

Challenges for a European utility considering the EU Directive on industrial emissions by the end of 2015

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Kurzfassung

Herausforderungen für einen europäischen Energieversorger unter Berücksichtigung der Einhaltung der EU Industrie Emissionsrichtlinien bis Ende 2015

Das im Jahr 1978 errichtete braunkohlgefeuerte Kraftwerk Maritsa East 3 in Bulgarien umfasst 4 Blöcke mit einer Leistung von jeweils 227 MW_{el}. Nach mehreren Eigentümerwechseln hat ContourGlobal die Anlage im Jahre 2011 erworben und in 2012 Steinmüller Engineering mit der Modernisierung des Feuerungssystems zu einer Low-NO_x-Feuerung beauftragt. Mit dieser jüngsten Modernisierungsmaßnahme des Kraftwerks ist Maritsa East 3 nun die erste braunkohlgefeuerte Anlage auf dem Balkan, die in voller Übereinstimmung mit den europäischen Umweltschutzstandards betrieben wird. Ziele des Projektes waren unter anderem die Reduktion von NO_x-Emissionen unterhalb von 180 mg/m³ (stp), die Vermeidung von Verschlackung und die Effizienzsteigerung im Feuerraum. Das Projekt musste unter extremem Zeitdruck umgesetzt werden.

Zur weiteren Verbesserung des SO_x-Abscheidegrads, beauftragte ContourGlobal ebenfalls Steinmüller Engineering. Der Absorber wurde parallel zur Modernisierung des Kessels am Block 1 modifiziert. Die neue technische Lösung wurde unter Berücksichtigung von CFD-Simulationen, einer Machbarkeitsstudie und des Detaildesigns der notwendigen Umbaumaßnahmen umgesetzt. Das Ergebnis ist eine gleichmäßigere Strömungsverteilung und Steigerung der Absorbereffizienz auf >96%. Die SO_x-Emissionen werden somit, verglichen mit der Ausgangssituation, um ein weiteres Drittel reduziert.

Die beiden zuletzt genannten Optimierungsprojekte am Kraftwerk Maritsa East 3 zeigen deutlich die positiven Auswirkungen hinsichtlich Wirkungsgrad und Umwelteigenschaften für ein bestehendes Kraftwerk bei vergleichsweise geringem Investitionsaufwand.

The challenge

The Maritsa East 3 thermal power plant was commissioned in the period 1978 to 1981. It consists of four lignite-fired units with a gross capacity of 227 MW each (210 MW prior to refurbishment).

The steam generator is designed to produce up to 730 t/h of superheated steam at a pressure of 140 bar(g) and a temperature of 545 °C, operating in mono-unit with turbine K 225-130-2M.

The plant was designed to burn Bulgarian lignite coal from the Maritsa East Basin having a calorific value of 1,400 to 1,700 kcal/kg in the so called “direct scheme” using mill fans/without preliminary drying of the fuel. The main characteristics of the boiler are as follows:

- “T”-shaped layout of flue gas tracts,
- Natural circulation of the water-steam mixture in the water walls,
- A two-flow water steam tract with two drums (the two flows are the same with an independent regulation from one another),
- The gas tract structure of the water walls is made of gas-tight pipe wall,
- The superheater tract has primary and secondary re-heating of steam.

In 2009 the rehabilitation and modernisation project was completed making ContourGlobal Maritsa East 3 the first thermal power plant in the Balkans to be retrofitted

for full compliance with the EU environmental Directives at the time.

As part of the refurbishment works, the plant was equipped with a low-NO_x burner system and a wet FGD installation. The key highlights of the rehabilitation were:

- 8 % increase in output,
- 17 % increase in efficiency,
- 20 times reduction in sulphur dioxide emissions,
- 2.5 times reduction in nitrous oxide emissions and
- 25 year lifetime extension.

