Investigations of Cost-Effective ESP-Upgrade Measures for a Life-Time-Extension in a Grid-Stability Operating Scenario

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Abstract

The transition to renewable energy sources and the simultaneous phase-out of coal presents a significant challenge for grid stability. To ensure a secure energy supply, many aging coal-fired power plants are being repurposed as grid stability reserves. These plants must be ready to run at full capacity on short notice, potentially for only a few hours per year, while adhering to stringent environmental regulations. The Electrostatic Precipitator (ESP) is a critical component in meeting emission standards, often operating at its design limits. This paper examines a case study of an ESP plant in a German power plant built in the late 1960s, now transitioning into a grid-reserve role for the next seven years. The study involved a comprehensive analysis of operational conditions, mechanical and electrical status, and the implementation of cost-effective upgrade measures to extend the plant's lifespan and ensure compliance. The findings and methodology presented in this paper can be applied to similar plants worldwide, offering a modular approach to ESP upgrades that can be tailored to meet specific emission requirements.

Keywords: Industrial ESP, operating experience, case study, ESP operation and maintenance, ESP Upgrade, VI-Curves

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1. Introduction

The global shift towards renewable energy and the phase-out of coal have created an urgent need for grid stability. Aging coal-fired power plants are being called upon to serve as grid stability reserves, requiring them to be readily available for operation while complying with environmental regulations. The Electrostatic Precipitator (ESP) plays a crucial role in controlling emissions, but many ESPs in these older plants are operating at their design limits. This paper presents a case study of an ESP plant in a German power plant, exploring the challenges and solutions for extending its operational life and ensuring environmental compliance in a grid-reserve scenario.

2. The Case Study: A 56-Year-Old Power Plant

2.1 Specific requirements for the grid reserve

Picture 1 – Aerial view of Power Plant in Germany

The case study focuses on the last two operational 345 MW hard coal fired units in a German power plant built in the late 1960s, which is now transitioning into a grid-reserve role for the next seven years. The plant's ESPs have been in service for 56+ years and now face the challenge of meeting modern emission standards while operating under a new, mostly unpredictable load regime.

The expected operating hours can range from only 100-150 hours per year op to 1.000+ hours, with high likelihood for frequent start-ups and shutdowns.

The unit must meet its strict emission limits from the moment it begins operation with the annual average emission limit being as low as 8 mg/Nm^3. Due to the expected low total number of operating hours, there is little to no chance to compensate higher values especially since the daily average is only 10 mg/m^3.

Load will be dictated entirely by grid requirements, i.e., compensation of fluctuations from renewable energies. This will also mean, that the boiler plant will most probably never run in a steady state condition. However, another challenge is, that the operating staff needs to stay on their toes, as they cannot know when they will be called to action. To keep their skills in good shape, it is envisaged to run the plant regardless of a grid requirement at least for a short stint once every month.

In essence, the ESP plant needs maximum resilience against fluctuations, i.e. existing and yet to be found margins towards the emission limit need to be increased by enhancing process controllability and other technical and process optimization measures.

3. The Methodology: The “3P-360° Approach”

To address the challenges faced by the aging ESP plant, a comprehensive “3P-360°” analysis was conducted. The fancy acronym sounds kind of modern, but actually it encompasses the three key areas that have always been the areas to look at when investigating ESP performance issues.

3.1 Process

Often enough, especially the first “P” for “Process” is forgotten in the analysis and the ESP is blamed for not running according to specification – even when the source of the flue gas is operating way beyond to what it was designed for. In fact, this is the case for most vintage ESP plants in power generation which in Germany have been designed for domestic fuels and base load operation.

Therefore, this investigation involves a detailed examination of boiler operations, load regime, test and measurement data, fuel supply and quality, conditioning systems, and operational practices. It may be helpful to compare such actual operating data to original design data to explain some of the encountered performance issues.

3.2 Periphery

The layout and peripheral systems of a plant may have a significant impact on ESP operation and performance. However, it is difficult if not impossible to produce a universal list of all sensitive areas in all applications – key thing is, to have a watchful and experienced eye on everything, that potentially affects ESP inlet and operating conditions. Few examples to illustrate potential impact on ESP-performance follow.

In a power generation plant, rotational direction of air heaters, duct layout including splitting and diverting gas streams into separate flue gas ducts and ESP casings – have an impact on the distribution of each of the components of the two-phase mixture of flue gas and solids and will have consequences manifested in the ESP-performance.

