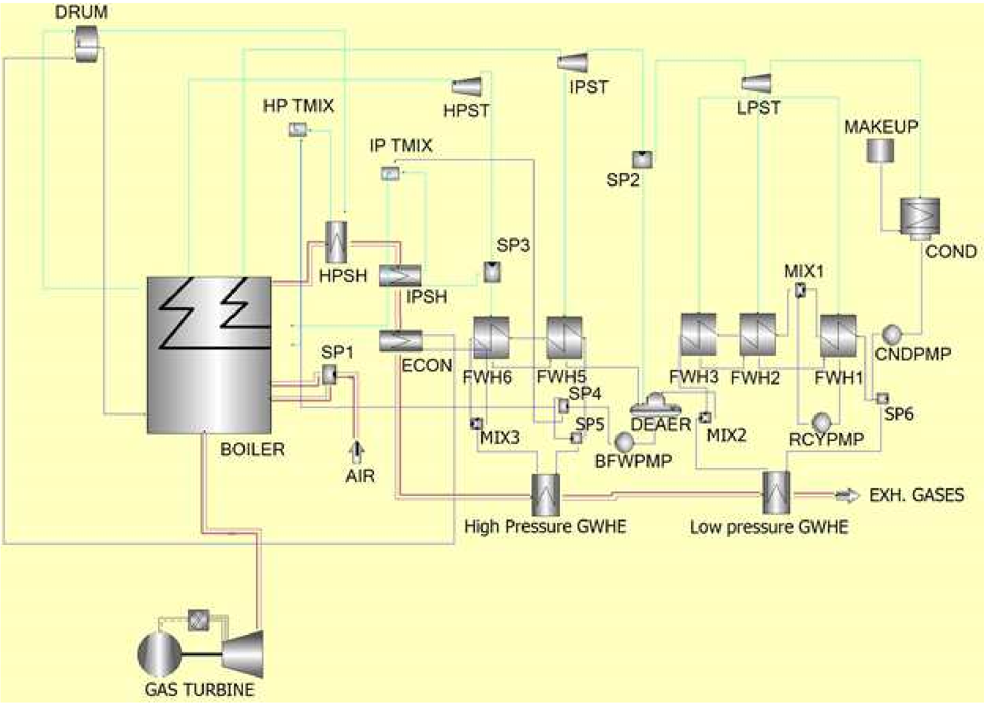

Figure 5: Model diagram of the simulated power plant after repowering (AR); HPST – high pressure steam turbine, IPST – intermediate pressure steam turbine, LPST – low pressure steam turbine, COND – condenser, CNDPMP – condensate pump, RCYPMP – recirculation pump, MIX1,2,3 – mixer No. 1,2,3, FWH1,2,3,5,6 – feed water heaters No. 1,2,3,5,6, DEAER – deaerator, BFWPMP – boiler feed water pump, SP1,2,3,4,5,6 – splitter ?1,2,3,4,5,6, ECON – economizer, HPSH – high pressure super heater, IPSH – intermediate pressure super heater, High Pressure GWHE – high pressure gas water heat exchanger, Low Pressure GWHE – low pressure gas water heat exchanger, HP TMIX – temperature control mixer in high pressure part, IP TMIX – temperature control mixer in intermediate pressure part, EXH. GASES – exhaust gases.

power was increased by 13.5% and total power of the power plant by 59.22%. The charts in Figs. 7 and 8 show the comparison of net cycle lower heating value (LHV) efficiency and heat rate before and after repowering. The efficiency was increased by 2.83% and heat rate was decreased by 6.77%, respectively. In the Fig. 9 there was shown an interesting fact that although the fraction of CO_2 increased by 7.19% after repowering, CO_2 emissions in boiler exhaust gases per megawatt power decreased by 7.43%. This finding may indicate that it is possible to increase the installed capacity with reducing the pollutants emissions by hot windbox repowering of thermal power plants.

