IMPACT OF CHANGE IN COAL QUALITY ON OPERATING PARAMETERS OF THERMAL POWER PLANT STANARI AND ITS RISK ASSESSMENT

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The technical and technological characteristics of the Stanari Power Plant block were designed based on the results of the analysis of coal samples from the Raskovac opencast mine. There haven't been any notable variations in the coal quality during the Stanari thermal power plant's present operating term from the project's stated values.

For the expected lifetime of mine, i.e., the thermal power plant operation until 2050, it is necessary to unearth the total remaining available coal reserves from the Stanari basin. The thermal power plant's operation may be significantly impacted by variations in coal quality at the Ostruznja opencast mine. The use of coal with quality parameters lower than designed can cause problems in the operation of the boiler, stoppages in operation, and an increased volume of maintenance and overhaul of the boiler. Coal quality control in the process of sampling, mining, transportation, and depositing of coal must be at a level that enables smooth operation of the thermal power plant.

This paper presents test results during the operation of the thermal power plant burning coal of different quality, (LCV in range from 9,100 to ≤7,500 kJ/kg), a risk assessment of long-term planning, and the effectiveness and economy of the thermal power plant operation. The potential economic effects and reliability of the operation of thermal power plants due to the increased consumption of coal, limestone and self-consumption in operating modes with significantly lower coal quality than designed were analyzed in particular.

Key words*: risk assessment, opencast mine, coal quality, thermal power plant, energy efficiency*

1. Introduction

The stable supply of thermal power plants with the required coal quantities of designated quality is the basis of reliable and profitable electricity generation. The technological process of electricity production in thermal power plants is designed for the known coal characteristics of constant values. Coal costs, together with dependent costs related to coal, represent a dominant percentage of the total costs of the production process in thermal power plants. The energy efficiency and economy of the production process depend on the actual characteristics of coal.

In the Stanari coal basin, about 34,000,000 t have been mined so far out of 90,687,471 t of total reserves. The remaining 56,000,000 t of reserves will be mined at the Ostruznja opencast mine [1].

Since the establishment of EFT-Mine and Thermal Power Plant Stanari (2005) in the Stanari coal basin, extensive geological explorations of coal have been carried out within the mining concession limits [1]. Coal samples were taken from drilled wells, and laboratory analyzes of the coal were performed. The quality parameters (LCV-lower calorific value of about 9,100 kJ/kg, carbon 27.5%, moisture content 49%, ash 7.5%, and sulfur 0.13 %) were determined from the analysis data of coal samples, which were necessary for planning the supply of coal to the Stanari thermal power plant, which was put into commercial operation in September 2016.

The Thermal Power Plant Stanari has an installed capacity of 300 MW, with subcritical steam parameters, a CFS boiler, (combustion in a circulating fluidized bed) and emissions compliant with EU directives. The cooling system is a dry cooling system with an Air Cooled Condenser (ACC). A special flue gas desulphurization system is not required because by adding ground limestone as a sorbent, directly in the boiler's combustion chamber, sulfur dioxide from the flue gas is bound. Bag filters are used in ash system.

The operation of the Stanari thermal power plant depends on the quality of the coal delivered from the mine [1, 4, 6, 7, 13, 16]. The coal at the Raskovac opencast mine mostly consists of three coal seams, and at other places, four coal seams. Between the seams, there is interburden of different thickness. Between seams I and II, the interburden ranges from 0-0.6 m, while between seams II and III it ranges from 0-10 m. The overall average for the limited space is 3.75 m. Apart from these two layers of interburden clay, there are several thinner interburdens less than 20 cm thick. Similar or significantly more complex engineering-geological conditions are present at the Ostruznja opencast mine, where preparatory work for the opening is underway and from which the thermal power plant will be supplied until the end of mining.

In order to homogenize coal, the opencast mine Raskovac is divided from north to south into 6 zones, 13 points, and each point into three layers. The zones are 150 m wide and the points 75 m wide. Samples are taken at mid-points every 50 m of coal front progress. After making composites by mixing coal of different quality, coal is delivered to the thermal power plant by a conveyer system (deposited at the stack and additionally homogenized or transported directly to the bunkers of the thermal power plant).

Since the beginning of the Stanari thermal power plant (TPP) operation, there have been no significant deviations in coal quality from the values defined by the project (LCV-lower calorific value of about 9,100 kJ/kg, carbon 27.5%, moisture content 49%, ash 7.5%, and sulfur 0.13 %). The most common variations of LCV were up to ±500 kJ/kg, where even values of 8,500 kJ/kg did not represent a serious obstacle for the operation of the block at full power. Based on the records and experiences from shorter periods of operation of the thermal power plant with LCV lower than the specified value, operational problems appeared.

Based on the established quality of coal in the Ostruznja opencast mine, where the remaining coal reserves are the most significant, it is difficult to meet the requirements for supplying the thermal power plant with coal of the designed capacity. In order to examine the possibility of burning coal with a lower LCV and other quality parameters and thus enable the rational use of deposits and reduce mining losses, testing was carried out in the thermal power plant by burning coal of different LCVs (from 9,100 to ≤ 7,500 kJ/kg). The final goal of the test is a comparative analysis of plant operation in several operating modes [2]. Based on records of burning coal whose LCV was about 8,000 kJ/kg of operating parameters during shorter periods of the block operation, predictions were made about the maximum and optimal power of the block as well as possible operation events, which served as the basis for defining test modes of operation.

2. Planned LCVs for the test operation of the thermal power plant

In order to secure coal with 7,500-8,500 kJ/kg LCV, coal sampling and analysis were carried out in the central and southern parts of the opencast mine Raskovac, where the III coal seam with clay interburden was discovered. In the central and southern part of the opencast mine Raskovac, there are a large number of interburdens of low thickness (often 0.15-0.30 m) and different positions in the coal seams. In order to simulate as realistic a quality of coal as possible, parts of the III seam for testing in the TPP were excavated partly together with thin interburdens and mixed with coal of higher LCV.