Picture 2 - Boiler ash injection pipe

An example of a tiny, yet important detail is shown in picture 2. Often it is considered an easy solution to get rid of boiler ash e.g., from the second pass of a boiler by injecting the gas/ash-stream upstream of the ESP – not considering the quite different temperature and ash concentration compared to the main flow. Such injection can cause significant disturbance in the first field of an ESP, since due to the temperature difference a mixing effect and diffusion of the ash into the main gas stream will not happen. As the electrical field is only as good as its weakest spot, such streaks of colder and highly dust-laden gas will cause higher spark rates and a lower average voltage and consequently, lower ash collection. So when performing an inspection of ESP periphery, look out for strange pipework pointing towards the ESP – there could be unwanted surprises waiting at the end of the pipe…

High attention should also be paid on the condition of the ash extraction and transport systems, especially when those are working at a pressure higher than prevailing in the ESP. In this case, gas-tight double-flap-valves or rotary valves should be employed at least in the last field to avoid ash being carried out of the hopper into the clean gas duct bypassing the outlet ESP field.

3.3 Precipitator

Obviously, the ESP and all its components need to be in their best possible working condition, considering age and remaining lifetime. Also, any upgrade e.g., in new high-voltage systems is useless if mechanical clearances and tolerances of the electrode systems are beyond OEMs recommendations.

Therefore, the assessment of the mechanical and electrical condition of the systems serves to determine the necessary repairs to filter internals, casings, flue gas ducts, gas distribution equipment and peripherals (dust discharge, etc.). This also offers important insights for ongoing maintenance.

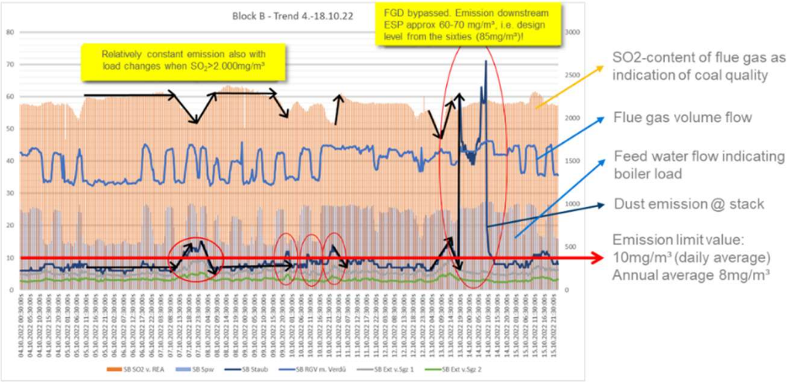
It is good practice, to record current and voltage characteristics before the inspection to identify fields that deviate from the expected electrical behavior. The analysis of such characteristics enables the experts to focus their inspection to those bus-sections, which showed a particularly weak electrical behavior thus helping the search for the root cause.

4. Key Findings and Challenges

The “3-P 360°” analysis revealed several key findings and challenges. They are all interrelated to each other but become more obvious and clearer especially regarding their root cause when looking at them from their point of origin, i.e., in one of the three areas process, periphery and precipitator.

4.1 The effect of process fluctuations

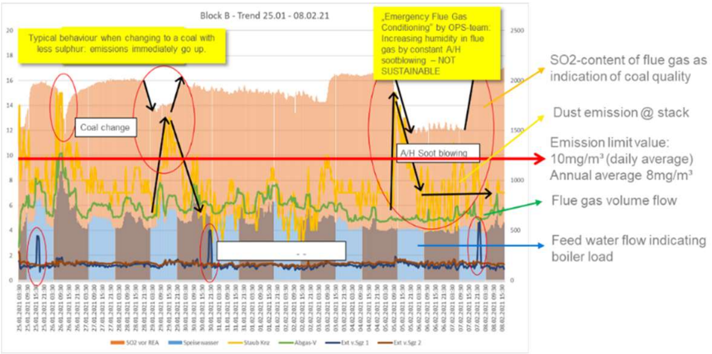
Analysis of a vast amount of data from taken from the plant control system revealed a strong sensitivity towards coal quality and boiler load. In the graph shown in picture 3 it becomes obvious, that as long as the SO_2-content of the flue gas is above 2.000 mg/m³, dust emissions are relatively stable even when load changes are carried out. However, once a different coal quality with less sulfur was fed, emissions at once increased above the daily average limit when load changes were requested at the same time. Since the existing ESP controllers are not able to automatically mitigate back corona, operators must react by switching back to a different coal stock with better coal.