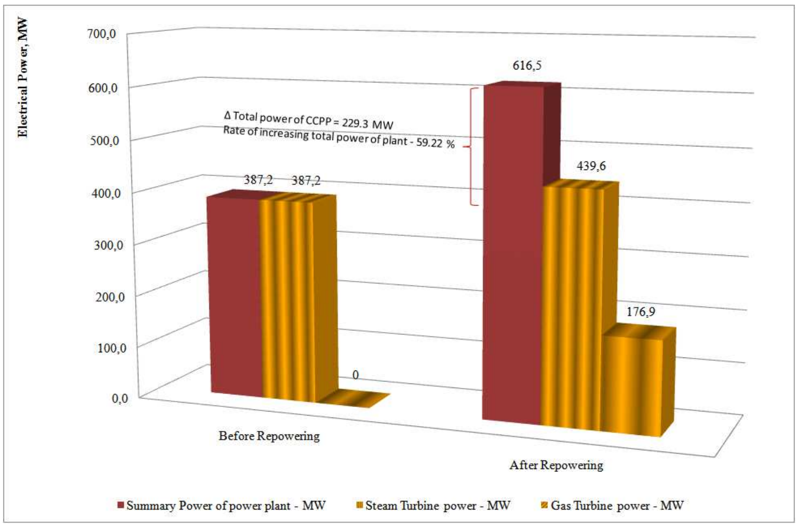

Figure 6: Gas and steam turbines and total electrical power before and after repowering.

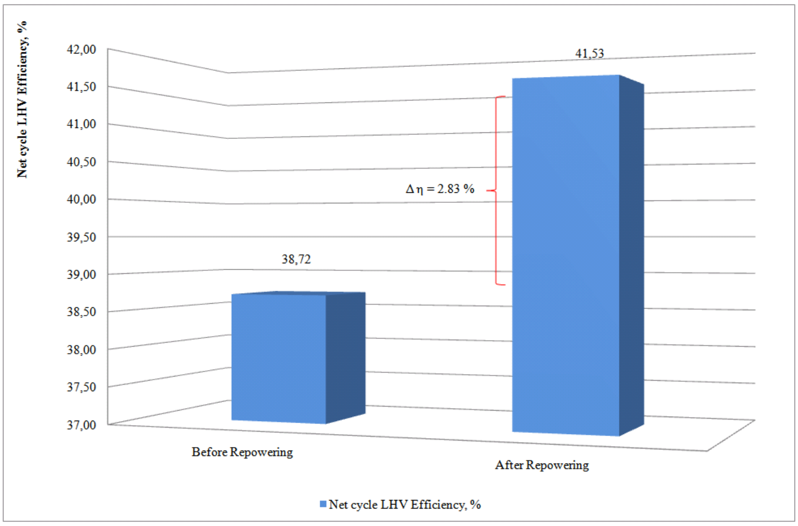

Figure 7: Comparison of net cycle lower heating value (LHV) efficiency of power plant.

As we stressed in the first section most important parameters, which explain repowering, are repowering efficiency η_{RP},(Eq. (1)), and gas turbine leverage λ_{GT}, (Eq. (2)). In case under considerations they are equal to 0.47 and 1.296, respectively.

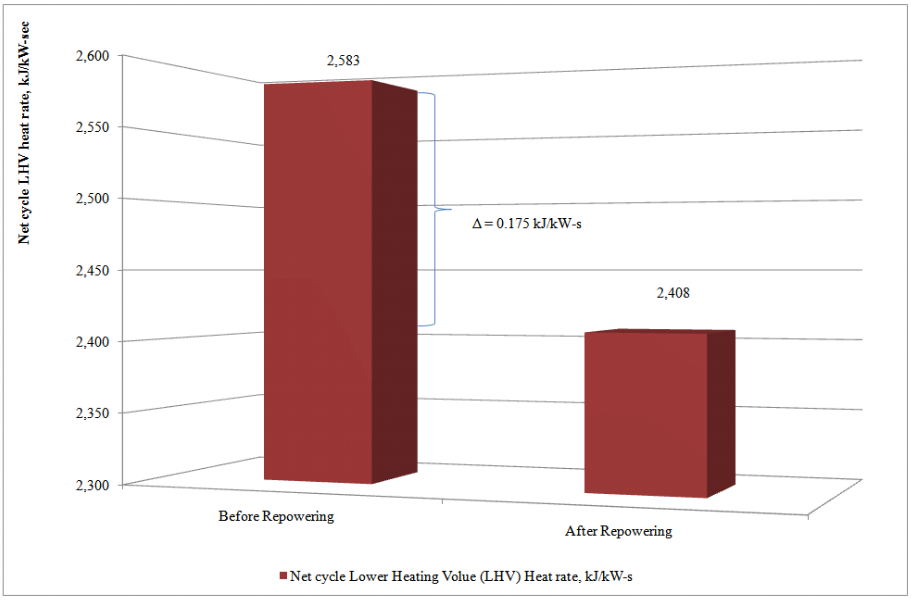

Figure 8: Comparison of net cycle LHV heat rate of power plant.