Shortly after the acquisition of the Maritsa East 3 power plant, ContourGlobal was faced with the challenge of meeting new and stringent SO_x and NO_x emission limits by the year 2016. In accordance with the EU Industrial Emissions Directive (2010/75/EU,) the nitrous oxide (NO_x) emission limit became more stringent from 500 mg/Nm³ to 200 mg/Nm³)¹ and the required desulphurisation rate increased from 94 % to 96 % (Figure 1).

The solution

NO_x reduction measures

The task of implementing the low NO_x modifications on all four boilers in the short time frame meant that each year the modification of one of the four boilers had to be completed. The technical complexity and tight schedule put the entire Maritsa team to the test considering that this was the first of such retrofitting in the Balkans. With no room for error, the team had to select the most suitable technical solution for the implementation of the project.

¹ All units converted to 6 % O₂, dry gas.

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Fig. 1. Maritsa East 3 thermal power plant.



Figure 2. Scrubber 3D model including duct [unit 12].

After careful consideration, it was decided to solely optimise the plant through the implementation of primary measures, i.e. modifications in the combustion process aiming at the reduction of air quantities in the burner area and completion of the combustion which is achieved through the injection of over fire air (OFA) at the top of the furnace. As a result, the flame temperature peak areas, where NO_x emissions are mainly formed, are reduced. This measure is advantageous because it does not require injection of ammonia or urea in the reduction process and is therefore more environmentally friendly and saves operational costs. The project took into account all main operational risks that could arise from this type of boiler modification, such as heavy slagging, sulphide corrosion on the furnace walls due to sub-stoichiometric combustion conditions, efficiency decrease due to high levels of unburnt carbon in the ash and an increase of CO. The very compact boiler geometry, especially in the combustion chamber, required careful consideration in order to guarantee the flue gas residence time needed for reducing the emissions by primary measures only. Significant risks were also posed due to the slagging properties and the high sulphur content of the Bulgarian lignite.

The modification was assigned as an EPC contract covering design, manufacture, installation and commissioning works required to upgrade the boilers at the power station. A very important and tough prerequisite for the successful completion of the project was and is to complete all installation works during the respective planned

major outages of each generation unit, in parallel to other planned maintenance activities thereby avoiding an extended outage period for the respective unit.

The retrofitting of the boilers essentially comprises of the following measures:

- Modification of the lignite distribution system to optimise combustion control.
- Replacement of the existing burners with completely new ultra low- NO_x lignite burners with optimised secondary air conveyance and flame stabilisation.
- Installation of side wall air systems for prevention of slagging and corrosion.
- Installation of 2 separated levels of over fire air injection.

The complete process design and the dimensioning were performed with CFD (computational fluid dynamics) modelling. The 3D-furnace model of the boiler comprises of 11 million cells. For each of these cells, depending on the boiler load, 50 to 100 equations were solved. In order to achieve converged CFD results, for each of the several design cases investigated, 30,000 to 60,000 iterations had to be performed with 48 hours of supercomputers calculation. Once the solution for the lignite distribution system was selected, the result was verified by physical model simulations in order to confirm the correspondence with the CFD model.

Objectives of the low- NO_x project:

- Reduction of the NO_x emissions below 180 mg/Nm^3 at 6 % O_2 ,
- Efficiency increase of the combustion chamber by reduction of the excess air ratio from 1.2 to 1.15 (at furnace outlet),

- Keeping CO emissions below 180 mg/Nm^3 at 6 % O_2 ,
- Preventing water wall corrosion,
- Preventing a deterioration of the slagging behaviour in the furnace,
- Keeping the parameters of the pressure parts in the same range as before the re-ramp and
- Using the already scheduled outage time for the entire realisation of the modification scope.

Further information on the NO_x reduction project is available in [1].

FGD optimisation

The FGD was to be optimised to increase the SO_x removal efficiency to over 96 % by optimisation of the flow distribution within the absorber, while the limestone consumption should be kept at the current values (as for 94 % desulphurisation rate).

The engineering work was performed in two stages: FGD computational fluid dynamics (CFD) study for calculation and definition of different upgrade scenarios and detailed design stage for the selection of the most suitable solution and provision of the related design (supply and installation) documentation.