Picture 3 - Process data showing influence of coal quality and FGD-effect

The role of the downstream wet Flue Gas Desulfurization (FGD) system is essential for meeting dust emission limits. When the FGD had to be bypassed due to operational issues, emissions at once went up to 60 – 70 mg/m³ which is approximately the original design level of the ESP-systems alone. Such operation is declared to be an emergency condition and is allowed and limited to occur only a few hours per year.

The uphill battle of the OPS-team can be seen on the next graph (picture 4). There are situations, when there is not alternative coal stock yard at hand when they need it. In those cases, their experience has taught them to deploy constant A/H soot blowing to increase humidity and so to improve ESP field strength.



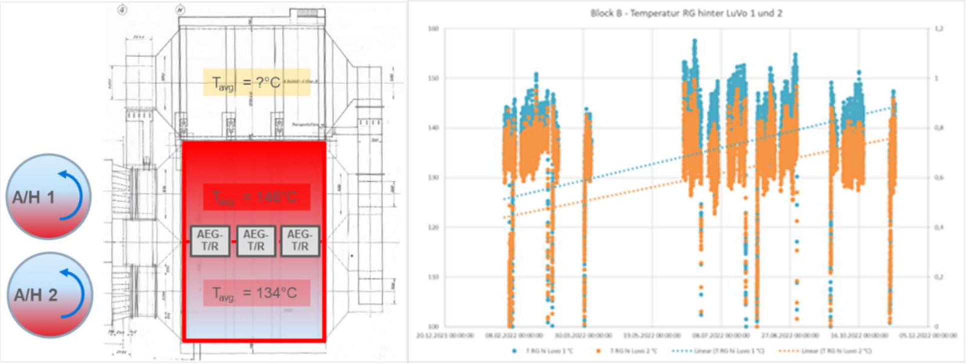
Picture 4 - "Emergency Flue gas Conditioning" by continuous A/H soot blowing

The effect of such “Emergency Flue Gas Conditioning” is quite amazing: Emissions can be brought down for a while until a better fuel is found on the stockyard or load must be reduced if no better is available. However, there are significant consequences for the A/H. Steam soot blowing in a continuous manner damages the heating surfaces which eventually will deteriorate A/H performance, which in turn has a negative effect on ESP performance when flue gas temperatures go up.

4.2 The effect of peripheral equipment

As discussed in the previous chapter, the A/Hs are sometimes crucial to save the daily average emission limit. Not quite what they are designed for, but the OPS team has to use every option available to manage the challenges of an ageing plant confronted with a fluctuating demand it was never designed for.

Deteriorating A/H condition will lead to a skewed temperature distribution which in turn will negatively affect ESP performance by influencing ash resistivity and flashover thresholds.



Picture 5 - Temperature distribution and inlet temperatures to Main ESP

Picture 5 and the corresponding graph show the variations of A/H outlet temperatures, which cause a significant temperature drop perpendicular to gas flow direction, i.e., across one bus section of the ESP.

Since there is only one voltage controller for each bus section, controllability of the rather large bus sections is relatively poor. Especially when lower sulfur coals are fired, it can be expected that this skewed temperature profile adds to the challenge by also producing an ash resistivity slope across the bus section.

Another potentially contagious peripheral detail is the ash handling of the boiler ash from the second pass. The pipe as shown before in picture 2 leads into the inlet area underneath the air heaters and is injected without any distribution device, just some wear protection sheets are welded to the duct walls – marks on the duct floor (picture 6) indicating a high ash concentration in this otherwise relatively small and colder gas stream. As mentioned in 3.2, we are likely to see some impact from such design of peripheral components – often conducted by engineers not aware of what’s happening in the next process step and thus creating unwanted effects.

Picture 6 - Boiler ash injection into inlet duct to Main ESP

It becomes clear, that because of the large size of the ESP bus sections, the condition and operating regime of peripheral equipment has a bigger impact than necessary. More insights will be given in the next chapter when we take a closer look at the ESP layout and design.

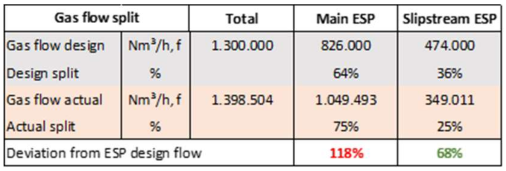
4.3 The effect of precipitator configuration and condition

The original boiler design was aiming at a delivery of 1.080 t/h of steam, which was revised to 1.200 t/h only few months later when construction was already underway. To cope with the increased volume flow, a Slipstream ESP was added in parallel to the Main ESP as only practical choice at the time.