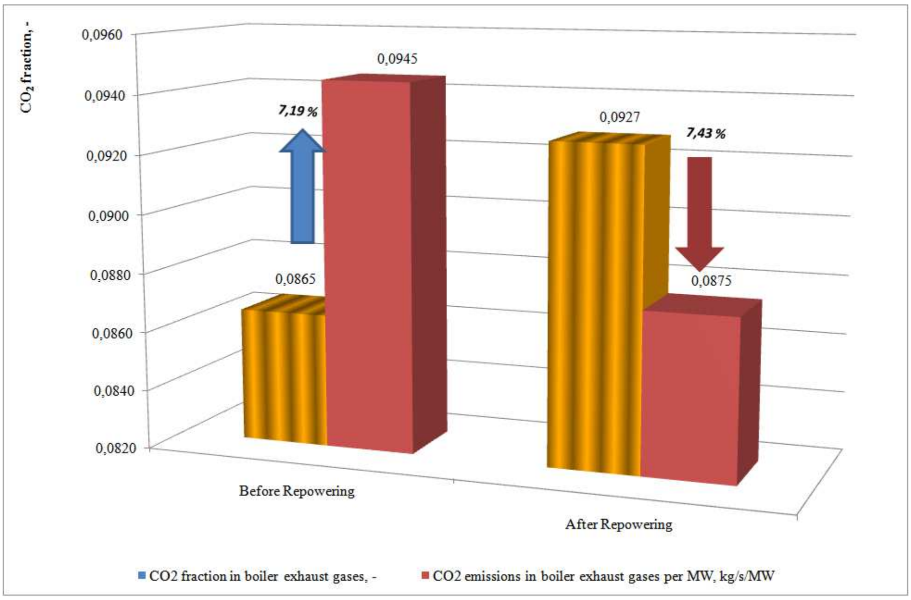

Figure 9: Comparison of CO_2 emissions before and after repowering.

Ad. 2. In the second part of calculations the analyzes were performed to be proved that the optimal value of distribution of feed water mass flow trough GWHE and regeneration system is correct. The GWHEs one installed parallel with feed water heaters (in high and low pressure parts). High pressure GWHE is installed parallel with FWH – 5 and FWH – 6, and low pressure GWHE is installed parallel with FWH – 3, FWH – 2 and FWH – 1.

There were considered 8 cases or regimes of variation of feed water distribution. The calculations were done at base load of the power plant. The feed water mass flow values were put beforehand in the 'Input' sections of Gatecycle simulator for HP GWHE and LP FWH and then feed water mass flow through LP GWHE and HP FWH was regulated automatically. Also the steam mass flow in steam turbine extractions was regulated automatically when the feed water mass flow through FWH was changed. In Case 6 the parameters were corresponded with design point parameters. In every case the value of feed water mass flow was changed with 10% compared to the previous value. In Tab. 3 there are shown the variation of feed water mass flow values in different cases or regimes.

Table 3: Feed water value distributed to the GWHE and FWH in different cases.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6 (design)	Case 7	Case 8
Feed water mass flow through HP FWH, kg/s	268.3	239.0	213.7	176.9	139.7	95.8	67.7	33.4
Feed water value through HP FWH, %	81	69	*60*	50	*40*	28	*20*	10
Feed water mass flow through HP GWHE, kg/s	65.0	105.0	140.0	175.0	210.0	250.0	275.0	305.0
Feed water value through HP GWHE, %	19	31	*40*	50	*60*	72	*80*	90
Feed water mass flow through LP FWH, kg/s	220.0	205.0	180.0	155.1	130.0	100	65.0	35.0
Feed water value through LP FWH, %	79	70	*59*	50	*41*	31	*20*	11
Feed water mass flow through LP GWHE, kg/s	57.4	86.5	125.1	155	190.9	224.5	260.7	291.5
Feed water value through LP GWHE, %	21	30	*41*	50	*59*	69	*80*	89

Based on the result of the calculations, charts were developed (Figs. 10 and 11) in which were drawn the steam turbine (ST) and combined cycle power plant (CCPP) total power values, as well as net cycle LHV efficiency of power plant in different cases.