Based on the results of the analysis of the samples [3], the mining zones, the quantitative share for mixing, and the required amount of coal for testing in the thermal power plant were calculated (Tab. 1).

Table 1. Coal excavation plan for testing in the thermal power plant

Date	**Required LCV (kJ/kg)**	**Loading point I**	**(I) LCV (kJ/kg) Moisture (%) Ash (%)**	**Coal I (t)**	**Loading point II**	**(II) LCV (kJ/kg) Moisture (%) Ash (%)**	**Coal II (t)**	**Average LCV (kJ/kg)**	**Total coal I+II (t)**
1	2	3	4	5	6	7	8	4 and 7	5+8
19.09.2020.-20.09.2020.	**8,500**	J-1III (S)-1-2	8,683 kJ/kg 49.35% 10.65%	14,131	/	/	/	**8,683**	14,131
21.09.2020.-22.09.2020.	**8,000**	C-1III-3 (S)	8,016 kJ/kg 46.39% 15.99%	7,106	J-1III-1-2 (J)	8,052 kJ/kg 51.49% 10.72	7,488	**8,034**	14,594
23.09.2020.-24.09.2020. (variant 1)	**7,500**	J-2III-3 (J)	5,884 kJ/kg 45.44% 23.84%	5,255	C-2III-2 (J)	9,036 kJ/kg 52.06% 6,32%	5,450	**7,460**	10,705
23.09.2020.-24.09.2020. (variant 2)	**7,500**	C-1III-3(J)	6,054 kJ/kg 44.99% 24.68%	5,381	C-2III-2(J)	9,036 kJ/kg 52.06% 6.32%	5,307	**7,545**	10,688

The results of analyzes performed on samples from geological exploration wells were used to assess coal quality. Practical experience has shown that there is a large discrepancy between expected and actual coal quality results. The results obtained on samples from exploratory wells are of low reliability. In order to obtain usable data, statistical processing of the parameters obtained during geological exploration drilling and the results of coal analyzes carried out by laboratories at the mine and thermal power plants over the last ten years was carried out. On the basis of these results, the functional dependence between the amount of ash, moisture, and calorific value of coal was determined. A model for evaluating coal quality was also developed.

3. Test of block operation when burning coal of different quality

Testing of block operations took place between September 19 and September 24, 2020. It occurred during a number of operating modes that were selected as representative for examination and appropriate for a comparative study of the plant's operating parameters (Tab. 2).

Table 2. Technical analysis of coal and Basic operating parameters of the block

Technical analysis of coal											
		Referential mode		**Mode 1**		**Mode 2**		**Mode 3**		**Mode 4**	
Parameter	**Mode**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
Hd', Lower heat of combustion (deliv. cond.)	[kJ/kg]	8,940	9,031	8,395	8,521	8,189	8,337	7,723	7,604	7,599	7,515
Total moisture, Mt	[%]	50.7	50.1	49.5	49.8	51.7	51.5	48.3	50.5	48.8	47.7
Ash, A'	[%]	8.12	8.69	11.42	10.72	9.76	9.38	15.23	13.29	15.14	16.25
Fixed carbon, Cfix'	[%]	16.3	16.2	15.1	15.4	15.3	15.2	14.4	14.2	14.3	14.5
Sulfur total, St'	[%]	0.110	0.120	0.133	0.136	0.140	0.137	0.165	0.136	0.158	0.169
Combustible matter, Cm'	[%]	41.1	41.3	39.1	39.4	38.6	39.1	36.5	36.2	36.1	36.1
Volatile matter, Vm'	[%]	24.8	25.1	23.9	24.0	23.3	23.9	22.1	22.0	21.8	21.6
Steam blowers	-					*		*		*	
Basic operating parameters of the block											
		Referential mode		**Mode 1**		**Mode 2**		**Mode 3**		**Mode 4**	
Parameter	**Mode**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
Start	[d.m. (hh:mm)]	16.9. (00:00)	16.9. (10:00)	19.9. (20:10)	19.9. (13:03)	20.9. (21:00)	20.9. (11:40)	22.9. (22:00)	23.9. (10:00)	24.9. (02:00)	24.9. (11:00)
The end	[d.m. (hh:mm)]	16.9. (08:00)	16.9. (17:00)	20.9. (08:00)	19.9. (19:37)	21.9. (05:00)	20.9. (20:20)	23.9. (09:00)	23.9. (17:50)	24.9. (09:00)	24.9. (20:45)
Duration	[h]	8.00	7.00	11.83	6.57	8.00	8.67	11.00	7.83	7.00	9.75
Gross power of the block	[MW]	**298.0**	**294.0**	**298.8**	**295.4**	**297.0**	**293.1**	**295.2**	**290.6**	**272.6**	**272.6**
Net power of the block	[MW]	**272.2**	**267.3**	**272.1**	**269.2**	**270.2**	**266.4**	**267.7**	**263.1**	**247.3**	**246.3**
Own consumption	[MW]	**26.6**	**27.4**	**27.6**	**27.1**	**27.7**	**27.6**	**28.3**	**28.3**	**26.3**	**27.3**
Coal consumption	[t/h]	**306.0**	**305.2**	**318.1**	**324.4**	**332.8**	**335.5**	**352.4**	**354.2**	**331.0**	**343.1**
Hd, coal (analysis)	[kJ/kg]	**9,032**	**9,193**	**8,626**	**8,625**	**8,313**	**8,328**	**7,828**	**7,819**	**7,784**	**7,704**
Hd, coal (analysis)	[kJ/kg]	**8,940**	**9,031**	**8,395**	**8,521**	**8,189**	**8,337**	**7,723**	**7,604**	**7,599**	**7,515**
Pressure in the vacuum system	[kPa]	**12.6**	**19.8**	**10.6**	**19.4**	**11.7**	**19.0**	**13.0**	**19.4**	**10.8**	**19.4**
Feed water flow	[t/h]	941	953	937	941	936	951	932	936	858	891
Fresh steam flow	[t/h]	913	924	909	916	901	922	900	909	829	868
Total air flow	[kNm^3/h]	828	829	856	837	829	833	830	837	800	825
Flue gas flow	[kNm^3/h]	1,354	1,350	1,405	1,382	1,401	1,398	1,411	1,420	1,373	1,388
Secondary air flow	[kNm^3/h]	424	418	444	429	421	428	422	436	415	440
Primary air flow	[kNm^3/h]	369	374	374	372	372	368	372	366	350	350
Limestone consumption	[t/h]	**1.86**	**2.60**	**2.43**	**6.16**	**4.06**	**6.93**	**4.89**	**4.79**	**3.58**	**4.54**
Compress consumption air	[t/h]	4.56	5.03	4.92	5.39	5.74	5.60	5.72	5.93	5.88	5.97
Pressure in the layer	[kPa]	7.9	7.6	8.3	8.4	8.0	7.8	8.8	8.3	8.4	8.7
DP fireplace L	[kPa]	1.1	1.1	1.4	1.3	1.5	1.5	1.7	1.6	1.4	1.5
DP fireplace D	[kPa]	1.0	1.0	1.2	1.1	1.3	1.2	1.4	1.3	1.2	1.2
Layer temperature	[°C]	882	877	869	877	865	869	858	858	847	849
SO_2 emissions	[mg/Nm^3]	**196.3**	**187.6**	**189.3**	**188.5**		**196.4**	**210.7**	**176.8**	**195.9**	**194.3**
NOx emissions	[mg/Nm^3]	**149.4**	**151.6**	**158.5**	**141.9**		**135.0**	**119.1**	**120.0**	**132.6**	**130.9**
Emissions of powdery substances	[mg/Nm^3]	**29.2**	**28.1**	**41.0**	**31.3**	**56.2**	**38.2**	**49.7**	**33.9**	**51.4**	**43.4**