4.3.1 Inlet/connecting duct design

Due to the limited space available in the layout, the routing of the connecting duct is particularly challenging. Extensive flow devices introduced directly downstream the air heaters designed to split the gas volume in a ratio of 64% for the Main ESP and 36 % for the Slipstream ESP have proven to be relatively effective regarding achieving separation of the gas volume. However, from ESP operating data and ash deposits in the ductwork it can be concluded, that existing maldistributions of temperature, ash load and streaks of both are prone to be frozen and carried through to both ESPs thus creating significant imbalance of those process parameters.

In a number of gas distribution tests at the inlet ductwork, it could be shown that the actual split of gas flow deviates from the design. Some measurements even showed a skew of +18% for the Main ESP with a correspondingly lower flow to the Slipstream ESP.

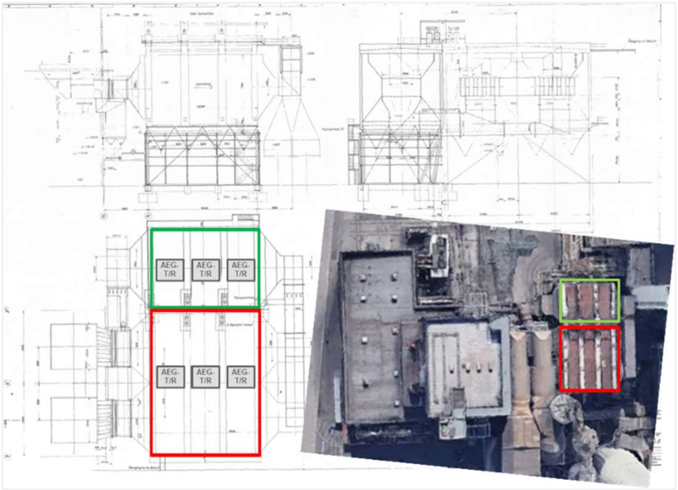


Gas flow split		Total	Main ESP	Slipstream ESP
Gas flow design	Nm³/h, f	1.300.000	826.000	474.000
Design split	%		64%	36%
Gas flow actual	Nm³/h, f	1.398.504	1.049.493	349.011
Actual split	%		75%	25%
Deviation from ESP design flow			118%	68%

Picture 7 - Design and actual gas flow balance

4.3.2 Electrical bus sections

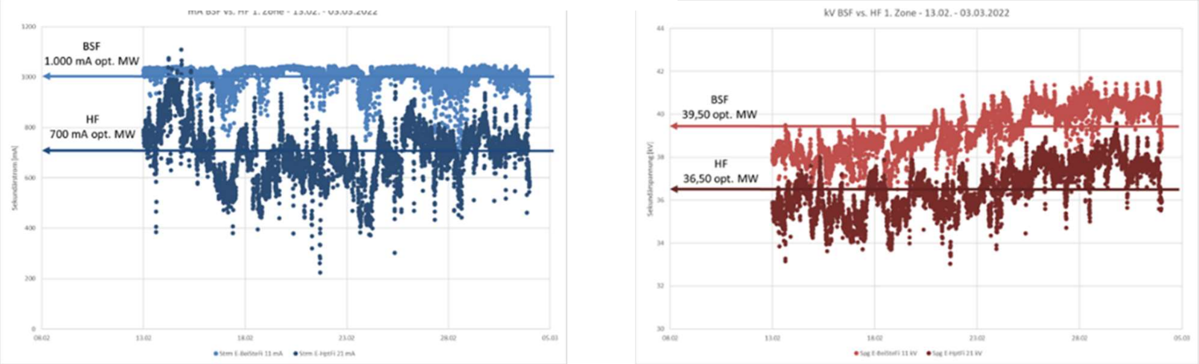
The electrical bus sections of the Main ESP are exceptionally large compared to industry practice – even at the time of construction in the late 60ties. It certainly made (economical) sense in the original plant design, also since a baseload operation with a symmetrical upstream duct design was originally planned. In the world of today, this layout proves to be the main challenge to cope with the actual operating conditions.