The project is to be implemented within the scope of the 2015 planned outage of the power plant. All the necessary materials, such as SiC nozzles and fittings have already been procured and are at the site.

A first assessment of the absorber geometry revealed that some constructional characteristics do not support optimal gas flow conditions. Therefore, possible modifications to improve the flow distribution inside of the absorber were identified. Uniform gas flow distribution is the basis for good contact between flue gas and absorption liquid and consequently for the absorption of SO_2 .

Absorber modelling

The scrubber geometry, as used in the 3D CFD simulations, is shown in Figure 2. The model starts at the cyclone tower inlet, where a uniform velocity distribution is assumed. The outlet of the model is located at the stack outlet at 150 m. The flue gas duct upstream of the FGD absorber is equipped with guide vanes, placed in the bends. Additionally, an ellipsoidal deflector plate (disc) is installed in the duct in order to make the flow distribution at the absorber inlet more uniform and to avoid backflows in the duct. The spray levels are modelled geometrically with the main headers and distribution pipes. The spray nozzles are modelled directly in the CFD model using spray angle, temperature, droplet size and spray velocity. The flat mist eliminator stages are visible as zig-zag-shaped volumes in Figure 2. A velocity dependent pressure loss is assigned to



Figure 3. Single tray element (PP).

these volumes in the CFD model. The 3D model also includes the main supporting structure and two wall rings located between spray levels #1 to #2 and #3 to #4. The absorber sump is not considered in the model as it does not have a direct influence on the gas phase flow.

The final CFD mesh for the FGD absorber and flue-gas duct consists of approximately 9.6 million cells. This amount of cells is required to ensure calculation stability and reliable results. The size of cells varies between 0.05 m and 0.40 m. FLUENT 14.5 is used for the calculations. To simulate the turbulences in the flow, the realisable $k-\epsilon$ model is chosen. For each cell, the solver calculates the Navier-Stokes-Equation and mass balance and two transport equations for the turbulent kinetic energy k and the dissipation rate ϵ . This model is suitable for most flow models without strong eddies. The liquid phase is defined as a discrete phase in the flue gas flow. The simulation is performed with bidirectional energy and momentum exchange between gas phase and liquid phase.

In a first step, the model of unit 12 (supplied by boilers 1 and 2) was validated using site measurements at the standard load case of the FGD (2 x 227 MW). The absorber inlet velocity profile influences the gas distribution inside of the absorber. Due to the complex inlet duct geometry, additional validation measurements were conducted directly at the inlet nozzle of the absorber. The outlet velocity profile was measured at the stack inlet on top of the absorber transition cone. The calculated inlet and outlet velocity profiles are in line with the measurements. Therefore, the modelling results for the standard load case are regarded as the verified basis for possible optimisations.

In the central area of the absorber, where the droplet concentration is lower because of the central suspension pipes, the gas flow turns upward. As a result, the gas flowing through the spray levels #1 and #2 is concentrated in the middle area of the absorber. This leads to low L/G values in the region of high gas volume flow. Simultaneously, a high liquid concentration is observed in the regions with low flow velocity. It may thus be concluded that the spray banks #1 and #2 contribute only partially to SO_2 absorption. In particular,

the situation directly above the gas entry is unfavourable. Upstream of spray level #2 the gas flow is distributed more uniformly over the cross section, so that a sufficient absorption through spray levels #3 to #6 can be assumed.

Modelling of the very complex chemical reactions inside the FGD is not satisfactory in commercial CFD code. Therefore, the SO_2 reduction efficiency is calculated with the Steinmüller Engineering FGD design program. The program has been developed using laboratory measurements and verified and further detailed at large-scale power station absorbers. The reliability and accuracy is much higher than with any physical model. The resulting overall efficiency in the standard load case shown above is 94.5 %. This value is in agreement with the respective values from the online emission monitoring system.