These modes included at least six hours of operation during which there were only minor variations in the lower calorific value of coal and the absolute pressure in the vacuum system. The reference mode of operation of the block, that is, the period of operation with coal of design quality (LCV roughly 9,100 kJ/kg), was also separated for the purpose of making the analysis of the block's performance indicators easier.

The most crucial TPP operational parameters for each of the four operating modes were compared using the data that was gathered [3]. During the duration of the mentioned operating modes, periods were separately observed when the absolute pressure in the vacuum system was <13 kPa, i.e., >19 kPa, in order to take into account the influence of ambient conditions on the operation of the unit.

In order to have a better overview of the results obtained during the test, in addition to the average values of the mentioned work parameters, energy performance indicators (EnPI) were also introduced. With the help of introduced indicators, the indicators of the block operation are reduced to MWh of electricity produced (gross) and simplify the comparison of the operation mode during the test with the previously defined reference mode.

Table 3 shows the values ei,j, which represent the ratio of defined energy performance indicators for individual operating modes during the EnPIi,j test (i=Mode 1, Mode 2, Mode 3, Mode 4; j=own electricity consumption, specific consumption of coal, limestone,..., compressed air) and the energy performance indicator of the selected reference operating mode, $EnPIR_{(1)},j$ or $EnPIR_{(2)},j$ depending on the achieved absolute pressure in the vacuum system during the test mode, i.e., for i = 1, 3, 5, 7, for i = 2, 4, 6, 8, that is:

$eij = EnPIij / EnPIR_{(1)}$ (-) for i=1,3,5,7 and $eij = EnPIij / EnPIR_{(2)}$ (-) for i=2,4,6,8

An increase in the coal consumption indicator is observed with a decrease in the lower calorific value of coal, as well as an increase in the value of the own electricity consumption indicator (it is a direct consequence of the increase in the load on the boiler fans). There was also a relative increase in flue gas flow and total air flow per MWh of gross electricity produced compared to the reference operating mode. The increase in air flow is the result of measures taken to reduce emissions of sulfur oxides, i.e., limestone consumption. The increase in the flue gas flow, in addition to the higher air flow, is additionally influenced by the higher moisture content in the coal.

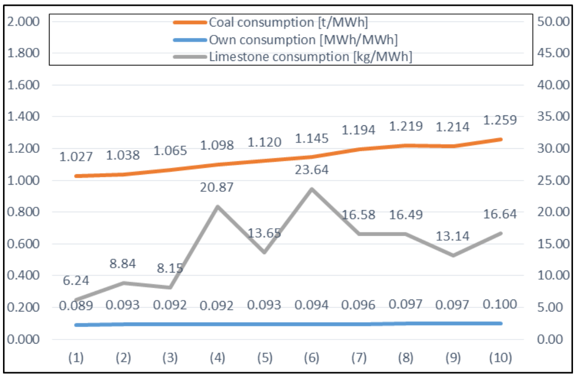

Figure 1. Values of defined energy performance indicators ($EnPI_{i,j}$)

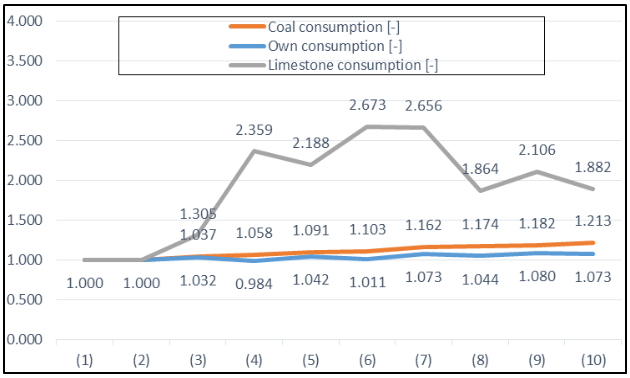

Figure 2. Values of e_{ij} ($e_{ij}= EnPI_{ij} / EnPI_{rj}$) for individual operating modes

The graphs on Fig. 1 and 2 clearly show increases in the indicators of coal consumption, limestone consumption, and the thermal power plants own consumption when the heating value of the burned coal decreases.

