TAMPEREEN TEKNILLINEN YLIOPISTO
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COST OPTIMIZATION METHODS FOR FLUIDIZED BED BOILERS

Master of Science Thesis

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TIIVISTELMÄ

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Tässä diplomityössä tutkittiin leijukerroskattiloiden käyttökustannusrakennetta ja menetelmää tämän rakenteen optimointiin. Työssä esitellään koko kattilan käyttökustannusrakenne, sekä tarkastellaan erilaisia lähtökohtia rakenteen optimointiin. Tutkimuksessa käytettäväksi menetelmäksi valittiin nuohoussyklin optimointi, koska se on teknisistä lähtökohdista soveltuva kohde optimointiin ja sillä on suoraviivaiset yhteydet leijukerroskattilan kustannusrakenteeseen. Työssä keskityttiin leijukerroskattiloiden yleisempään muotoon, kiertoleijukattilaan, mutta teoria ja tutkitut menetelmät soveltuvat pääosin myös kuplivaan leijukerroskattilaan.

Työn tavoitteina oli tunnistaa mistä tekijöistä leijukerroskattiloiden käyttökustannusrakenne koostuu, tunnistaa kustannusnäkökulmasta tärkeimmät prosessi-indikaattorit sekä tutkia nuohoussyklin optimoinnin vaikutusta käyttökustannusrakenteeseen.

Diplomityö jakaantuu teoria- ja laskennalliseen osioihin. Teoriaosassa esitellään kattavasti teknillistaloudellinen tausta kiertoleijukattilatekniikkaan, mukaanlukien kiertoleijukattiloiden kustannusrakenne. Omana osionaan esitellään prosessi-indikaattorien teoria ja optimoinnin menetelmiä sekä referenssejä tämän hetken tieteellisen tutkimuksen tasosta liittyen nuohoussyklin optimointiin.

Työn metodologia-osiossa esitellään kehitetty menetelmä nuohoussyklin optimointiin. Menetelmää sovellettiin kuudelle eri voimalaitokselle, joiden historiadatasta laskettiin kustannusmielessä optimaaliset nuohoussyklit perustuen savukaasuhäviöiden käyttäytymiseen nuohoussyklien välillä. Tulokset selkeästi osoittavat, että voimalaitosten operaattorit operoivat nuohousta liian tiheään, sillä kaikissa tapauksissa lasketut kustannusmielessä optimaaliset nuohoussyklit olivat pidempiä kuin keskimäärin käytetyt syklit. Optimoinnilla saavutetut laskennalliset säästöt olivat vuositasolla 200:sta 12 800:een tonnia polttoainetta. Tulokset selkeästi osoittavat nuohoussyklin optimoinnin olevan validi keino kustannusoptimointiin leijukerroskattiloissa.

ABSTRACT

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In this Master of Science thesis, the operational cost structure and a method to optimize this structure are studied. The whole operational cost structure and different basis for optimization are presented. Optimization of the soot-blowing cycle was chosen as the studied method as it is a feasible target for optimization from technical point of view and it is linked to the cost structure in a straightforward manner. This thesis of focused on the most common form of fluidized bed boilers, circulating fluidized bed boilers, but the theory and studied method are for the most parts also applicable to bubbling fluidized bed boilers.

Research targets of this thesis were to identify factors that form the operational cost structure of a circulating fluidized bed boiler, to identify the most critical Key Performance Indicators from cost point of view and to study the feasibility of soot-blowing optimization as a cost optimization method.

This thesis is divided into theoretical and computational parts. In the theoretical part the techno-economic background of circulating fluidized bed boiler technology is introduced, including the operational cost structure of circulating fluidized bed boilers. Theory of Key Performance Indicators and state of the art references regarding soot-blowing optimization are presented in their own Sections.

In the computational part the developed method for soot-blowing optimization is presented. This method was applied to six different power plants and the most cost optimal soot-blowing cycles for these power plants were calculated from history data based on the behavior of flue gas losses between soot-blowing cycles. The results clearly indicate, that power plant operators initiate soot-blowing cycles too often as in all inspected cases the calculated optimal cycles were longer than the cycles that were used on average. The calculated potential savings on a yearly level varied from 200 to 12 800 tons of fuel. These results clearly indicate, that soot-blowing optimization is a feasible cost optimization method in fluidized bed boilers.

PREFACE

This Master's Thesis was concluded in R&D Department of Sumitomo SHI FW Energia OY in Varkaus Finland during time from May to November in 2018.

Firstly, I would like to thank my supervisor University Lecturer Henrik Tolvanen for guiding me throughout the writing process. Your insight on how to process and represent information has made me a better writer and researcher. Thank you also for pushing me to the limit to ensure best possible performance and outcome.

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Finally, the greatest thanks I owe to my loved one, Anna. I would not have gotten where I am today without you. This accomplishment and all my future accomplishments are possible because of the love and support you have given me throughout our time together.

In Varkaus, 19.11.2018

Jussi Hujanen

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ABBREVIATIONS

ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
e-KPI	Energy based Key Performance Indicator
FB	Fluidized Bed
FEGT	Furnace Exit Gas Temperature
FI	Fouling Index
FLES	Fuzzy Logic Expert System
GA	Genetic Algorithm
GSHP	Ground Source Heat Pump
HHV	Higher Heating Value
KPI	Key Performance Indicator
LHV	Lower Heating Value
NN	Neural Network
NN-ISB	Neural Network based Intelligent Soot-Blowing
PA	Primary Air
PC	Pulverized Coal
PGU	Power Generating Unit
RC	Rankine Cycle
RDF	Refuse Derived Fuel
SA	Secondary Air
TES	Thermal Energy Storage

SYMBOLS

$\alpha_{conduction}$	Conduction heat transfer coefficient	[W/m^{2}K]
$\alpha_{convection}$	Convective heat transfer coefficient	[W/m^{2}K]
$\alpha_{radiation}$	Radiation heat transfer coefficient	[W/m^{2}K]
φ_{x-y}	Heat transfer rate over process states x and y	[MW]
ΔT	Temperature difference	[K]
A	Area	[m^2]
$Cost_{total}$	Total cost of the inspected unit or process	[€]
$C_{fuel,unit}$	Unit price of a fuel	[€/kg]
h_x	Enthalpy in process state x	[kJ/kg]
$\dot{m}_x$	Mass flow in process state x	[kg/s]
$t_{operation}$	Operation time of the inspected unit or process	[h]
U	Overall heat transfer coefficient	[W/m^{2}K]

1. INTRODUCTION

Fluidized bed (FB) boiler technology entered commercial markets for the first time in the 1970s [1]. This thesis will focus on the commercially most relevant form of fluidized bed technology, circulating fluidized bed (CFB) technology. Current energy market demands efficiency and flexibility and at the same time even stricter emission limits must be met. Therefore, CFB boilers are gaining market share from more traditional alternatives, such as pulverized coal (PC) boilers, as CFB boilers are chosen for their better fuel flexibility, lower emissions and economic reasons [2, 3].

Nowadays CFB boilers from established manufacturers are technically relatively similar and these companies have historically dominated the CFB boiler market. Recently new manufacturers especially from China and India are catching up in technology as coal is a major source of energy in those areas. Especially Chinese have invested a lot of resources into the development of CFB technology. A review of the current state and progress of research and development work regarding CFB coal combustion technology in China was concluded in 2017 by Yue et al [4]. These Chinese and Indian manufacturers are starting to expand to foreign markets and have been starting to gain more market share in the previous years [2]. This creates a very competitive and diverse market situation and boiler manufacturers are starting to compete more and more with additional services such as digital optimization tools. This is done not only to differentiate from their competitors but also to serve their existing customers better.

The purpose of this thesis is to find and develop methods for cost optimization in a CFB boiler which can later be applied to a digital platform. Even though this thesis is focused on CFB boiler technology, the developed methods should also be applicable to bubbling fluidized bed (BFB) boilers. The whole CFB boiler island in too large of a concept to be optimized in one thesis, hence the scope of this thesis was narrowed to soot blowing optimization in the convective part of the CFB boiler. Even though the scope is narrowed to a single method this thesis still aims to provide enough information to work as a baseline for full boiler island optimization. The restriction to soot-blowing optimization is a justified restriction as fouling is a widely identified problem in all boiler types and multiple studies regarding fouling can be found [5-7]. Fouling also has straightforward connections to the operating cost structure of the boiler, as it weakens the heat transfer in the heat transfer surfaces and thus lowers the operating efficiency of the boiler. Fouling is even more prominent problem with boilers that fire biomass and the share of biomass as fuel is expected to rise in the near future, as can be seen from Figure 5. Hence this problem and finding cost effective solutions to it is a subject with great importance also in the future.