Flow optimisation options

Steinmüller Engineering use their well proven (e.g [2, 3]) advanced nozzle positioning (ANP) method to achieve the highest removal efficiency with the lowest impact on the existing system. The ANP procedure focuses on the bi-directional interaction of spray droplets and gas flow. During the iterative design, the influence of different spray nozzle positions and nozzle types on the gas flow distribution is evaluated. As a result, the optimal layout of each of the absorber spray banks is achieved.

The reason for the non-uniform flow distribution in the described absorber is the narrow clearance between the top of the flue gas inlet nozzle and the first spray level. It is not possible for the flue gas flow to distribute evenly within the short distance. Five different options for absorber optimisation – evaluated by using CFD simulation – were developed by Steinmüller Engineering. The different options and the simulation results are described in the following.

Option 1 – Installation of a tray

A typical tray consists of several tray elements with perforated bottoms. Figure 3 shows a single tray element. The primary purpose of the trays is to achieve uniform flue gas distribution across the absorber. Furthermore, the flue gas flows through the tray contacting slurry gathered in the tray. This effect increases the absorption efficiency. On the other hand, a tray causes an additional pressure drop on the gas side. Therefore, the available performance of the ID-fan should be considered before the tray technology can be successfully implemented.

Due to space constraints, the tray is located between the two lower spray banks (#1 and #2). The flow distribution is considerably more uniform in comparison to the current state. As expected, the calculated

pressure loss is higher than the current pressure loss of about 24.5 mbar. The increase of 20 % pressure loss with tray is approx. 30 mbar, which exceeds the current available ID fan capacity. Nevertheless, the tray option yields the best velocity profile and removal efficiency of all optimisation options, and therefore remains interesting for future modifications. To reduce the absorber pressure loss, spray levels would need to be switched off.

Option 2 – Installation of a partial tray

The intention of option 2 is to reduce the pressure losses when using tray technology. In this case, the tray covers only a part of the absorber cross section. The diameter of the tray equals to about 2/3 of the absorber diameter. The calculation results for option 2 show that the flow distribution inside the absorber is improved, but is less uniform compared to option 1. The additional pressure loss for option 2 of approximately 27 mbar 10 % would still be too high., which makes the implementation of this option difficult.

Option 3 – Adjustment of the spray nozzles at the lower levels

Option 3 uses other nozzle types in the centre of the lower spray levels #1 and #2. Instead of the double tangential nozzles, new single tangential nozzles are used, spraying only downwards (Figure 4). The intended effect of this modification is to increase the counter pressure in the middle section of the absorber. Consequently, the gas flow is forced to spread more uniformly over the absorber cross section.

In addition, the mass flow through the spray nozzles (spray levels #1 and #2) in the region above the gas inlet is reduced by 20 %. The remaining liquid mass flow is distributed uniformly to the remaining spray nozzles at levels #1 and #2 in order to keep the slurry mass flow per spray level unaffected.

The combination of the two described changes leads to a significant improvement of the flow distribution within the absorber. The pressure loss of 24.8 mbar is only slightly higher than at current operating conditions.

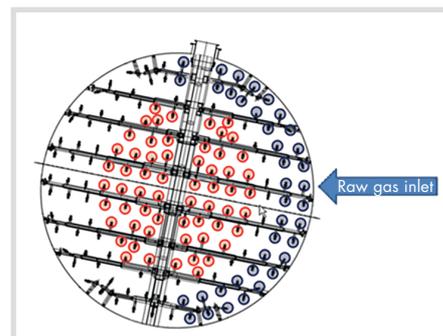


Figure 4. Modified spray nozzles on lower spray banks.