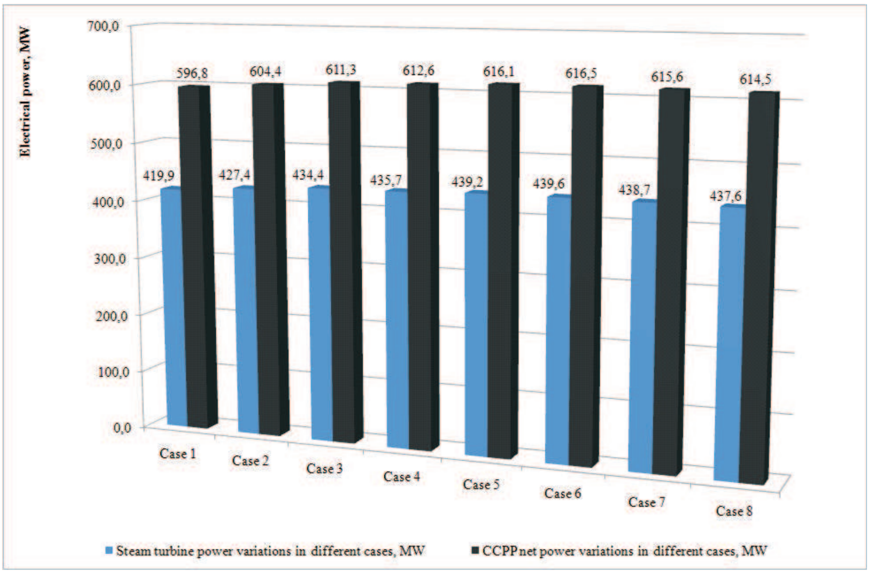

Figure 10: Steam turbine and combined cycle power plant power variations in different cases.

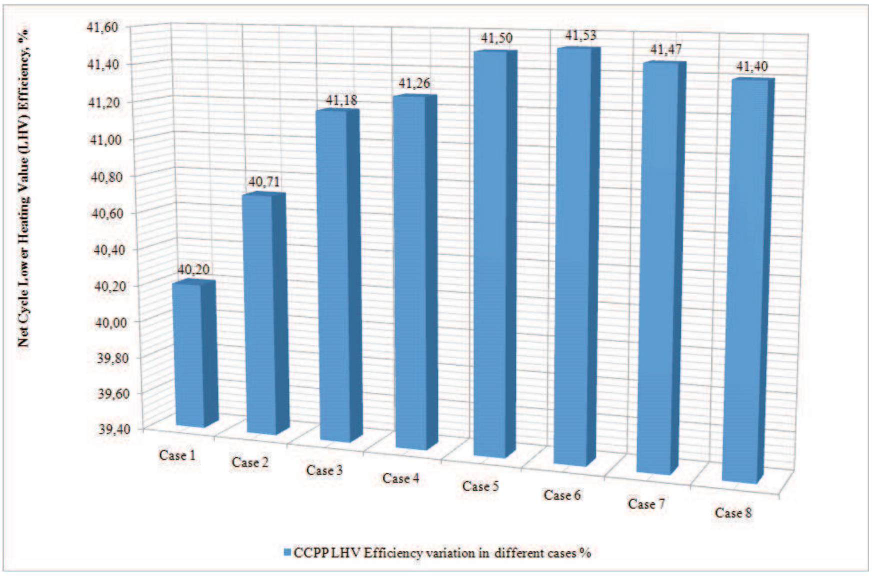

Figure 11: Combined cycle power plant net cycle lower heating value efficiency variation in different cases.

From those charts it is obviously that in Case 6 (design parameters) there were available the biggest values of ST and CCPP capacity, which equal to 439.6 MW and 616.5 MW, respectively. Net cycle LHV efficiency is the highest in Case 6 and equal to 41.53%. It demonstrates that chosen design parameters for feed water distribution are optimal.