Soot blowing is the technological solution to fouling and it is a widely used and known technology. Typically soot-blowers operate with steam and this means, that operating soot-blowers requires typically additional fuel consumption to produce the additional required steam. Therefore soot-blowing optimization has also an environmental aspect, as avoiding excessive fuel consumption would mean smaller CO_2 emission. This is extremely important aspect considering the recent climate policy studies, that clearly demonstrate the need for even stricter emission limits. As soot-blowing is an established technology, several commercial systems for soot blowing optimization are already available [8, 9]. Multiple scientific studies that represent the state of the art of soot blowing optimization can also be found [10-12].

The required modelling work and soot-blowing optimization is concluded with Matlab and Excel in the research part of thesis. The theoretical part of thesis covers the whole concept of developing methods for cost optimization. This includes identifying the overall variable cost structure of the CFB boiler and the most critical Key performance indicators (KPI) from a cost point of view. Even though the fouling index (FI) and flue gas losses were chosen as KPIs of interest in this thesis, other possibilities also exist. Studies that aim to optimize the cost structure of a CFB boiler from another point of view are for example the following:[13, 14] Some of the results of these studies are used for benchmarking the results gained with soot-blowing optimization in this thesis.

Then main research target of this thesis can then be defined as answering to the following research questions:

- *Which factors form the operational cost structure of a CFB boiler?*
- *What are the most critical Key performance indicators of a CFB boiler from operational cost point of view?*
- *Can soot-blowing optimization be proven to be suitable for cost optimization?*
- *How large monetary savings can be achieved with soot-blowing optimization?*

The theoretical part begins from Chapter 2 which introduces the techno-economic background for this thesis. This chapter begins with a brief overlook on the market share of CFB and trends regarding CFB boilers and the fuel types of CFB boilers in Chapter 2.1. This is followed with an introduction to CFB boilers and its parts and their properties on a general level in Chapter 2.2.1. After that a closer look into the theory of heat transfer in CFB boilers and the theory of slacking and fouling in a CFB boilers can be found in Chapters 2.2.2-2.2.3. In the following Chapter 2.3, the operating cost structure of a CFB boiler is introduced. This chapter also aims to answer to the first research question. Finally, the control variables and their effects on a CFB boiler are presented in Chapter 2.4.

Chapter 3 includes the theory of Key performance indicators and references about the state of the art of KPI monitoring in industry applications. This chapter also considers how they can be applied in a power plant environment and aims to identify the most critical KPIs of CFB boiler island from a cost point of view. Hence this chapter aims to answer to the second research question

Theoretical part of this thesis ends in Chapter 4, where the suitable mathematical and numerical methods and tools for the chosen optimization problem are considered. This section also includes references of different optimization problems related to power plants and especially references of soot blowing optimization methods.

Development of the soot blowing optimization tool and methodology and technical framework for this optimization problem are explained in detail in Chapter 5. The results and future applications are discussed in Chapter 6. This thesis then ends with conclusions in Chapter 7.

2. TECHNO-ECONOMIC BACKGROUND

To be able to build accurate and functional models and tools for cost optimization the techno-economic background of the subject at hand should be considered thoroughly. This Section aims to cover the whole techno-economic background including the driving market forces and trends, fundamentals of CFB boiler technology, the cost structure of CFB boilers and the control variables of CFB boilers. Chapter 2.3 also aims to answer to the first research question: *Which factors form the operational cost structure of a CFB?*

2.1 CFB Market share and trends

For successful operation as business, it is crucial to understand the market situation and trends. These market forces are also the reason that drives companies to develop new applications and features, such has optimization tools. Also, for the development work of such tools, it is beneficial to understand the market situation, as this helps to understand the customers' needs better. Then more suitable and functional tools can be developed. In this chapter a closer look into CFB technology from market point of view is taken and trends for different fuel types and boilers sizes are inspected closer.

CFB is newer technology compared to the more traditional PC boiler technology and because of that PC boiler have dominated the coal-based boiler market in the history. As older coal-based power plants come to the end of their life cycle, they are usually replaced with more modern power production choices, that vary depending on the market area. Current trend in more developed areas, such as Europe, is that coal-based power is replaced with renewable energy sources like solar or wind power.[15] There are still large developing market areas, especially in Asia, where combustion is the most economical choice of technology. Currently especially China and South-Korea are investing in combustion technology and in these areas CFB boilers are gaining market share from PC boilers in a rapid rate. Currently in China there are 150 CFB units within range of 100-150 MWe, 12 units in the 300 MWe class and 50 new projects in the planning phase. These currently operating CFB units in China account for 10 percent of the country's coal-based power. On a global level, according to International Energy Agency data, CFB technology accounts for two percent of the world's total power generating capacity.[2]

Predicting the future is a difficult and inexact task and results of projected market shares can vary depending on the sources used. Transparency Market Research has estimated that the global CFB market is expected to reach Compound Annual Growth Rate of 11,25 percent between 2015 and 2023. Same market study estimated that the installed capacity of CFB boilers is expected to increase from 92,0 GWe in 2014 to 241,9 GWe by the end of 2023.[3] Same type of rising trend can be seen in Figure 1, which is based on internal sources of Sumitomo SHI FW. Data that this figure is based on excludes Chinese markets, as they are dominated by domestic boiler manufacturers. Figure 3 clearly shows how CFB boilers are gaining market share in the coal market in an accelerating rate also in the traditional developed markets.

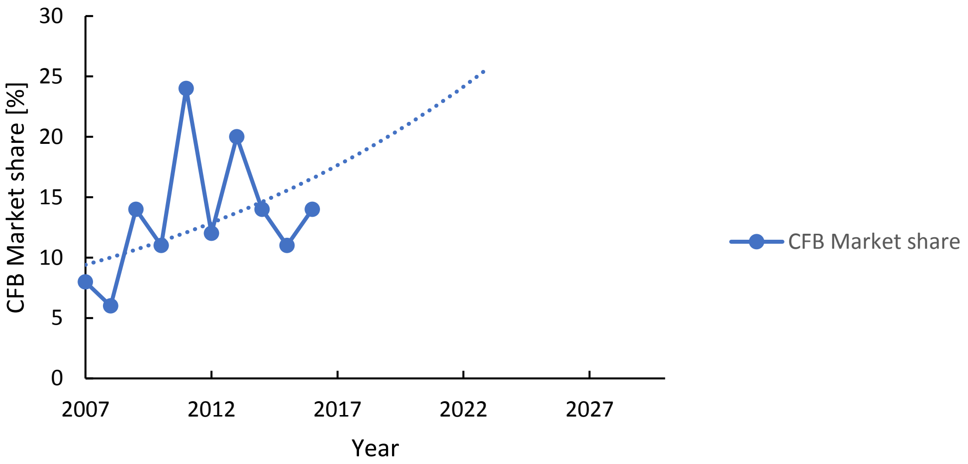


Figure 1. CFB boiler former and projected market share of the coal-based boiler market. Data excludes China. Adapted from a presentation by Sumitomo SHI FW.

The variation in the market share is due to dynamic nature of the market; older boilers are replaced with newer ones that are typically larger in capacity, therefore on a yearly level the market share can vary depending on size of PC and CFB boilers that were started up and decommissioned during that year. CFB technology is still progressing as new research and development work is done by manufacturers and CFB-based power plants with larger power outputs enter the market. This trend can be seen from Figure 2, which demonstrates the increase of power output of boilers that are manufactured by Sumitomo SHI FW. As Sumitomo SHI FW is a market leader in CFB boilers with a market share as high as 40 percent, it is reasonable to assume that similar trends can be found throughout the CFB boiler industry.