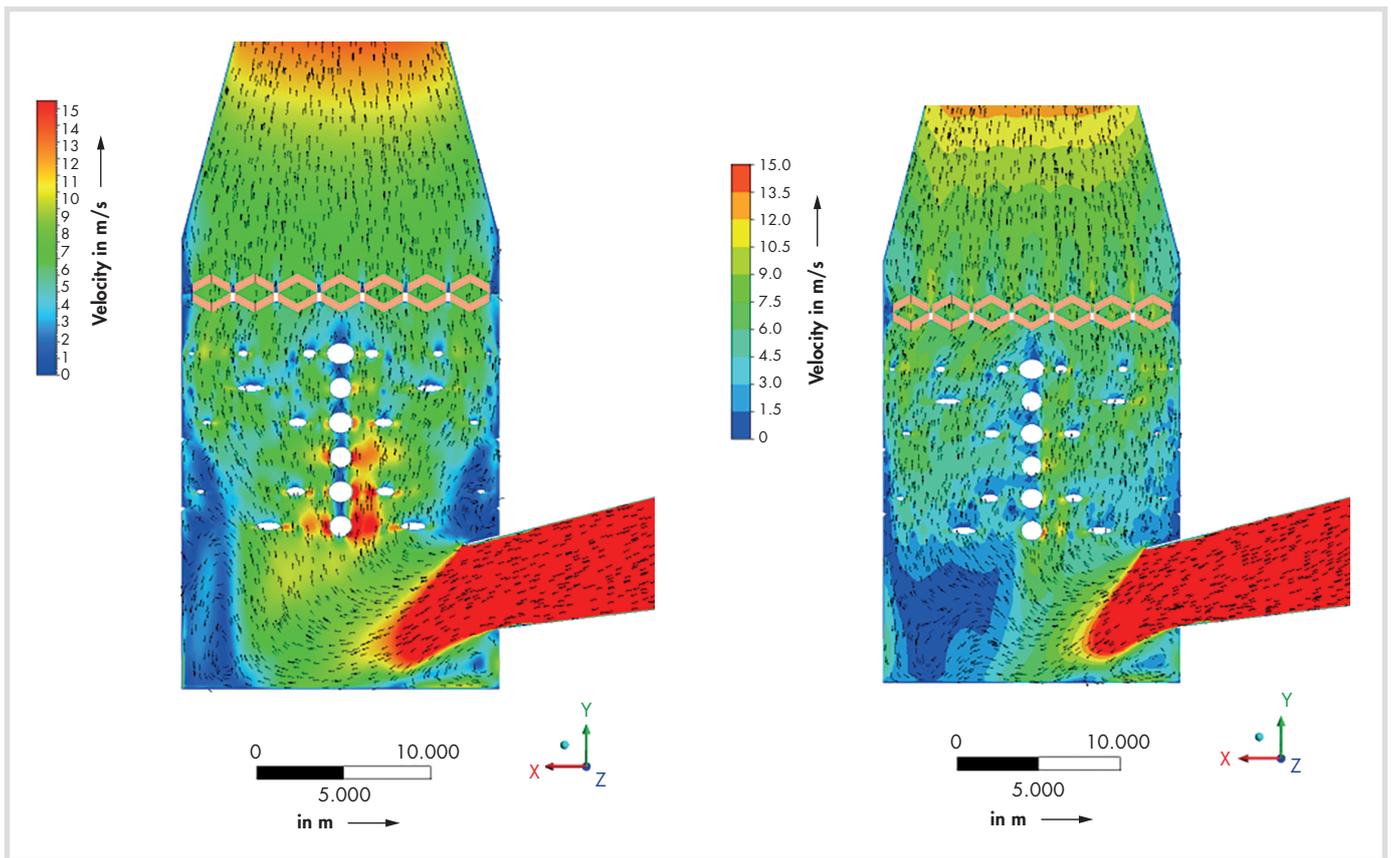


Figure 5. Standard load case before optimisation (left) vs. combination of option 3 and modified nozzles at spray banks #3 to #5 (right).

Option 4 – Adjustment of the spray nozzles at the upper levels

For Option 4, the existing double tangential spray nozzles at spray levels #3 to #5 are replaced with single hollow cone nozzles within the region above the gas inlet. With this measure, a higher impulse against the gas flow direction is generated which leads to a reduction of the gas flow through the critical absorber region, where the SO₂ peaks were observed. The results of the simulation for the combination of options 3 and 4 are presented in Figure 5. The standard load case before optimisation is shown for comparison.