Picture 9 - layout of inlet ductwork and bus sections

Any disturbances, skews and streaks now have a massive impact on one third of the collecting area of the main ESP already running at 118% of its design flow, resulting in repeatedly reduced collection efficiency and a very fragile emission behavior.

Monitoring secondary voltage and current of the inlet field of both Main ESP and Slipstream ESP shows the different operating regime both ESPs are facing. If the gas splitting devices had been effective in creating an even distribution of all parameters, one should expect very similar readings of the electrical parameters. The graphs in picture 9 however give a different impression.



Picture 8 - Electrical operating data (mA – left graph, kV – right graph) of Main ESP vs. Slipstream ESP

The Slipstream ESP (BSF) runs at a significantly higher average secondary current with a significantly lower sparking rate compared to the Main ESP (HF), which seems to receive a higher particulate load with probably coarser distribution. Consequently, also secondary voltage is at lower values than the Slipstream ESP.

5. Available solutions and selected upgrade measures

From the analysis of the findings in all three areas process, periphery and precipitator and apart from mandatory maintenance and repair work of the ESPs, two potential areas of activity can be identified and need further investigation:

1. Bring gas flow balance back to design values and/or
2. Upgrade of the HV-systems, controllers and bus-sections of both ESP's

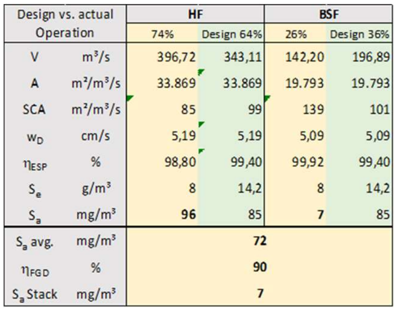
Both options could be employed either simultaneously or in a staged approach until the required emission behavior is achieved.

5.1 Base case: Modelling actual operating conditions

Starting point for the assessment of the improvement options is the design case at current process conditions, extrapolated to today's operation at higher flow rates.

With this base assumption, the results of the modelling shown in picture 10 mirrors today's actual behavior, i.e. emissions from the combined ESPs of approx. 72 mg/m³ - refer also to picture 3 with FGD in bypass operation. In combination with a FGD dust collection rate of approx. 90%, the resulting stack emission is approx. 7 mg/m³ under favorable and stable conditions.

Scope and expected effects will be discussed in the following chapters.



Design vs. actual Operation		HF		BSF	
		74%	Design 64%	26%	Design 36%
V	m^3/s	396,72	343,11	142,20	196,89
A	$m^2/m^3/s$	33.869	33.869	19.793	19.793
SCA	$m^2/m^3/s$	85	99	139	101
w_D	cm/s	5,19	5,19	5,09	5,09
η_{ESP}	%	98,80	99,40	99,92	99,40
S_e	g/m^3	8	14,2	8	14,2
S_a	mg/m^3	**96**	85	**7**	85
S_a avg.	mg/m^3	**72**			
η_{FGD}	%	**90**			
S_a Stack	mg/m^3	**7**			

Picture 10 - Comparison of design and modelling of actual operating case

5.2 Boiler Process and Operations Optimization

5.2.1 Coal quality

Because of the obvious impact of sulfur (and other components) in coal on ESP performance and emissions, a clear recommendation goes to coal purchasing. Since the unit will not operate anymore in a baseload scenario with huge quantities of coal burnt every day, but rather likely only few hours per year, more focus should be put on procuring a suitable blend that supports the specific needs of the plant and avoids load limitations due to coal quality issues. The blending would need to happen at the port since no sufficient space is available anymore on the plant site.

Benefits from being able to run at the load as requested will certainly outweigh procurement savings by far…

Picture 11 - Coal stock yard

5.2.2 Start-up and Shut-down operation

The boiler plant will see longer periods, i.e., several weeks of stand-by operation, which will result in the plant cooling down completely. Due to saving of auxiliary energy and of course for environmental reasons, it is not advisable to keep heating systems in operation for such extended periods of time.

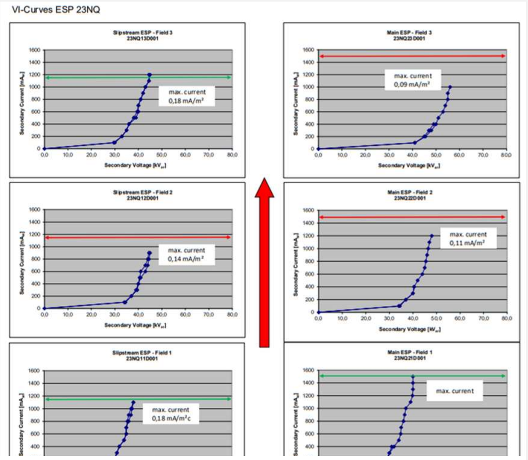
Therefore, specific procedures regarding operation of ESP rapping systems and ash transport need to be adopted to enable such standby periods without creating sticky ash deposits and serious clogging of ash transport systems.