Table 3. Energy performance indicators $EnPI_{ij}$ and e_{ij} (e_{ij}= $EnPI_{ij}$ / $EnPI_{rj}$) relation

Parameter		**Mode**	**Referential mode**		**Mode 1.**		**Mode 2.**		**Mode 3.**		**Mode 4.**	
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Start		d.m. (hh:mm)	16.9. 00:00	16.9. 10:00	19.9. 20:10	19.9. 13:03	20.9. 21:00	20.9. 11:40	22.9. 22:00	23.9. 10:00	24.9. 02:00	24.9. 11:00
The end		d.m. (hh:mm)	16.9. 08:00	16.9. 17:00	20.9. 08:00	19.9. 19:37	21.9. 05:00	20.9. 20:20	23.9. 09:00	23.9. 17:50	24.9. 09:00	24.9. 20:45
Duration		[h]	8.0	7.0	11.8	6.6	8.0	8.7	11.0	7.8	7.0	9.8
Gross power of the block		[MW]	**298.0**	**294.0**	**298.8**	**295.4**	**297.0**	**293.1**	**295.2**	**290.6**	**272.6**	**272.6**
Net power of the block		[MW]	**272.2**	**267.3**	**272.1**	**269.2**	**270.2**	**266.4**	**267.7**	**263.1**	**247.3**	**246.3**
Hd, coal (acc. value)		[kJ/kgK]	**9,032**	**9,193**	**8,626**	**8,625**	**8,313**	**8,328**	**7,828**	**7,819**	**7,784**	**7,704**
Hd, coal (analysis)		[kJ/kgK]	**8,940**	**9,031**	**8,395**	**8,521**	**8,189**	**8,337**	**7,723**	**7,604**	**7,599**	**7,515**
Pressure in the vacuum system		[kPa]	**12.6**	**19.8**	**10.6**	**19.4**	**11.7**	**19.0**	**13.0**	**19.4**	**10.8**	**19.4**
$EnPI_{i,j}$	**Own energy consumption**	[MWh/MWh]	**0.089**	**0.093**	**0.092**	**0.092**	**0.093**	**0.094**	**0.096**	**0.097**	**0.097**	**0.100**
	Coal consumption	[t/MWh]	**1.027**	**1.038**	**1.065**	**1.098**	**1.120**	**1.145**	**1.194**	**1.219**	**1.214**	**1.259**
	Limestone consumption	[kg/MWh]	**6.24**	**8.84**	**8.15**	**20.87**	**13.65**	**23.64**	**16.58**	**16.49**	**13.14**	**16.64**
	Degree of conv. th. energy to el.	[(MJ/MWh)*10^3]	**9.27**	**9.54**	**9.18**	**9.47**	**9.31**	**9.53**	**9.34**	**9.53**	**9.45**	**9.70**
	Feed water flow	[t/MWh]	3.16	3.24	3.14	3.19	3.15	3.25	3.16	3.22	3.15	3.27
	Fresh steam flow	[t/MWh]	3.06	3.14	3.04	3.10	3.03	3.15	3.05	3.13	3.04	3.18
	Total air flow	[kNm^3/MWh]	2.78	2.82	2.86	2.84	2.79	2.84	2.81	2.88	2.93	3.03
	Flue gas flow	[kNm^3/MWh]	4.54	4.59	4.70	4.68	4.72	4.77	4.78	4.89	5.04	5.09
	PAF A + PAF B	(MWh/MWh)*10^3	11.00	11.11	10.98	11.31	10.95	11.21	11.57	11.50	11.23	11.81
	SAF A + SAF B	(MWh/MWh)*10^3	7.49	7.92	8.83	7.94	8.02	8.92	8.68	9.30	8.53	10.07
	IDF A + IDF B	(MWh/MWh)*10^3	17.67	18.49	19.36	19.86	20.10	20.30	20.59	21.36	19.67	21.40
	Compressed air	(MWh/MWh)*10^3	3.04	3.59	3.14	3.58	3.59	3.65	3.93	4.37	4.28	4.40
Ratios of defined energy performance indicators for individual operating modes during the EnPIi,j test and energy performance indicators ref. mode of operation EnPIr, j												
$e_{ij} = \frac{EnPI_{ij}}{EnPI_{Rj}}$	**Own energy consumption**	[-]	**1.000**	**1.000**	**1.032**	**0.984**	**1.042**	**1.011**	**1.073**	**1.044**	**1.080**	**1.073**
	Coal consumption	[-]	**1.000**	**1.000**	**1.037**	**1.058**	**1.091**	**1.103**	**1.162**	**1.174**	**1.182**	**1.213**
	Limestone consumption	[-]	**1.000**	**1.000**	**1.305**	**2.359**	**2.188**	**2.673**	**2.656**	**1.864**	**2.106**	**1.882**
	Degree of conv. th. energy to el.	[-]	**1.000**	**1.000**	**0.990**	**0.993**	**1.004**	**0.999**	**1.007**	**0.999**	**1.019**	**1.016**
	Feed water flow	[-]	1.000	1.000	0.993	0.983	0.997	1.001	0.999	0.993	0.996	1.008
	Fresh steam flow	[-]	1.000	1.000	0.993	0.986	0.990	1.000	0.995	0.995	0.992	1.013
	Total air flow	[-]	1.000	1.000	1.030	1.006	1.004	1.008	1.011	1.022	1.056	1.073
	Flue gas flow	[-]	1.000	1.000	1.035	1.019	1.039	1.038	1.052	1.064	1.109	1.108
	PAF A + PAF B	[-]	1.000	1.000	0.998	1.017	0.995	1.009	1.052	1.035	1.020	1.062
	SAF A + SAF B	[-]	1.000	1.000	1.180	1.002	1.072	1.126	1.160	1.174	1.140	1.271
	IDF A + IDF B	[-]	1.000	1.000	1.096	1.074	1.138	1.098	1.165	1.156	1.113	1.157
	Compressed air	[-]	1.000	1.000	1.032	0.997	1.181	1.017	1.293	1.217	1.410	1.228
Steam blowers		-					*		*		*	