Option 5 – Deflector plate downstream of the gas entry

Option 5 involves the installation of a deflector plate, which is placed in front of the gas inlet nozzle inside the absorber. The function of the deflector plate is to re-route a part of the raw gas towards the critical absorber area directly above the gas inlet nozzle. The resulting gas flow and slurry distribution is similar to the calculation results of option 3. However, the pressure loss through the deflector plate is about 5 % higher than the current operation condition.

Chosen option

The velocity distribution over spray levels #2 and #5 before optimisations was compared to the calculated velocity distribution for the optimisation options. The opti-

mised configurations yield a more uniform flow distribution. The combination of options 3 and 4 was chosen for the upgrade project. It offers a lower pressure loss than option 1. The predicted removal efficiency for the chosen option is approximately 96 %. This removal efficiency should be achievable as long as the plant operation is monitored carefully.

The modifications of the chosen option were transferred to the second absorber 34 (supplied by boiler units 3 and 4). The orientation of the absorber spray banks is the same but the inlet nozzle is mirrored. Therefore, the proposed modifications had to be simulated and evaluated separately. The achievable removal efficiency is also around 96 %.

Hydraulic assessment

The intention of this assessment is to check if the new design, developed with the above CFD calculations, can be operated with the existing pumps and spray level piping. The hydraulic conditions in the spray level piping were checked with a hydraulic calculation for each spray level.

On spray levels #1 and #2 three different nozzle types are in operation with the new design. The volume flow distribution on these spray levels must be checked.

Using the *Bernoulli* equation:

$$\Delta p = \frac{\rho u^2}{2} \left(\lambda \frac{l}{d} + \sum \zeta_i \right)$$

with Δp pressure difference [Pa],
 ρ density [kg/m³],
 u velocity [m/s],
 λ coefficient of friction [-],
 l length [m],
 d diameter [m],
 ζ pressure loss coefficient [-],

the pressure loss of the standpipe and of the spray level itself is calculated. Together with the geodetic pressure difference the overall pressure loss up to each nozzle can be calculated. This is done iteratively until the volume flow of the pump and of the nozzles is equal.

The current design works at the design point of the nozzles while the new design of spray level #1 and #2 operates with a system pressure slightly higher than the design case. The new design can be operated with the existing pumps. The higher system pressure of the nozzles results in a higher volume flow compared to the design point; this again results in smaller droplets. Smaller droplets have no negative effect on the absorber operation and might even improve the removal efficiency.

PP welding and stress calculation

The existing spray levels are made of polypropylene (PP). The nozzles are welded with a V-weld. Nozzle types need to be exchanged and relocated to obtain the higher removal efficiency. In some cases, transition pieces are necessary.

The strength of thermoplastic materials has two significant parameters beside the

Tab. 1. Maximum allowed stress at 65 °C after x years.

Years	Max. allowable stress at 65 °C			Welding type
	Pipe	Butt weld	V-weld	Welding factor
10	3.2	2.56	1.92	N/mm ²
15	2.8	2.24	1.68	N/mm ²
25	2.3	1.84	1.38	N/mm ²

Tab. 2. Safety factors for operating conditions.

Years	Operation condition			
	Butt weld		V-weld	
	dry	wet	dry	wet
10	2.6	1.9	2.0	1.1
15	2.3	1.7	1.7	1.0
25	1.9	1.4	1.4	0.9

Tab. 3. Safety factors for starting conditions.

Years	Starting condition (breakdown)			
	Butt weld		V-weld	
	dry	wet	dry	wet
10	2.1	1.5	1.6	0.9
15	1.8	1.3	1.4	0.8
25	1.5	1.1	1.1	0.7

chemical resistance. The first parameter is the operating temperature and the second is the stress duration. The operating temperature is the limiting factor because it has a higher influence on the operating time of the material. Figure 6 shows the creep rupture strength diagram for PP.

A higher temperature results in a lower life expectancy at constant load. After a certain operating time, the diagram shows a clear drop when the material significantly loses life expectancy. For PP at 65 °C this is approximately after 8 years. The strain of 4.2 N/mm² refers to original supplier's documentation. A safety factor of 2 is used for this kind of application (2.1 N/mm²). Table 1 shows the maximum allowable stress of PP depending on the welding type and operating time.