Picture 12 - Ash deposits on collecting and discharge electrodes

When inspecting the ESPs in July this year after an extended period of standstill, both discharge and collecting electrodes were found to be covered with layers of hard and dry fly ash (picture 12). Hoppers were found to be reasonably emptied.

Voltage/current characteristics in picture 13 taken some while before the inspection under presumably similar cold air conditions indicate a very late corona onset which is due to the isolating nature of the ash cake enclosing the discharge wires [1].

However, the ash deposits were not susceptible to normal rapping operation, i.e., manual cleaning would be needed before the next start up. While manual cleaning using sand blasting or other rather rough methods are quite effective removing ash layers from the electrodes, they also bear the risk of significantly damaging electrodes if not handled with utmost care. Alternative methods using dry ice (solid carbon dioxide) should be investigated.



Picture 13 - Cold air V/I characteristics before ESP inspection

With the next start-up of the boiler with a clean ESP, only the first field should be energized for as long as oil-firing is in place. The potentially sticky oil soot will be precipitated in the inlet of the first field, which after switching to coal will be "naturally cleaned" by coarser ash entering the ESP. Only when coal mills are in service and emissions gradually go up and temperature is rising in the ESP, other fields should be energized.

On shut down, electrodes should be as clean as possible so all rapping systems should be switched to continuous e.g. one hour before shut down in order to have as little as possible deposits remaining on the electrodes, which eventually would form hard-to-remove layers once air humidity is entering the ESP during standstill.

5.3 Mechanical repair work

It goes without saying (really?): the mechanical condition and alignment of electrodes needs to be absolutely in order! Otherwise, any upgrades of electrical equipment such as controllers and modern T/R-sets will not perform to the best of their abilities and limit if not hinder success of the retrofit.

Picture 14 - Misalignments in electrode system

Such repairs should be part of any normal maintenance routine. Apart of the exchange of exhausted wear parts in rapping systems, door seals, cracked insulators, worn gas distribution screens and baffle plates etc. that includes especially realignment of electrode systems to ensure maximum voltage and field strength can be achieved in operation. This is the more critical, the smaller duct spacing is. The same 10 mm deviation have a much larger impact at 250mm spacing compared to the same tolerance in a 400mm spacing ESP.

Picture 14 show examples of unacceptable deviations from the center line that need to be corrected.

5.4 Gas Flow Distribution

In this specific case study, gas flow distribution outside the ESP is in the focus due to the deviation of volume flows between the casings compared to the intended design. One can assume that the standard design of the internal gas distribution screens in this particular ESP is sufficient to achieve an even distribution inside the casing, if their condition is without any holes or other damages.

A Computational Fluid Dynamics (CFD) analysis of the inlet flow towards the ESPs will be helpful to determine the design of suitable flow correction devices that will bring the balance of flow back to design values. Although an obvious solution, this option involves major redesign of flow distribution internals and addition of a potentially significant flow resistance into or up-/downstream the main ESP.

A number of gas flow tests have also been performed to determine, whether the imbalance is stable across the load range and if it is the same in both units to be prepared for grid reserve. The conclusion was that the imbalance is existing, however has not been found to be as strong in two measurements following the first one dated 2013 shown in table 7. Considering that once flow devices have been put into the duct are fixed and not adaptable during operation, the recommendation is not to go ahead with such option. Alternatively, installing control valves downstream the outlet hoods of the Main ESP would be too expensive and too complicated to install due to space constraints [2].

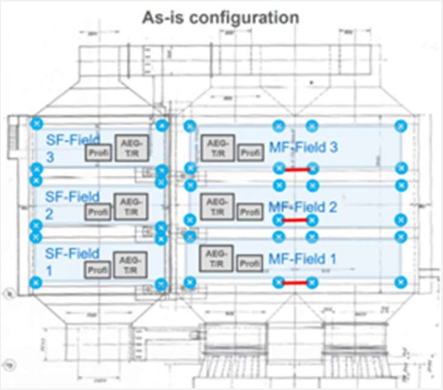
5.5 ESP Controller and HV-Supply Upgrade

For the reason outlined in 5.4, the focus is on electrical upgrade options. They are very promising due to the fact, that there has never been any significant upgrade done on the ESPs since their commissioning in the early seventies.