Ad. 3. In the last third part of analyzes there were changed fossil boiler heat load from 100% to 75% to establish the advantage of parallel hot windbox repowering in part loads. Decreasing the heat load of boiler below 75%, gas turbine (GT) load have to be changed. In this paper was discussed only the effect of changing boiler heat load without changing GT load. To change the boiler heat load there was input manually the required value in ‘boiler load method/desired LHV heat load’ section.

In Fig. 12 were shown steam turbine power before repowering, as well as CCPP total power and ST power after repowering depending on live steam mass flow in part loads. The variation of CCPP power was from 616 MW to 523 MW, and within these limits live steam mass flow variation was from 346.0 kg/s to 255.6 kg/s.

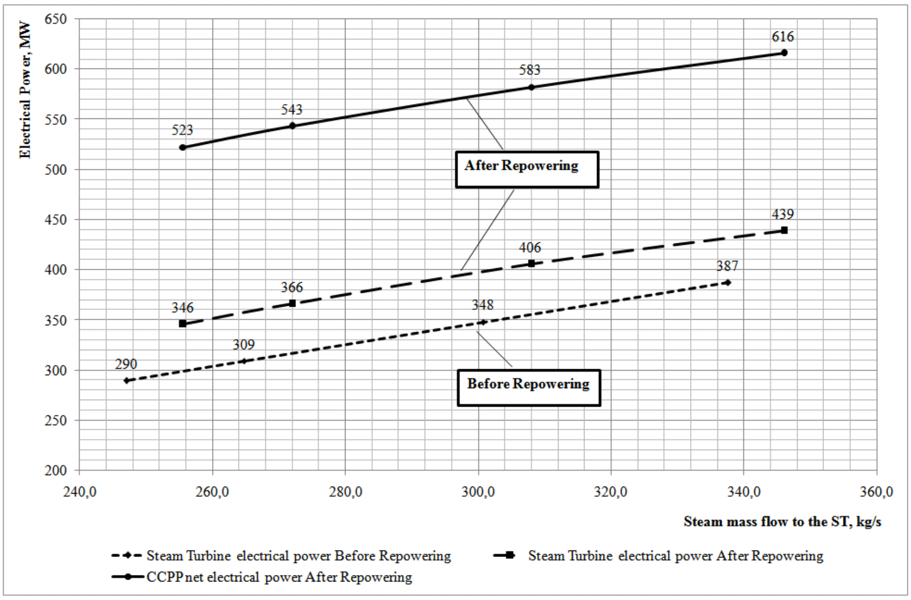

Figure 12: Variation of electric power in part loads.

In the last plot (Fig. 13) were shown net cycle LHV efficiency variation as well as fossil boiler heat load variation in part loads before and after repowering. The highest efficiency was available in 75% boiler heat load, and was equal to 42.32%. In that case boiler heat load was 0.75 GW and live steam mass flow equal to 255.6 kg/s. This shows the advantage of Combined-Cycle power plants with parallel hot windbox repowering. Such types of power plants have high efficiency in part-loads. It means during part-load regimes the heat of exhaust gases coming from GT can compensate heat balance when the mass flow of fuel at the inlet of boiler burner was decreased.

However the opposite fact of this effect is available. Without gas turbine, steam cycle power plant efficiency was decreased with decreasing boiler heat load. For example in 75% boiler heat load the efficiency is decreased till 38.59%, when live steam mass flow was 247.0 kg/s.