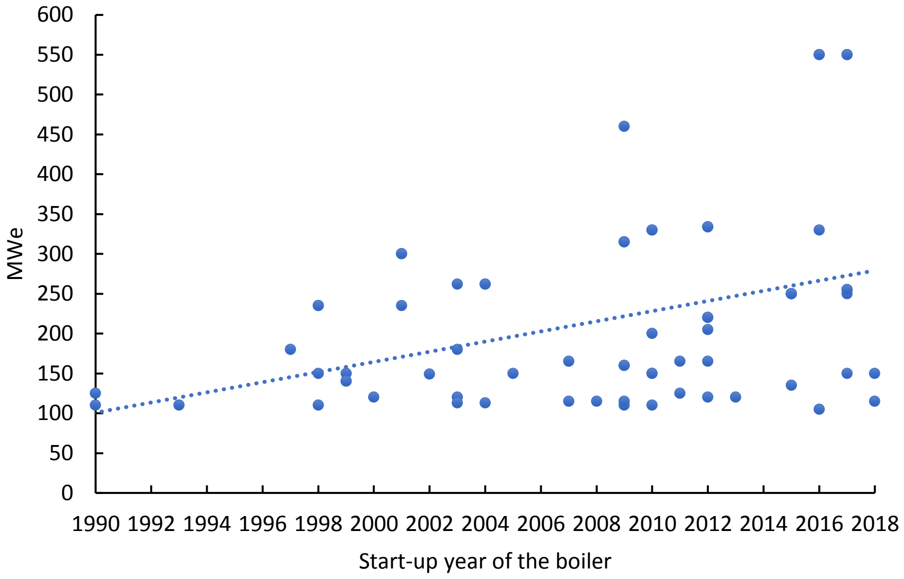


Figure 2. *Capacity of all CFB boilers over 100 MWe manufactured by Sumitomo SHI FW.*

A closer look into the subject reveals, that these rising trends in increase of power output of boilers can be found for both boilers, that fire mainly coal and boilers that fire only biomass and waste. This information is presented in Figure 3 and Figure 4.

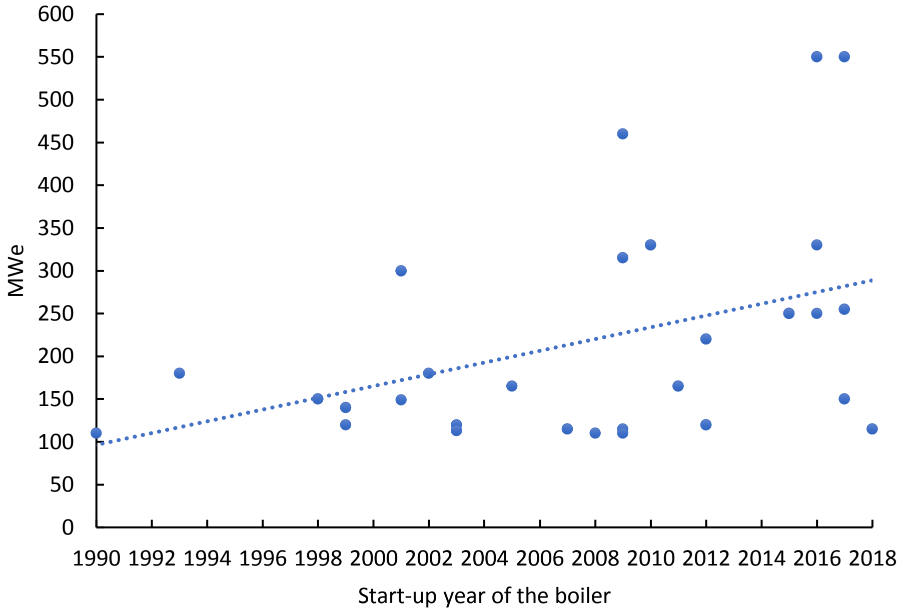


Figure 3. *Capacity of all coal-based CFB boilers over 100 MWe manufactured by Sumitomo SHI FW.*

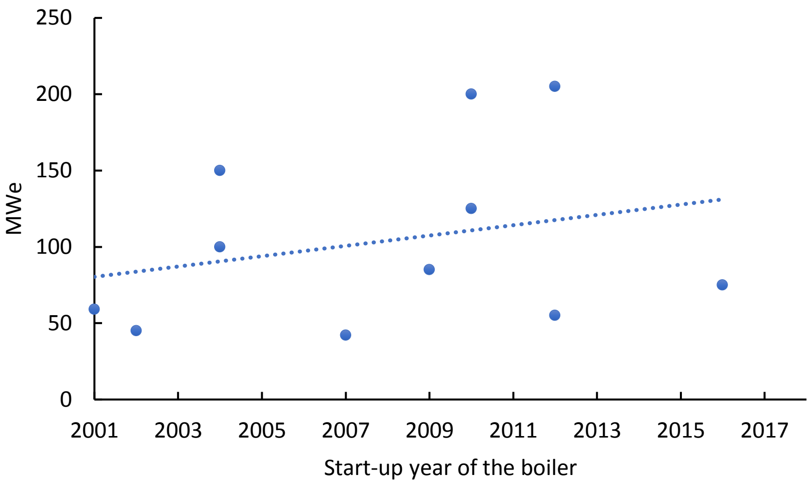


Figure 4. *Capacity of all biomass and waste-based CFB boilers over 40 MWe manufactured by Sumitomo SHI FW.*

These trends demonstrate that rising trends in maximum power capacities of CFB boilers can be found regardless of the fuel type. The rising trend of coal-based CFB boilers seems to be slightly more noticeable. This is very much expected and in-line with nature of the fuel-types as newer coal-based CFB plants are located in Asia, where these boilers are used in utility level power plants producing electricity for base load needs of the grid.

Biomass is considered to be carbon neutral and sustainable energy source, as the plants consume CO_2 as they grow, so using them as fuel does not lead into net increase of CO_2 in the atmosphere. The share of biomass as energy source has increased significantly during recent years and it is expected to keep on increasing. This trend can be seen from Figure 5.

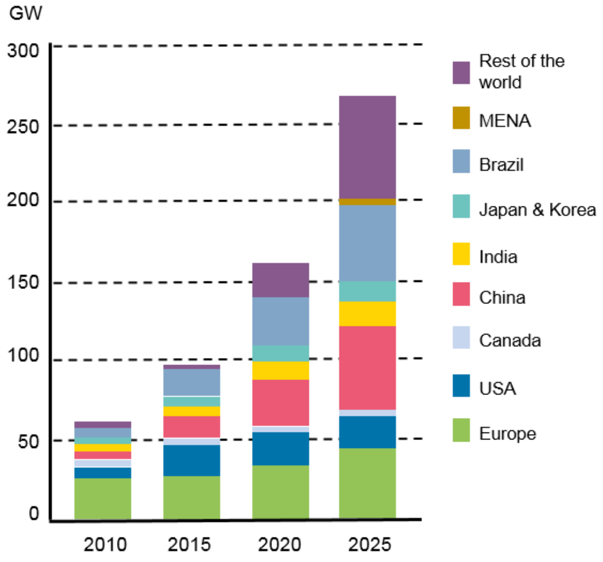


Figure 5. *Biomass as fuel. Projected biomass and waste installed capacity for 2010-2030. Adapted from a presentation by Sumitomo SHI FW.*

Coal still has significantly higher share in the energy portfolio compared to biomass and this this trend will most likely stay as it is in the near future.

CFB boilers are widely used for firing biomass and the fuel flexibility allows CFB boilers to utilize various combinations of fuels; they can fire up to 100 percent of biomass or combination of biomass and coal or combination of biomass and waste derivatives. Current trend is that the maximum power capacity of newer biomass-based power plants is growing larger. Current world's largest CFB boiler that fires 100 percent biomass is a boiler submitted by SFW and owned by GDF Suez Energia Polska, located in Polaniec, Poland. This power plant produces 205 MWe and fires a combination of wood residues and agro biomass. MGT Teesside Ltd. CFB Boiler, that is planned for operation in 2020, will be the world's largest 100 percent biomass-based power plant as it is designed to fire wood pellets and chips and it will produce 299 MWe. [16]

2.2 CFB Boiler technology

CFB boilers are a member of the fluidized bed (FB) boilers family, where the other most significant members are Bubbling Fluidized Bed (BFB) boilers. FB combustion has developed into one of the most important techniques to burn solid fuels in an environmentally friendly manner. The environmental benefits in FB combustion are inherently low NO_x emissions, feasible possibilities for sulfur capture and low amounts of unburned substances. Technical and economic benefits of FB combustion are the ability to fire varying and low-grade fuels without complex fuel pre-handling systems and ability to respond fast to varying demands on the load.[1, 17]

In FB boilers the fuel is burnt in so called fluidized state. The main difference between CFB and BFB boilers is that in a BFB boiler the combustion of the fuel takes place in bubbling layer whereas in a CFB boiler the combustion occurs in a turbulent layer.[17] In a CFB boiler the so called fluidizing velocity is higher than in a BFB boiler. This higher velocity enables the formation of turbulent layer for combustion and the escape of hot solid particles from the furnace. These escaped hot solid particles are then returned to the furnace in a manner demonstrated in the next Section. These beforementioned technical differences create opportunities to add alternative heat-transfer surfaces to CFB boilers, that could not be applied to other boiler types, increasing the efficiency of CFB boilers.[1] This thesis focuses on CFB boilers; hence only CFB boilers are introduced in a more detailed manner. More information on BFB boilers and other applications can be found on [1, 17].