Particularly characteristic are the graphs in Fig. 3 and 4, which show the ratio of defined energy performance indicators for the reference operating mode (columns 1 and 2) and operating modes with coal LCV≤7500 kJ/kg [mode 3 (columns 7 and 8) and mode 4 (columns 9 and 10); Tables 2 and 3].

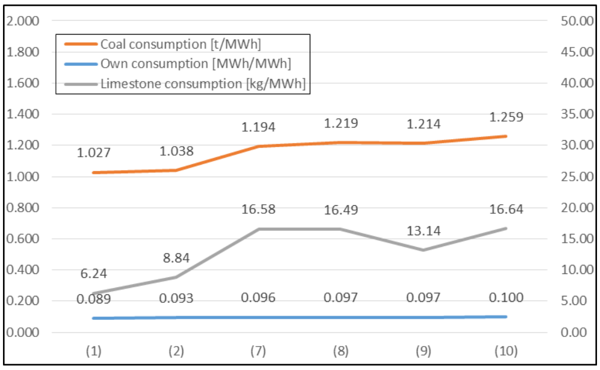

Figure 3. Display of $EnPI_{i,j}$ values for reference mode and operating modes with LCV ≤7,500 kJ/kg

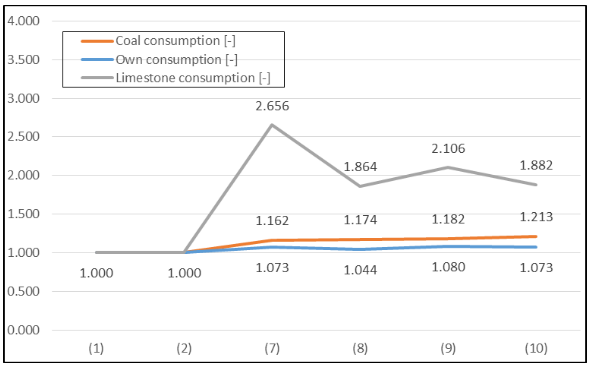

Figure 4. Values of e_{ij} ($e_{ij}= EnPI_{ij} / EnPI_{rj}$) for reference mode and operating modes with LCV ≤7,500 kJ/kg

4. Thermal power plant test results

The complete multi-day examination of the unit operation took place in accordance with the planned course to the greatest extent, and based on the analysis of the obtained results, the conclusions about the operation of the production plant of TPP Stanari can be considered relevant [4].

The operation of the unit during testing was stable, and parts of the plant functioned without significant disturbances, reliably, and without failures in operation, even at maximum design capacities. The temperatures when burning coal with a caloric value lower than 8,500 kJ/kg, were up to 30°C lower than usual values, but without major fluctuations or collapse that would require the introduction of liquid fuel for the purpose of stabilizing the process. This confirmed the significant advantage of combustion organized in a circulating fluidized layer, confirmed through the operation of the block with a coal LCV of 7,500 kJ/kg.

The direct consequence of burning coal with lower calorific values than the designed one is increased coal consumption, i.e., an increased load on gravimetric coal dispensers. On several occasions, during the course of the testing, coal consumption values higher than 360 t/h were recorded for a short period of time. The operation of gravity feeders close to their maximum designed capacities potentially increases the possibility of outages and further complicates the possibility of stopping the operation of one of the coal feeders or ash coolers in order to service the observed defects. In the case of stopping one of the coal dispensers, the problem of controlling sulfur oxide emissions also arises, whereby maintaining the SO_2 value below the prescribed limit value is almost impossible.

During the test, difficult control of SO_2 emissions was noted, i.e., increased consumption of limestone as well as increased emission of powdery substances in the flue gas.

In addition to the increased load on the coal dispenser and ash cooler, when burning coal with an increased content of mineral impurities, additional possible problems were also recorded on the bag filter system. The limitations mentioned are related to the increased frequency of shaking the bags and the capacity of the filters themselves, as well as the limited capacity of the fly ash transport system under the bag filters. Increased wear and tear on almost all parts of the ash transport system was also observed, where ensuring conditions for damage repair during unit operation would also be difficult during long-term burning of coal whose LCV is ≤7,500 kJ/kg.

The influence of the presence of a large amount of layer material, that is, ash in the boiler hearth on the abrasion of the wall of the evaporator tubes can be quantified by introducing the abrasion coefficient δ. According to the empirical formula, the abrasion coefficient δ directly depends on the concentration or density of the material of the layer in the higher zones of the combustion chamber and the third degree of velocity, i.e., flue gas flow. As shown in the following Eq. 1:

$$\delta\ =\ \lambda\,\mu\,\omega 3\,\tau\ [-] \tag{1}$$

Where: λ - relative abrasion coefficient, which depends directly on the diameter of the coal particle, μ - concentration of ash in the transition and rarefaction zone in the combustion chamber, ω - speed (flow) of flue gas, and τ - time.