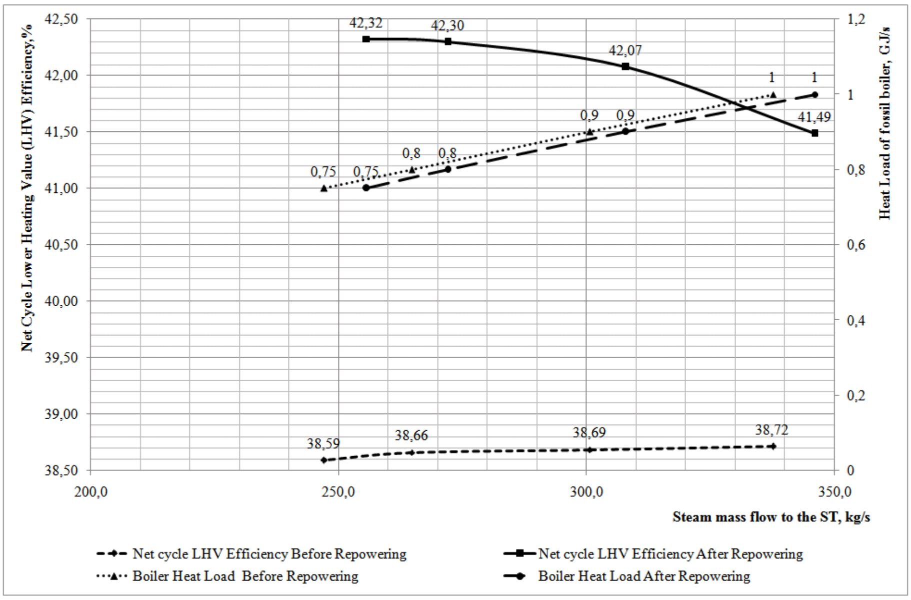

Figure 13: Net cycle LHV efficiency variation depending live steam mass flow in part loads.

5 Conclusions

In this paper was presented analysis of the effect of hot windbox repowering of fossil fuel power plant with 387 MW capacity, as well as the effect of gas water heat exchangers installed parallel with ST regeneration system used the heat of boiler exhaust gases. Calculations were performed in 3 parts:

1. Calculation and comparison of the thermodynamic parameters as well as CO_2 emissions of power plant model before and after repowering gas turbine with 176.9 MW capacity.
2. Analysis of the optimal value of feed water mass flow through gas water heat exchangers.
3. Calculation of thermodynamic parameters in values 100%, 90%, 80%, and 75% of fossil boiler heat loads.

The results showed that the total generating electrical power of CCPP increased by 59.22% and net cycle LHV efficiency increased by 2.83%, however CO_2 emissions in boiler exhaust gases per megawatt power decreased by 7.43%. The optimal value of feed water distribution corresponded 30% of feed water mass flow through ST regeneration system and 70% through gas water heat exchangers. In that case there were available the highest efficiency (41.53%) and the biggest capacity (615.6 MW) of power plant. In part-loads net cycle LHV efficiency of combined cycle power plant was increased from 41.49% to 42.32%, when boiler heat load was decreased from 1 GW to 0.75 GW, whereas steam cycle LHV efficiency was decreased from 38.72% to 38.59%.

The scope of the paper was to show the effect of parallel hot windbox repowering, so the parameters for the analyzed power plant were chosen from the library provided within the software application for performance efficiency. The work was made for academic case only. Though they do not correspond to the real power plant parameters nowadays, they allowed to explain that effect.

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References

[1] Wołowicz M., Milewski J., Badyda K.: *Feedwater repowering of 800 MW supercritical steam power plant.* J. Power Technol. **92**(2012), 2, 127–134.

[2] Wołowicz M., Badyda K.: *Gas turbine selection for feedwater repowering.* J. Power Technol. **95**(2015), 4, 302–308.

[3] Mehrabani K.M., Faniyazdi S.S., Mehrpanahi A.A., Naserabad S.N.: *Heating using genetic algorithm.* Indian J. Sci. Res. **1**(2014), 2, 183–198.

[4] Stoll H.G., Smith R.W., Tomlinson L.O.: *Performance and Economic Considerations of Repowering Steam Power Plants.* GE Power System GER-3644D, Schenectady, NY 1996.

[5] Kehlhofer R., Rukes B., Hannemann F., Stirnimann F., *Combined-Cycle Gas and Steam Turbine Power Plants*, 3rd Edn. Tulsa, 2009.

[6] Ahmadi G.R., Toghraie D.: *Parallel feed water heating repowering of a 200 MW steam power plant.* J. Power Technol. **95**(2015), 4, 288–301.

[7] Yilmazoglu M.Z., Durmaz A.: *Hot windbox repowering of coal-fired thermal power plants.* Turkish J. Eng. Environ. Sci. **37**(2013), 33–41.

[8] Kehlhofer R., *Combined-cycle Gas and Steam Turbine Power Plants.* Tulsa 1997.

[9] https://getotalplant.com/GateCycle/docs/GateCycle/index.html