2.2.1 Structure of a CFB boiler

Here in this chapter the different parts of CFB boiler are introduced in more detail. The CFB boiler can be divided into two different zones; the CFB loop, or as known in the industry, the hot-loop, and the convective part, in the industry better known as the back-pass. This is demonstrated in Figure 6.

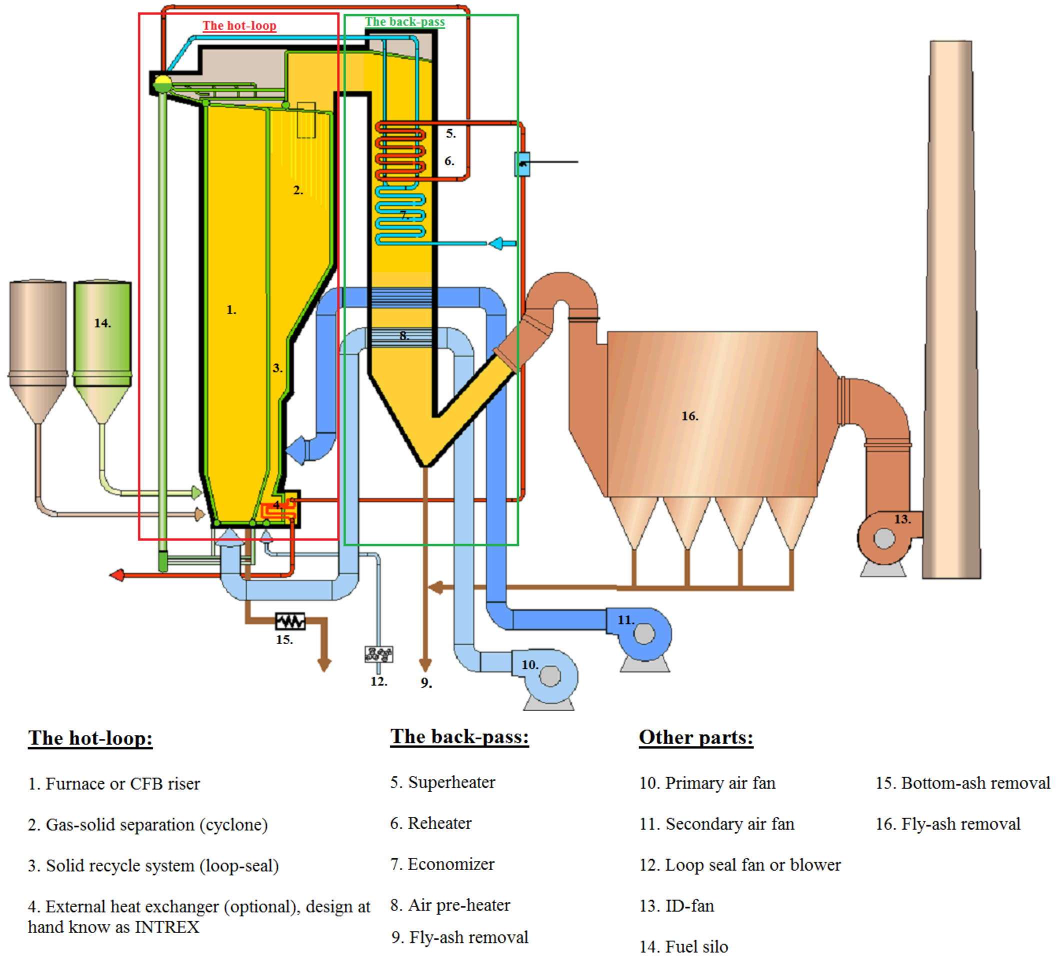


Figure 6. *Cross sectional representation of a CFB boiler. Adapted from presentation material by Sumitomo SHI FW.*

The most important parts of the hot-loop are furnace and solid recirculation system as the purpose of the hot-loop is to provide necessary equipment and conditions for efficient combustion and hot solid circulation. The heat transfer surfaces in the hot-loop are used to vaporize water into steam. Heat transfer in the hot-loop is governed by convection, radiation and conduction.[1]

The back-pass is mainly composed of the flue gas duct, multiple heat-transfer surfaces and ash-removal system. The back-pass is also known as the convective part as in the back-pass the source of heat are the hot flue gases exiting the furnace and heat transfer in this part is governed mostly by convection. Hence the heat transfer surfaces in the back pass are convective surfaces and they are used to superheat or reheat steam (5-6) or to preheat feedwater (7) or air (8).[1]

Other main parts are the fans (10-13) that are the main components of air system of a CFB boiler. These fans are responsible for providing sufficient air for combustion, fluidizing solid particles in the furnace and creating suction so that flue gases exit the duct. Air system of the CFB boiler is introduces in more detail in Chapter 2.4.2.[1]

There are many variations to the CFB boiler design as especially utility size boilers are designed to customers' needs and therefore vary from project to project. The major difference is state of art boilers is the choice between traditional boiler with steam drum or supercritical Once-through (OTU) boiler. In OTU boiler the feed-water evaporates into steam in one pass in the boiler and there is no need for steam drum. OTU design is illustrated in Figure 7.

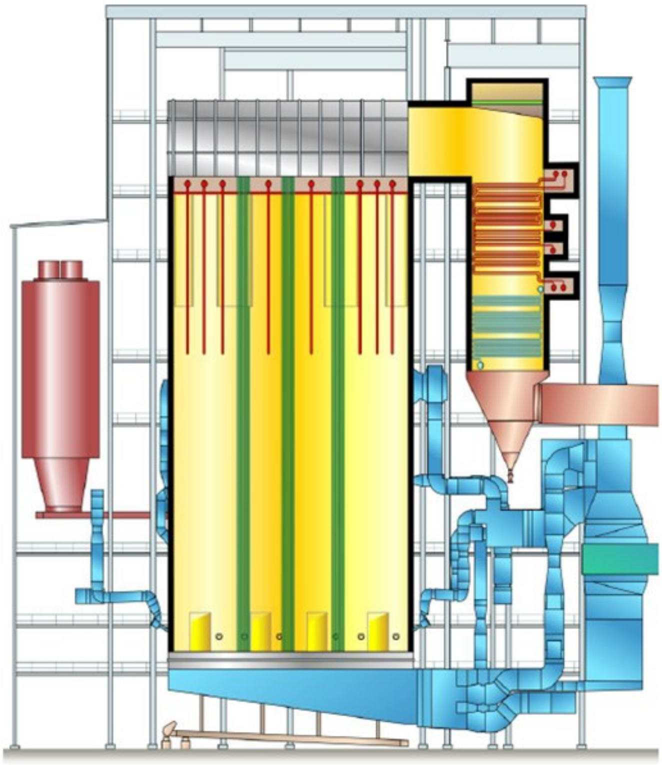
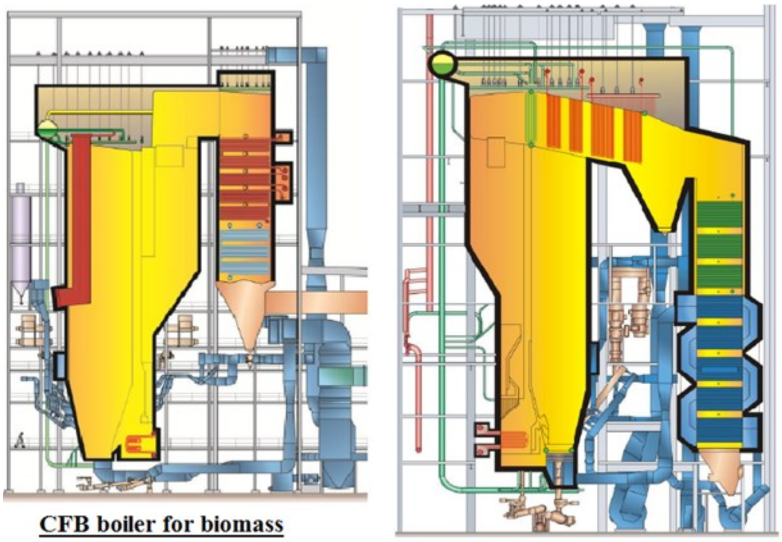


Figure 7. *Supercritical Once-Through CFB boiler. Adapted from presentation material of Sumitomo SHI FW.*

Even the traditional steam drum boilers vary somewhat and typically fuel is the deciding factor for the design. Typical differences in design are related to the design of the convective part and types of superheaters, that can be utilized. Design comparison for CFB boilers designed for biomass and demolition wood is illustrated in Figure 8.