Technical analyzes of the coal burned during the test showed that the increased content of mineral impurities (and not moisture) was the ballast that led to the lower lower caloric value of the coal. This is also the most unfavorable scenario for the operation of the plant in several aspects. One of the most important aspects is the degree of abrasion of the boiler pipe system, which in this test could only be quantified based on the presented empirical formula of the material density in the thinned fluidization zone and flue gas flow through the combustion chamber.

Given the uniform geometry of the particles during testing and the fact that the mentioned phenomena are observed over a period of time, the relative abrasion coefficient λ and time τ in this case do not affect the value of the coefficient δ and can be equated to 1. As a measure of the density of the layer in the transition and in the rarefied zone, the differential pressure (dp) in the boiler combustion chamber was taken for calculation, while the flue gas flow measured by the CEM system was taken as a measure of flue gas velocity. Table 4 shows the relevant parameters of work and the calculated values of the coefficient of abrasion during the duration of the test, where the increase in the value of the coefficient of abrasion can be seen with the increase in the differential pressure in the combustion chamber and the increase in the flow of flue gas.

Table 4. Analysis of the parameters affecting the abrasion of the evaporator tubes wall

Parameter	**Examination mode**	**Reference mode**		**Mode 3.**		**Mode 4.**	
	Units	(1)	(2)	(7)	(8)	(9)	(10)
Start	d.m. (hh:mm)	16.9. (00:00)	16.9. (10:00)	22.9. (22:00)	23.9. (10:00)	24.9. (02:00)	24.9. (11:00)
The end	d.m. (hh:mm)	16.9. (08:00)	16.9. (17:00)	23.9. (09:00)	23.9. (17:50)	24.9. (09:00)	24.9. (20:45)
Duration	[h]	8.0	7.0	11.0	7.8	7.0	9.8
$H_{d,\,r.v.}$	[kJ/kg]	9,032	9,193	7,828	7,819	7,784	7,704
H_d'	[kJ/kg]	8,940	9,031	7,723	7,604	7,599	7,515
Flue gas flow	**[kNm^3/h*10^3]**	**1.35**	**1.35**	**1.41**	**1.42**	**1.37**	**1.39**
***dp* Fireplace**	**[kPa]**	**1.07**	**1.05**	**1.54**	**1.42**	**1.28**	**1.37**
Abrasion coefficient, δ	**[-]**	**2.64**	**2.59**	**4.31**	**4.07**	**3.30**	**3.66**
Steam blowing	-			*		*	

Figure 5 shows that the increase in the value of the abrasion coefficient is particularly pronounced in mode 3 and mode 4 when burning coal with LCV of ≤7,500 kJ/kg, which is accompanied by an increased presence of mineral admixture.

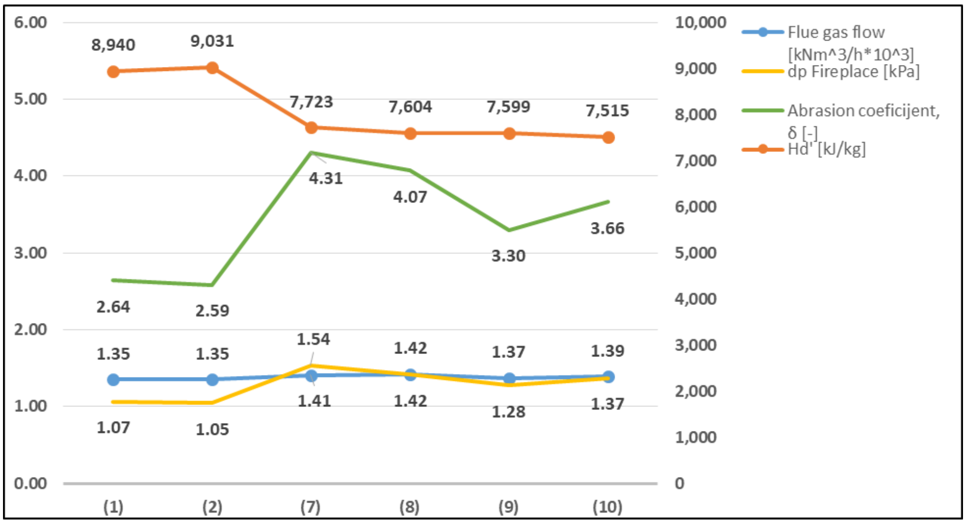

Figure 5. Relation between the abrasion coefficient and the flow of flue gas and the dp of the combustion chamber (for the reference operating mode and operating modes with coal LCV of ≤7,500 kJ/kg)

Longer periods of boiler operation under conditions of increased material concentration in the combustion chamber were recorded only in 2016, and thus, through experience, operation in such a mode was characterized as extremely unfavorable from the aspect of abrasion in the combustion chamber. Hence, in addition to all the measures that are taken from year to year to improve and provide additional protection of the boiler's evaporation system, the general operating philosophy was also changed at the beginning of 2017, which is currently based on working with less material inside the combustion chamber, consequently allowing slightly elevated temperatures in the layer and consumption of limestone above the design level.