5.5.1 Increasing number of bus-sections

The ESP design offers a comparatively straightforward way to increase the number of bus-sections. For construction reasons and due to the structural design of the supporting system of the internals, the 96 gas ducts were split into two separate discharge systems, which are connected by one simple copper rod in the roof beam (picture 15). Removing the rod already now allowed the operations team to isolate one half of the field in case of persisting short circuits or other failures inside the casing, which otherwise would have led to the failure of one complete field, i.e., one third of the total collecting area of the Main ESP.

The size of the bus sections of the main ESP is 11,290m², which is considerably larger than a recommended size of max. 4,800m² for good operating and control behavior. By dividing the bus sections to 5,645m² and of course adding new HV-equipment to the newly created bus sections, a significant improvement of the resilience of the ESP against imbalances coming from air heaters in poor condition or ash streaks from the boiler ash injection can be expected.

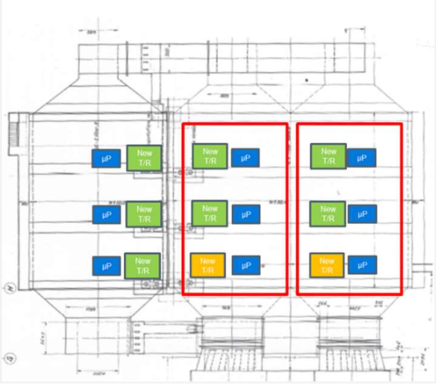


Picture 15 - Original design and layout of bus sections

5.5.2 New high-voltage (HV) technologies

Both ESPs will receive completely new HV-equipment including transformer-rectifier (T/R) sets, voltage controllers and rapping control integration. New HV technologies in the first field, i.e., 3-phase or SMPS HV units will significantly increase the power input into the field and thus significantly improve the separation overcoming the limitations currently met due to excessive spark rates (see picture 9).

New T/R-sets for the Slipstream ESP and fields 2 and 3 of the Main ESP will deal with potential ash resistivity issues, which the current equipment is not able to do. Apart from that critical feature, all new digital controllers will enable better and faster response and control under fluctuating conditions.



Picture 16 - New layout with added bus sections and HV-equipment

5.6 Other potential upgrade measures

The performance calculation will show that with the options discussed above the required emission safety margins of the ESP plant can be achieved. Therefore, further available upgrade options are not considered necessary. Due to the nature of the planned operation as grid reserve and limited lifetime of approx. seven years, any major rebuild is not considered practical and economically feasible. Thus, an ESP enlargement, ESP-to-Fabric Filter conversion or even new technologies as Hybrid Filters are not discussed in this project.

5.6.1. One remark about Flue Gas Conditioning

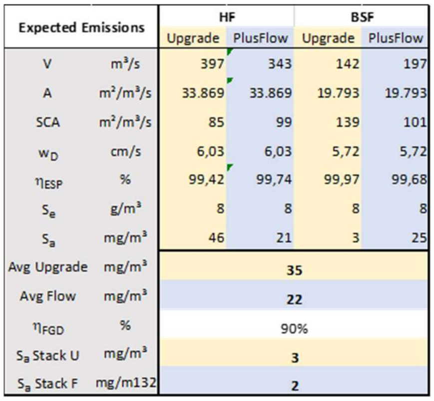
However, why has Flue Gas Conditioning - being a quite popular, cost effective and quick fix choice - not been considered here? For one, high ash resistivity is not always an issue in this plant because of the broad coal range used. But the main reason is, that for an optimal use of FGC systems, injection and distribution of the conditioning agent needs treatment time and suitable flow conditions. Both is not available in the layout of the plant. There is literally no straight inlet duct towards the Main ESP which would be the one needing a performance boost the most.

Some FGC does work also here, though. In the process data graph 4, the influence of moisture conditioning is clearly visible: when the ops team deploy soot blowers in the air heaters in continuous mode as a last resort for a short period, emissions go down significantly. The rotating air heaters provide excellent mixing and homogenous distribution of the water vapor which brings temperature and volume flow down plus increases flash-over voltage of the flue gas thus enabling higher power input and lower emissions.