CFB boiler for biomass

CFB boiler for demolition wood

Figure 8. *CFB boiler design comparison for biomass and demolition wood. Adapted from presentation material of Sumitomo SHI FW.*

As can be seen these designs utilize different types of superheaters and the convective part is different as in the design for demolition wood there is vertical pass before the traditional horizontal pass.

2.2.2 Heat transfer in CFB boilers

Heat transfer in a CFB boiler is governed by three different heat-transfer modes, that are conduction, convection and radiation. Conduction means heat transfer through a surface area, for example transfer through a wall of a pipe is governed by conduction. Convection is heat transfer from moving fluid to surfaces, for example using air to heat or cool an object is governed by convection. Radiation means heat transfer that takes place through long distances and energy is transferred by photons, from example heat transfer from the sun to earth is governed by radiation. Usually in real life applications multiple modes of heat transfer are present at the same time, but in many cases one form is responsible for such high percentage of the transferred heat so that other modes can be neglected. The CFB furnace is a good example of heat transfer applications, where all three beforementioned modes are present. This is demonstrated in Figure 9.

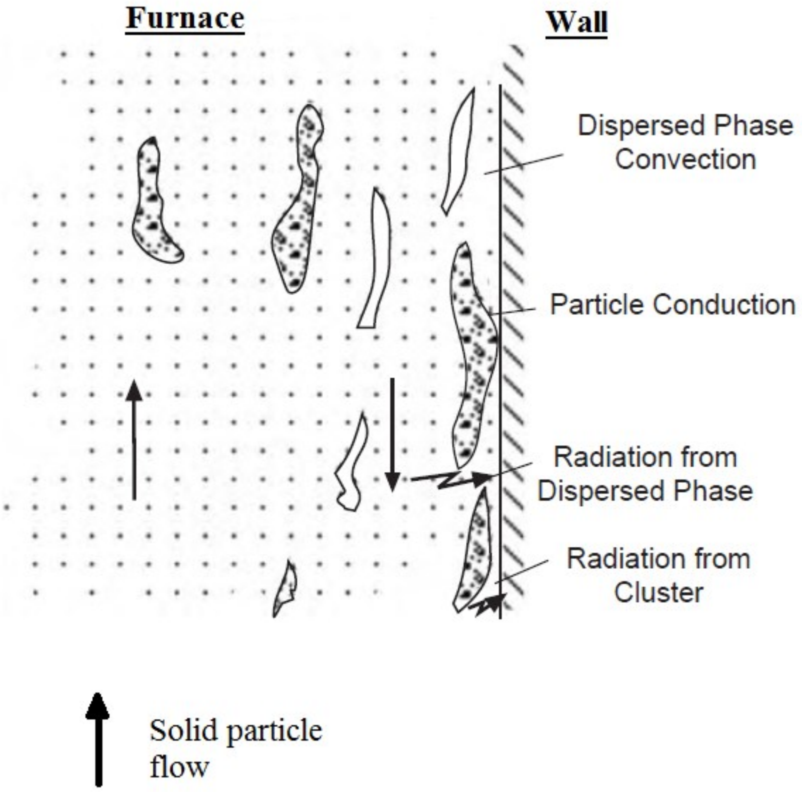


Figure 9. *Heat transfer to the walls of a CFB furnace. Modified by author based on Basu [1]*

The most significant forms of heat transfer in a CFB boiler are convection by gases, convection by solids and radiation by gas-solid suspension. Total heat-transfer coefficient is a combination of these three and thus can be defined as

$$\alpha_{total} = \alpha_{radiation} + \alpha_{convection} + \alpha_{conduction} \tag{1}$$

where heat transfer coefficient α_{total} $[\mathrm{W/m^2K}]$is defined as a sum of each different heat transfer modes coefficients α.

Heat transfer by radiation weakens significantly as temperatures drop and in practice it is negligible in temperatures under 500-600 °C. It is very difficult to examine radiation explicitly, because of complex boundary layers and the scope of this thesis is focused on the back pass, where convective heat transfer is most dominant, hence radiative heat-transfer is not considered more thoroughly in this thesis.[17]

The heat exchangers in the back-pass are typically cross-flow heat exchangers. The functionality of a cross-flow heat exchanger is illustrated in Figure 10.

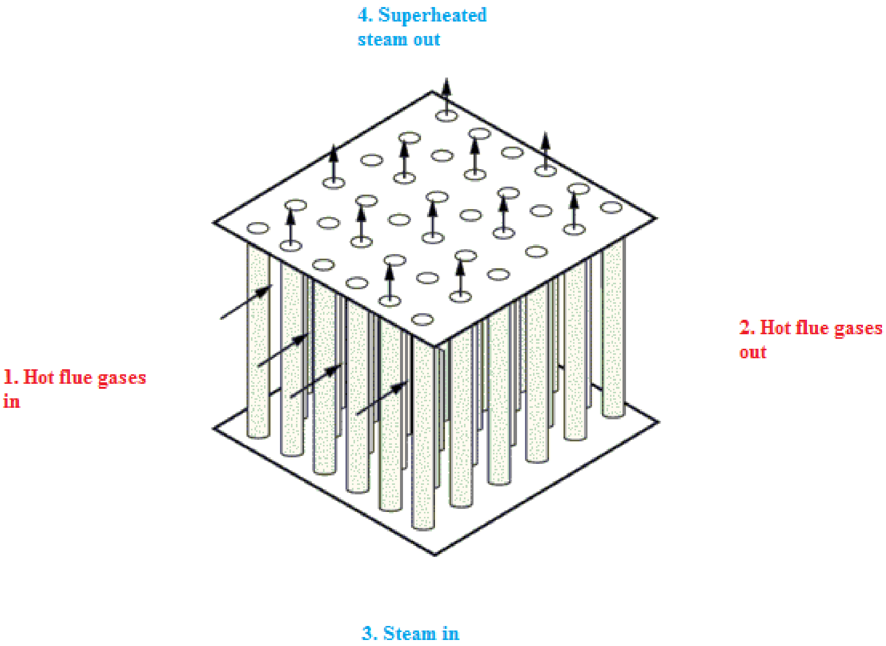


Figure 10. *Functionality of a cross-flow heat exchanger. Modified by author based on [18]*

Figure 10 demonstrates the functionality of cross flow heat-exchanger, but the design does not present realistic superheater design. Superheaters are typically tube packages that are either hanged from the ceiling of the duct or bended from the wall. More realistic image of superheater design can be seen for example from Figures 8 and 11.

The heat-transfer rate φ [MW] in a cross-flow superheater if all the fluid properties in all process states are known can be calculated from the following equations:

$$\varphi_{1-2} = \dot{m}_1(h_2 - h_1) \tag{2}$$

$$\varphi_{3-4} = \dot{m}_3(h_4 - h_3) \tag{3}$$

Here $\dot{m}$ refers to the fluid mass-flow [kg/s] and h [kJ/kg] is enthalpy of the fluid.