Based on the analysis of the coal dosing system, the recommended values of the maximum permanent coal consumption of ~330 t/h and the maximum short-term (transient) consumption of ~360 t/h were defined. The mentioned value of coal flow (~330 t/h) was used as a basis for calculating the maximum gross power of the block for values of LCV less than 8,500 kJ/kg (dashed blue line in Fig. 6). However, as already emphasized, during the testing when burning coal of LCV ≤ 8,000 kJ/kg, it was observed that the maximum design capacities of the bag filter systems and the pneumatic transport of ash and compressed air were reached. In order to enable the smooth functioning and regular maintenance of these parts of the system, and taking into account the content of mineral impurities from the technical analysis of the coal during the test, the calculation was corrected, and then the optimal permanent gross power was determined in the function of LCV (solid red line).

The calculation results are shown graphically in Fig. 6 and are valid for the design value of the absolute pressure in the vacuum system (12.6 kPa). Through the daily production plans, the announced ambient conditions would be taken into account, whereby an increase in absolute pressure in the range of 1.2-1.4 kPa corresponds to a correction of the gross power by 1 MW lower with the same coal consumption. The optimal net power of the block as a function of the lower calorific value of the coal is shown in the diagram with the solid green line.

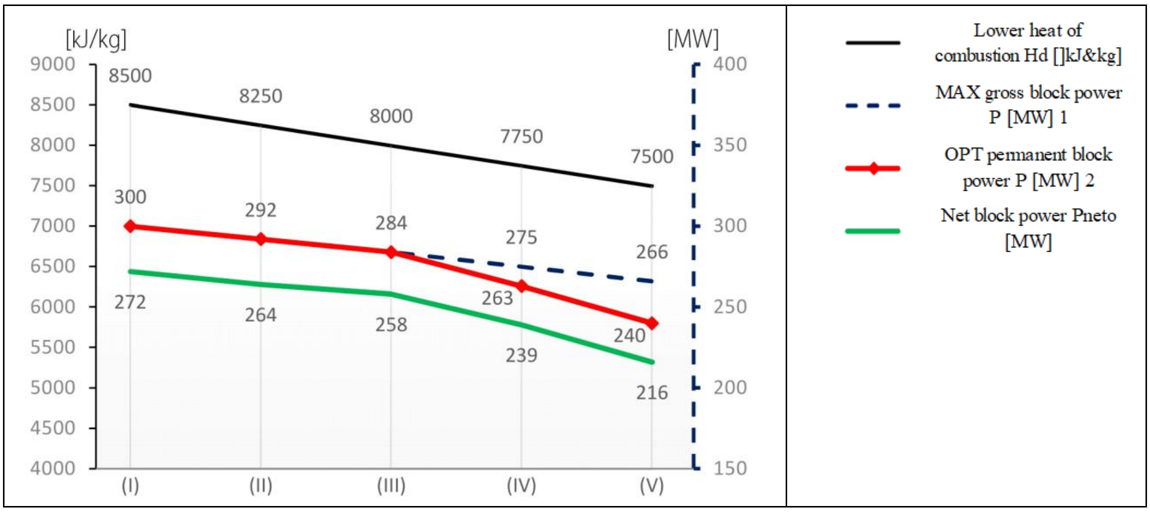

Figure 6. Recommended values of block gross power for coal of different LCV

5. Risk analysis for the TPP block operation with coal quality parameters lower than designed

The results of the test showed that the deviation from the designed qualitative characteristics of coal [3, 5] leads to disruption of the performance of the production process, faster wear and tear of the plant, difficult control of pollutant emissions, and an increase in the unit price of production.

Many authors have dealt with the impact of burning coal of a worse quality than designed on the operating parameters of the thermal power plant. Many authors wrote about the homogenization and quality control of coal before entering the thermal power plant [6, 7, 14] or the techno-economic parameters of the power plant operation in the mentioned conditions [13, 15, 16, 17]. The authors also assessed the business risks [8-12] over a long period of time during the operation of a block with coal parameters of lower quality than planned from the perspective of economic parameters.

Table 5 shows the results of the production of the Stanari thermal power plant in the period 2017-2021. The observed period is characterized by the supply of the thermal power plant with coal of the designed quality and the operation of the thermal power plant in the planned mode of operation. Seeing as 2016 was a year of trial, it was not taken into account.

Table 5. Achieved results of the thermal power plant in the period from 2017 to 2021

Parameter	**Unit**	**Year**					
		2017	**2018**	**2019**	**2020**	**2021**	**2022**
TPP production (gross)	(MWh)	2,235,148	2,260,736	2,275,741	2,201,816	2,068,262	2,361,847
TPP production (net)	(MWh)	2,040,592	2,056,001	2,068,319	2,001,569	1,872,474	2,128,201
Time online	(h)	7,515	7,591	7,641	7,438	6,979	7,951
Offline time	(h)	1,245	1,169	1,119	1,346	1,781	809
Average gross power	(MW)	297	298	298	296	296	297
Average net power	(MW)	272	271	271	269	268	268
Coal consumption	(t)	2,265,84	2,288,643	2,320,508	2,266,816	2,132,701	2,433,006
Average coal consumption	(t/h)	302	301	304	305	306	306
Average coal consumption	(t/MW)	1.01	1.01	1.02	1.03	1.03	1.03

From the graph in Fig. 6, it is clear that the recommended values of the block gross power of the coal with an LCV of ≤ 7,500 kJ/kg are significantly lower than the power achieved during coal combustion with the designed quality parameters (Tab. 6).

Table 6. Realized powers of the block when burning coal with LCV ≤8,500 kJ/kg

Parameter	Unit	Position				
		(I)	(II)	(III)	(IV)	(V)
LCV H_d	(kJ/kg)	8,500	8,250	8,000	7,750	7,500
MAX gross power P 1	(MW)	300	292	284	275	266
OPT permanent power P 2	(MW)	300	292	284	263	240
Net block power P_{neto}	(MW)	272	264	258	239	216

The test results, based on energy performance indicators for individual operating modes during the test, showed an increase in coal consumption, own electricity consumption, and limestone consumption. Increases in the mentioned parameters are especially characteristic for operating modes with coal with an LCV of ≤7,500 kJ/kg.