6. Conclusions

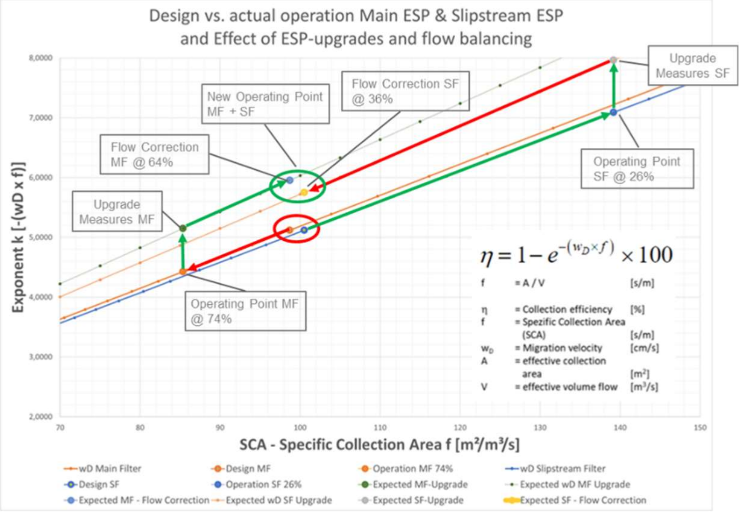
The original design of the emission downstream ESP in 1967 was 85mg/m³, of course without downstream FGD system. When the FGD was retrofitted in the eighties, it also contributed to the particulate emission reduction, where statutory limits had been tightened compared to the original design. However, the FGD dust collection estimated and confirmed from experience at 90% helped to still be compliant without any modifications on the ESPs for many years to come.

Even today, under stable operating conditions and without any disturbances in the ESP, emissions are even below today's stringent levels of 10 mg/m³. However, the plant has no technical margins left and the ability of the FGD to absorb more ash is limited, too.



Expected Emissions		HF		BSF	
		Upgrade	PlusFlow	Upgrade	PlusFlow
V	m³/s	397	343	142	197
A	m²/m³/s	33.869	33.869	19.793	19.793
SCA	m²/m³/s	85	99	139	101
w_D	cm/s	6,03	6,03	5,72	5,72
η_{ESP}	%	99,42	99,74	99,97	99,68
S_e	g/m³	8	8	8	8
S_a	mg/m³	46	21	3	25
Avg Upgrade	mg/m³	35			
Avg Flow	mg/m³	22			
η_{FGD}	%	90%			
S_a Stack U	mg/m³	3			
S_a Stack F	mg/m132	2			

Picture 17 - Expected emissions with and without gas flow correction



Picture 18 - Design calculations in Deutsch-diagram

From the design calculations shown in picture 17, we can see that the expected improvement of ESP performance with upgrade measures as described in chapter 5 should be sufficient to achieve a margin large enough to cope with fluctuations encountered so far. The graph of the Deutsch-equation in picture 18 shows the effect broken down to each upgrade measure. In total, all measures selected will result in a fairly large margin which should allow the plant to operate safely below the statutory limits.

Additional correction of the gas flow would result only in an added benefit of only 1 mg/m³ at the stack – not worth the risk and effort.

6.1 Some thoughts on guarantees

With the future operating regime totally at random depending on grid demand – i.e., the weather and other external factors -, operators will need to focus on running the plant in the most effective way to ensure grid stability without having to concentrate on emission excursions. However, collaboration between operations, maintenance, fuel management and OEMs are essential for success.

When inviting OEMs to bid for a job like this, it should be noted and understood, that this is not a standard design and sizing process for a new ESP plant. Understandably, OEMs will not be in a position to take any process guarantees due to the unpredictability of operating conditions, the uncertainties in the condition and technical integrity of a foreign vintage ESP design and many other real-life external influences. Let alone the relatively limited value of their equipment compared to a new ESP plant brought in will not provide enough financial margin to cater for any substantial “make-good” exercise. The best scenario therefore is a trustful and transparent collaboration on figuring out the actual potential of the existing assets – potentially also using neutral experts for a second opinion - without expecting any miracles from a plant at the end of its operational lifetime.

Keeping that in mind, the project demonstrates that even vintage ESP plants can be expected to achieve significant emission reductions through careful analysis and targeted upgrades. By adopting a proactive and integrated approach as suggested in this paper, power plant owners & operators can ensure the continued viability of their assets, supporting grid stability and environmental compliance during the transition to a carbon-free future.

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