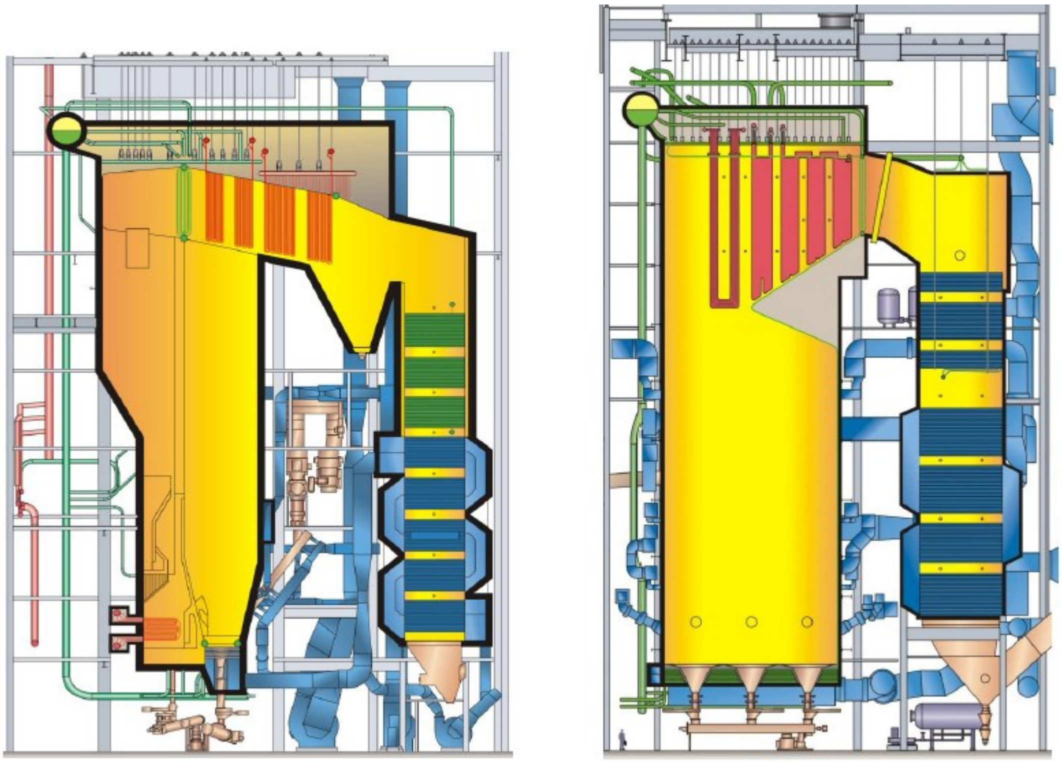
The overall heat-transfer to a surface can be described with a thermal circuit, where convection, conduction and radiation are presented in a circuit. The overall heat transfer to a surface can therefore be defined by the equation:

$$\varphi = UA\Delta T \tag{4}$$

where U is the overall heat transfer coefficient (W/m^{2}K), A is the area of the surface (m^2) and ΔT is the overall temperature difference (K).[19]

2.2.3 Slagging and fouling in CFB boilers

Ash-related issues during combustion, slagging and fouling, are the single biggest reason for unexpected shutdowns in most boiler types. There are some differences regarding ash between CFB and BFB boilers. The most significant difference is that amount of fine fly-ash can in certain cases be higher in BFB boilers than in CFB boilers due to the absence of cyclone. The coarser particles that are separated in cyclone in CFB boilers typically do not leave the furnace in BFB boilers due to smaller fluidizing velocities. Hence the structure of the back-pass is quite similar in CFB and BFB boilers. This design comparison of CFB and BFB boilers of similar scale is illustrated in Figure 11.



Small-scale CFB boiler

BFB boiler

Figure 11. *Structural comparison of CFB and BFB boilers of similar scale. Adapted from presentation material of Sumitomo SHI FW.*

As can be seen from Figure 9 in both fluidized bed boiler types similar structures and similar heat-transfer surfaces can be found. It is therefore reasonable to assume, that optimization methods and tools related to this area are suitable for both boiler types. The theory of ash formation and slagging and fouling is also unrelated to boiler type. This theory is presented in following chapters and it applies to both types of fluidized bed boilers and therefore the theory is presented for boilers on a general level.

These ash-related problems form as a sum from many different factors. Figure 12. illustrates the formation chain of ash in a plain form.[17]

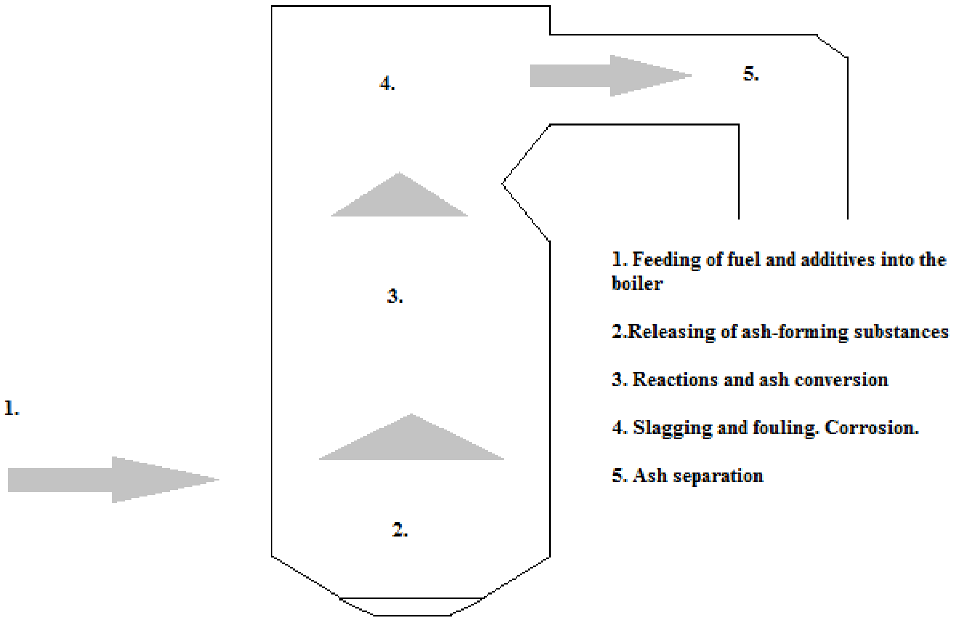


Figure 12. *Different stages of ash in the boiler. Modified by author based on information from [17]*

Slagging and fouling tendencies are tied to the chemical composition of the fuel. The most deciding factors are ash percentage in the fuel and presence of certain elements, such as silicon, phosphor, alkaline earth metals and alkaline metals, in the ash. Terms slagging and fouling refer to two different types of ash related problems. Slagging describes a problem, that is more present in the furnace area and the ash-deposit layers there are usually thick and molten from the surface. Fouling refers to a problem in the convective parts of the boiler, where temperatures are lower and the ash-deposit layer there are mostly in a solid form. The deposit layers form as flue gas stream transports ash particles and due to the kinetic energy of the particles in the stream they impact the heat-transfer surfaces.[17] The slagging and fouling areas of a boiler are illustrated in Figure 13.

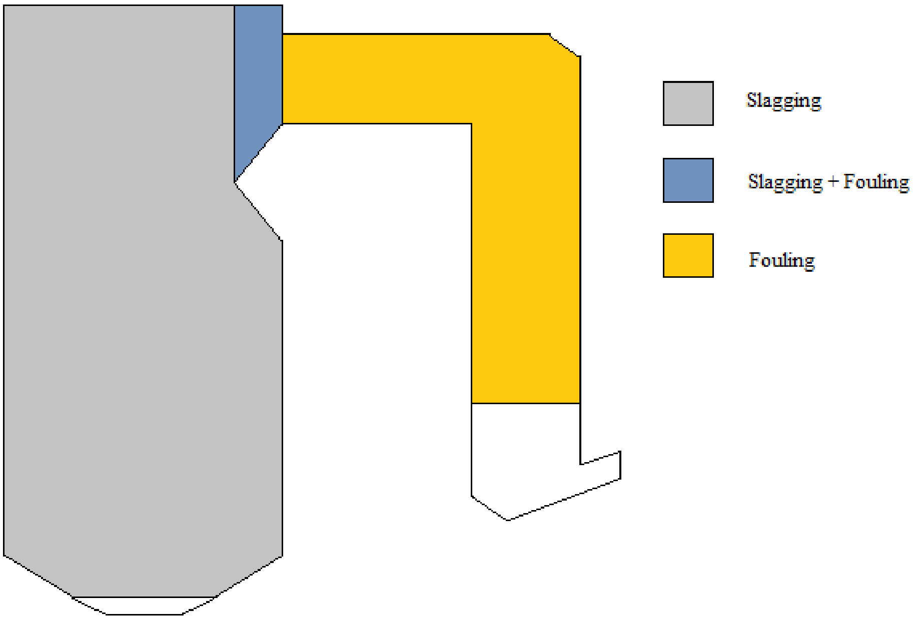


Figure 13. *Slagging and fouling areas of a boiler. Modified by author based on information from [17]*

As can be seen from Figure 13, there are areas where both forms are present, but in the back-pass fouling is more prominent and hence the focus of this thesis is more on fouling.