It was already stated that it is very difficult to meet the requirements for supplying the Stanari thermal power plant with coal of the designed capacity until the end of the life of mine at the Ostruznja opencast mine, where the remaining coal reserves are the most significant. The thermal power plant will have to work with optimal permanent block power during the entire period in which the coal supply will be with an LCV of ≤ 8,000 kJ/kg and an increased content of mineral impurities. For the aforementioned reasons, the potential impact of these parameters [9, 10] on the economic effects of the operation of the thermal power plant will be analyzed.

The increase in coal consumption indicators with the decrease in LCV of coal in all operating modes is evident. It ranges from 1.037 t/MWh (I mode with an LCV≈8,500 kJ/kg) to 1.213 t/MWh (IV mode with an LCV≈7,500 kJ/kg). Considering that the maximum permanent coal consumption of ~330 t/h was defined and recommended, which was also used as a basis for calculating the maximum gross block power, it is clear that during the entire future operating period, when working with coal with an LCV of ≤ 8,000 kJ/kg, average coal consumption is going to be 10% higher than projected and achieved so far. For an average of 7,500 hours of work per year on the network, it is necessary to provide an average of about 230,000 t per year more coal than up to the observed period. That is approximately one month's production of the thermal power plant, and the estimated market value of electricity is about 17,000,000 EUR.

An increase in the limestone consumption indicator for the operating regimes with an LCV ≤ 8,000 kJ/kg is also evident. The consumption of limestone in the reference mode (project coal) was 2 to 2.5 t/h. In the modes of operation of the plant with an LCV ≤ 8,000 kJ/kg coal, the consumption of limestone increased almost two times, that is, approximately 50 t/day. The potential increase in costs on an annual basis in the mentioned modes of operation could be estimated at around 500,000 euros (estimated market price of limestone: 30 EUR/t).

Based on the remaining reserves and documentation, the remaining planned lifetime of the thermal power plant is until 2050. Very significant negative economic effects on the operation of the thermal power plant can be expected considering the facts about the quality of coal from the Ostruznja opencast mine, only from the aspect of increased consumption of coal and limestone when supplying the thermal power plant with an LCV of ≤ 8,000 kJ/kg coal.

On the basis of the entire analysis of the results of the TPP operation in the modes of operation with designed coal quality and coal of lower quality, the authors (authors of the study [3], which served as the basis for this paper, and experts who have many years of experience in managing complex energy systems) provided a value analysis of the risk assessment for the operation of the thermal power plant in the mentioned conditions (Tab. 7).

Table 7. Risk assessment during the operation of the TPP Stanari with coal LCV lower than designed

Risks		TPP Stanari operation modes																								
		Referential mode LCV=9,000 kJ/kg					**Mode 1** LCV=8,500 kJ/kg					**Mode 2** LCV=8,000 kJ/kg					**Mode 3** LCV=7,500 kJ/kg					**Mode 4** LCV≤7,500 kJ/kg				
		Evaluation criteria																								
		VH	H	S	L	NI	VH	H	S	L	NI	VH	H	S	L	NI	VH	H	S	L	NI	VH	H	S	L	NI
1	**Block power reduced**	/	/	/	/	*	/	/	/	*	/	/	/	*	/	/	*	/	/	/	/	*	/	/	/	/
2	**Increased coal consumption**	/	/	/	/	*	/	/	/	*	/	/	*	/	/	/	*	/	/	/	/	*	/	/	/	/
3	**Increased own consumption**	/	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	/	*	/	/	/
4	**Increased consumption of limestone**	/	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	/	*	/	/	/
5	**Increased pipe system abrasion**	/	/	/	/	*	/	/	*	/	/	/	*	/	/	/	*	/	/	/	/	*	/	/	/	/
6	**Difficult regular and interventional maintenance**	/	/	/	/	*	/	/	*	/	/	/	*	/	/	/	*	/	/	/	/	*	/	/	/	/
7	**Difficult control of pollutant emissions**	/	/	/	/	*	/	/	*	/	/	/	/	*	/	/	/	*	/	/	/	/	*	/	/	/
8	**Increased amount of ash**	/	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	*	/	/	/	/

VH- very high; H- high; S-significant; L- low; NI-no impact

6. Conclusions

Based on the relevant tests and test results with burning coal of a lower quality than the designed values, it is evident:

- Coal-burning modes with an LCV of 8,500 kJ/kg did not present a serious obstacle to the operation of the block at full power
- When burning coal whose LCV is less than 8,000 kJ/kg, with an increased content of mineral impurities, the most significant problems are:
  - Increased wear of system parts,
  - Difficult regular or interventional servicing of equipment in the specified conditions,
  - More difficult control of pollutant emissions and increased consumption of limestone,
  - It is especially problematic to operate in coal burning modes with an LCV of ≤ 7,500 kJ/kg due to a large increase in the consumption indicators of coal and limestone, the own consumption of the thermal power plant, and increased abrasion of the pipe system.

- Possible deviation from the production plan due to equipment failure, especially when working at the maximum coal block load LCV ≤ 8,000 kJ/kg
- There is a high probability of an increase in production costs and a significant impact on the economy and effectiveness of the operation of the thermal power plant.

The results of the test indicate the necessity of applying measures to create a model of the Ostruznja deposit, a technological model, and homogenization of coal in order to fully control the quality of coal for the supply of the thermal power plant and to reduce possible significant negative economic effects during the operation of the thermal power plant with poor coal quality (LCV ≤ 8,000 kJ/kg).

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