The PP material has the tendency to absorb water. At about 70 °C it can absorb up to 0.3% water. Table 2 shows the safety factor for operating conditions for butt welds and V-welds for different material conditions (dry or wet). Wet means that water has been absorbed into the material due to the operation time that the material has already experienced. A low safety factor corresponds to a bad welding connection. DIN EN 16965 and DVS 2205 state that a safety factor of 2.0 should be the base for piping constructions under operating conditions. Assuming a dry material, this safety factor can be met with the butt welding technique for an operation time of nearly 20 years.

The highlighted cell shows approximately the current value. The real existing values

depend on the quality of every single weld seam. Nevertheless, the chance of nozzle breaking is relative high, because the safety factor of 2 is not achieved. For starting conditions (breakdown) the safety factor should be 1.0 according to DIN EN 16965 and DVS 2205. This safety factor is obtained with the butt welding technique,

but not with V-welding (Table 3).

To evaluate the possible influence of the absorbed water and the welding type, additional mechanical tests were conducted. New PP pieces were welded to samples of the existing (aged) material. Blister formation was observed, indicating that a non-negligible amount of water had already been absorbed. The different welding methods can be seen in Figure 7.

Even if the butt welding seams seem to be less smooth from the outside, they have the advantage that fewer bubbles are captured in the welding area. During the V-welding procedure, the steam bubbles can neither escape downwards to the root nor upwards where they are being covered with welding material. Therefore, the connection to the base material cannot be ensured. During the butt welding procedure (pressing the pipe ends against each other) the steam bubbles are pressed out of the seam area. Subsequent bending stress tests confirmed that butt welds should be used for the new connections.

The achievable safety factors are higher if the butt welding technique is used. Assuming 0.3 % of water absorption, the safety factor is lower than required by European standards, but still sufficient for a safe operation for at least the next 12 years.

The result

In addition to the required reduction of the NO_x emission levels below the limit over the entire load range and the improvement of the desulphurisation rate, a boiler efficiency increase by almost 1 %