As described earlier, fouling tendencies are tied to the chemical composition of the fuel and hence it varies between different fuel types. High-grade coals are the easiest to fire from a fouling point of view and it becomes more difficult when downgrading to lower grade coals or to biomass and waste fuels. This is due to biomasses containing more of the harmful substances described earlier. The fouling tendencies of different fuel types are illustrated in Figure 14.

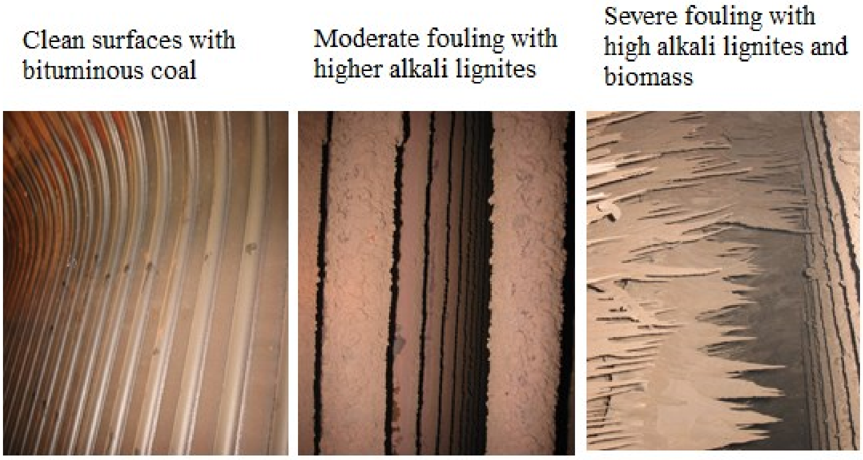


Figure 14. *Clean heat-transfer surface and foul surfaces with different fuel types. Adapted from a presentation by Sumitomo SHI FW.*

The corrosion protection of a traditional alloy in high temperatures is based on the protective oxide layer on the surfaces. This protective layer does not stop corrosion, but it can slow it down the corrosion rate significantly. In the furnace and the back-pass corrosion is usually a result of ash deposit layers, as these layers can create locally promotive environments for corrosion. This situation occurs, if the ash contains substances that can promote corrosion, such as sulfur or chlorine compounds like sulfites or chlorides.[17] The corrosion levels with different fuel types is illustrated in Figure 15.

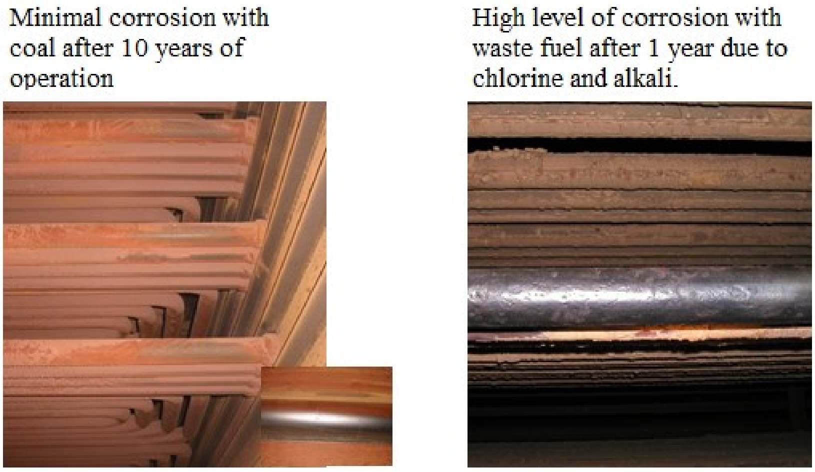


Figure 15. *Corrosion in superheater surfaces. Adapted from a presentation by Sumitomo SHI FW.*

In this thesis the fouling monitoring of a CFB boiler is concluded by inspecting flue gas losses and fouling indexes (FI) of individual heat-transfer surfaces. Between soot-blowing cycles as the boiler starts to foul, the FIs decrease and flue gas losses begin to rise, thus decreasing boilers operating efficiency.[20] From mathematical point of view the ash deposit layer that forms on heat transfer surfaces reduces the value of the overall heat transfer coefficient U presented in equation 4 and therefore lowers the heat transfer rate of the surface.

Flue gas loss and FI values are therefore very important for the operation of the boiler and they can be categorized as Key performance indicators (KPI) of a CFB boiler island. Flue gas losses can be defined as amount of heat lost outside of operation in flues gas flow, whereas FI is calculable index that describes the real-time heat-transfer rate of a heat-transfer surface compared to the clean state heat-transfer. This index is defined by the following equation

$$FI = \left(\frac{\varphi_{actual}}{\varphi_{ref}}\right) * 100 \tag{5}$$

where φ_{actual} is the real-time heat-transfer rate and φ_{ref} is the clean-state heat-transfer rate. The reference value φ_{ref} is calculated as engineering fit from process data assuming linear correlation between main-steam flow and actual heat-transfer rate. By doing so the dependency of steam load is filtered away and FI=100 corresponds to clean state heat-transfer regardless of current steam load. The behavior of FI of a superheater over time is illustrated in Figure 16.

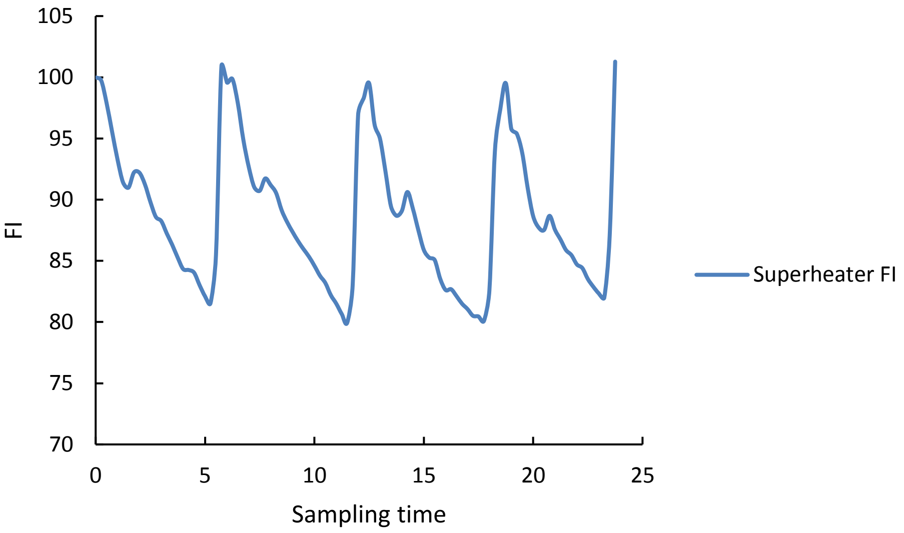


Figure 16. *FI of a superheater over time.*

As can be seen from Figure 16, FI of a superheater decreases over time due to fouling of the tube surfaces. FI decreases after a soot-blowing sequence is initiated and the surface is returned to clean state. In the beginning the fouling seems to be faster and of logarithmic nature until it starts to slow down and approach linear state.

Heat transfer based fouling monitoring was also used in a study by Teruel et el in 2005 [6]. In this study the degree of fouling was determined by measuring the heat fluxes in heat transfer surfaces and the fouling rate was then modelled using artificial neural networks (ANN). The model presented in this study managed to predict the fouling rate in an excellent manner matching well with measurements. Another heat transfer based fouling monitoring system was presented in a study by Afgan et al in 1996 [5]. Authors suggested an expert system for fouling monitoring consisting sensors for heat flux measurement, data analysis and modelling systems and a computer for data storage. A thesis by Tamminen in 2017 [7] aimed to assess the viability of heat transfer based fouling monitoring and the results stated it to be a widely used and viable tool for fouling monitoring.

Soot-blowing is the technical solution aiming to solve slagging and fouling in boilers. Soot-blowing aims to clean the heat-transfer surfaces and return the boiler to a clean state operation mode. There are different types of soot-blowers, but the most commonly used types of soot-blowers operate with steam taken from the power plant process. Other types of soot-blowers are based on soundwaves and physical impact, but these types are rarely used in utility level boilers. The steam-based soot-blowers are preferred as steam is available in the power plant and it is proven to be effective at cleaning the surfaces. It is therefore relatively simple to install and operate these types of soot-blowers.