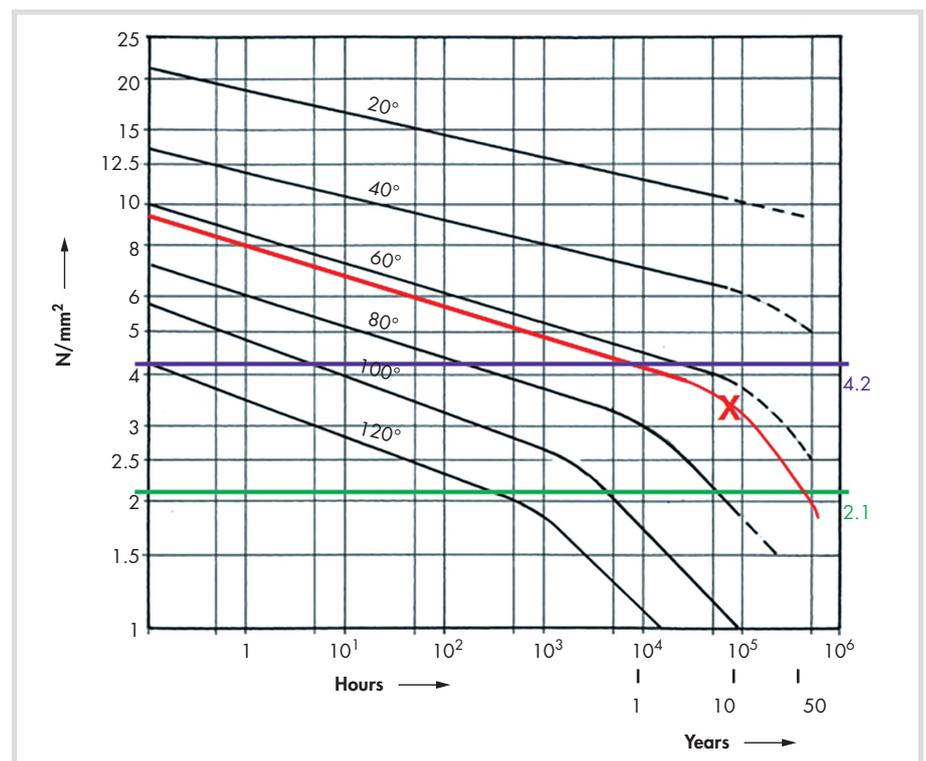


Figure 6. Creep rupture strength diagram for the power plant.

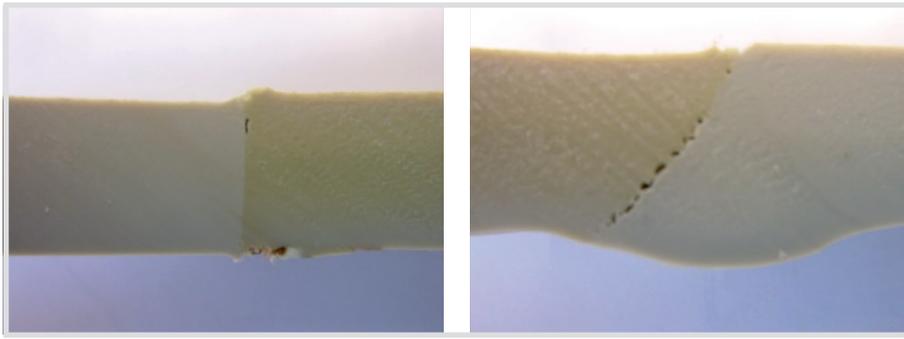


Figure 7. Butt welding seam cut: blister surface $< 10\%$ vs. V-welding seam cut: blister surface on the old material side $> 30\%$.

was achieved. At the same time, a more reliable protection against slagging and corrosion was provided by means of operating experience sharing and furnace wall atmosphere measures (Figure 8).

Currently three units at the TPP Maritsa East 3 have been successfully refurbished. The units are now operating with NO_x levels below the new limit and the fourth unit is being modified. The both FGDs were modernised in the first half of 2015.

TPP ContourGlobal Maritsa East 3 is the first lignite-fired power plant in the Balkans to be retrofitted to address the issue and successfully implement the measures to achieve NO_x emissions reduction below the 2016 limit, affirming ContourGlobal as power operator highly dedicated to environmental sustainability.

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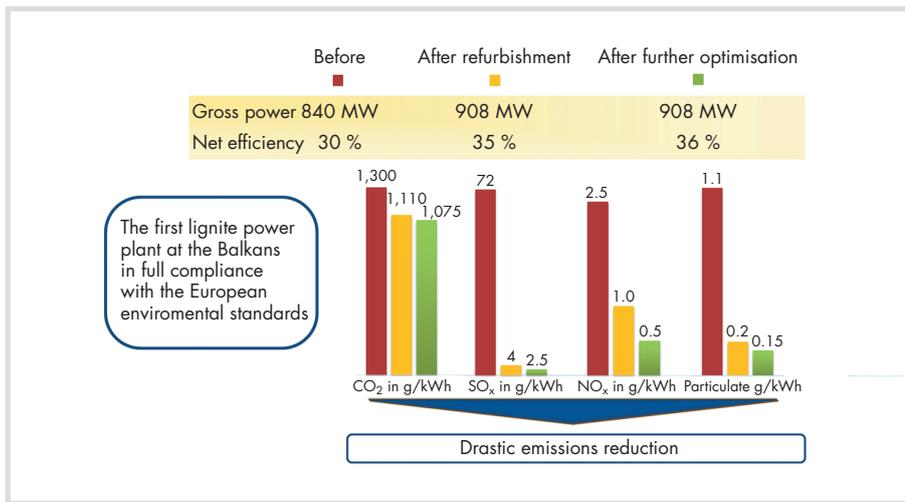


Figure 8. Success indicators – before and after.

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