2.3 Operating cost structure of CFB boilers

In this Section the operating cost structure of a CFB boiler is demonstrated. Focus in on the variable cost structure, but Section 2.4.5 gives insight on how optimization of the variable costs can also affect the fixed cost structure.

2.3.1 Fuels

Price of the fuel for the end user is greatly dependent on the fact whether it is domestic or imported. Usually the transportations costs, in some countries taxes, customs and other handling fees lead to a situation, that the cheaper purchase price of the imported fuel is not enough to make it more economically viable than the more expensive domestic fuel.

The fuel costs for a given time period can be calculated from equation:

$$Cost_{fuel,total} = \dot{m}_{fuel} * C_{fuel,unit} * t_{operation} \tag{6}$$

where $Cost_{fuel,total}$ is the total fuel cost for the given time interval [€], $\dot{m}_{fuel}$ is the average mass flow rate during that time [kg/h], $C_{fuel,unit}$ is the unit cost of the given fuel [€/kg] and $t_{operation}$ is the inspected time interval [h].

Prices of typical fuels used in power plants in Finland and trends of these prices during recent years can be found from Figures 17. and 18.

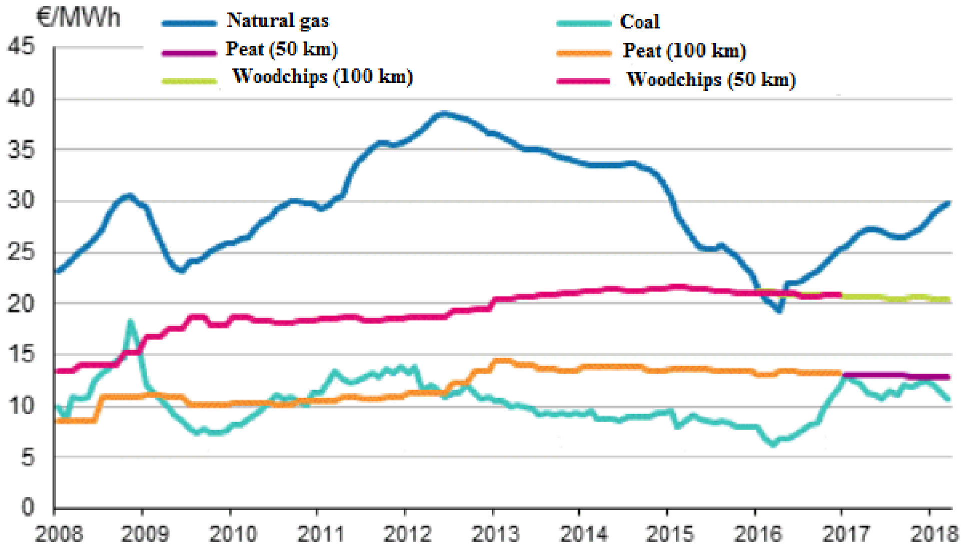


Figure 17. *Powerplant fuel prices in electricity production in Finland. Source: Statistics Finland [21]*

In Finland the prices of fuels are different for electricity and heat production. Figure 17 demonstrates the prices for electricity production over time and in Figure 18 the fuel prices for heat production over time are illustrated.

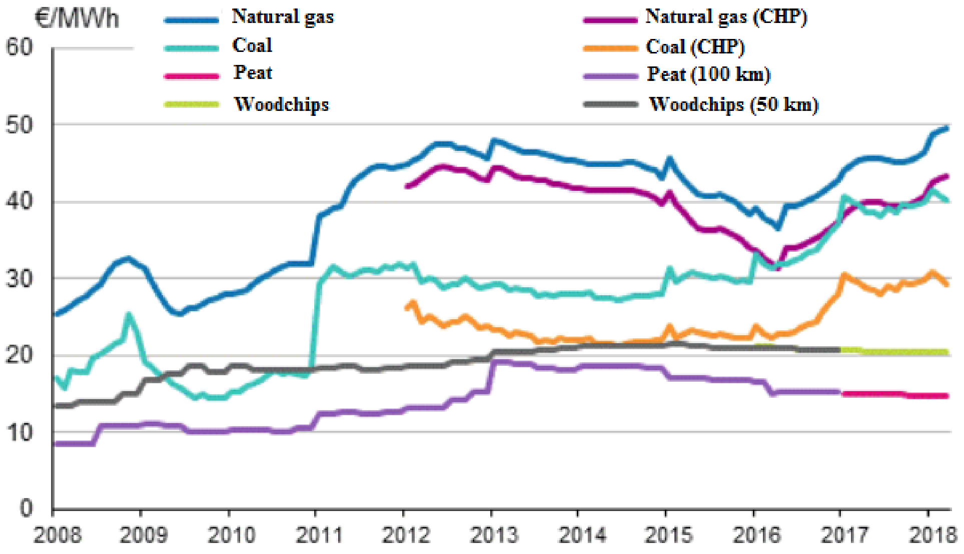


Figure 18. *Powerplant fuel prices in heat production in Finland. Source: Statistics Finland [22]*

It needs to be noted, that in Finland fuels in electricity production are not taxed since 1.1.1997. The prices in heat production include all taxes, including the CO_2 tax. It also needs to be noted that the CO_2 tax for coal and natural gas used for CHP was reduced to half in the beginning of 2011. As a reference point for the fuel prices in Finland, Figure 19. presents the monthly prices of Indonesian coal during 2012-2016. The Indonesian coal is a very commonly used fuel in powerplants in Asia. The prices were converted from USD to € by author using the course rate of July 2018.

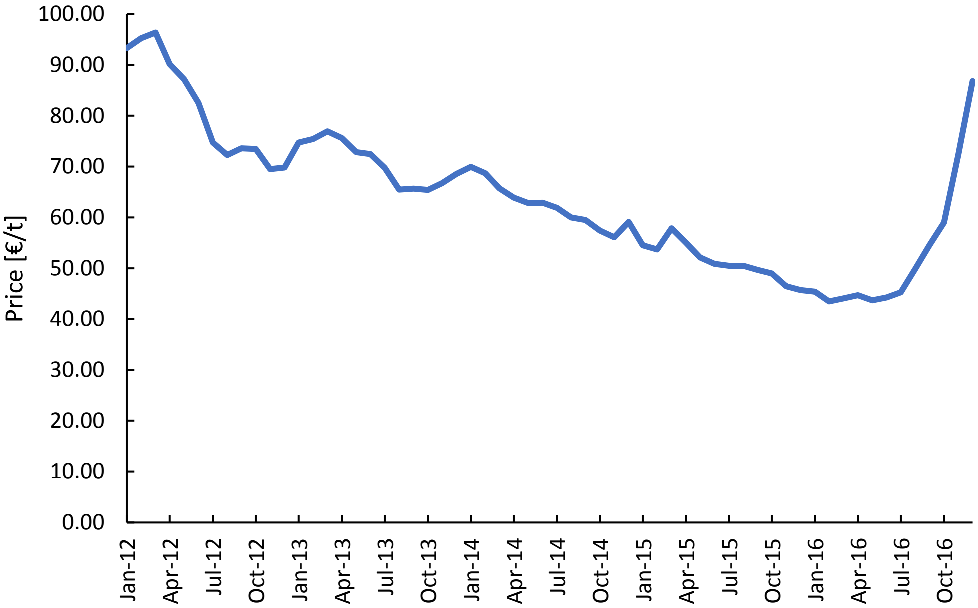


Figure 19. *Monthly prices of Indonesian coal in [€/t]Based on data available at [23]*

In Section 2.4.1 it is described how in multi-fuel boiler cases the operator of the power plant can adjust the fuel composition to some degree to optimize the cost of fuel. As can be seen from Figures presented above, prices of fuels do vary over time and the changes can be drastic at times, as was for example in case of Indonesian coal in 2016. It is then safe to assume that it is indeed possible to optimize fuel costs if multiple fuel types are available and the boiler design allows changing of fuel composition. Section 2.4.1 also describes some issues that might occur with this kind of chances in fuel composition. Those issues are something that need to be carefully considered as the cost of those unexpected problems usually overcome the short term saving that were created with the chance of fuel composition. This is due to the fact, that those problems in the worst cases lead to shutdown of the power plant, during which the monetary output of the power plant is zero, and usually create extra costs during maintenance. Those extra costs occur, since these problems can lead to a decrease of lifecycle of certain parts.

2.3.2 Auxiliary power

One weakness of a CFB boiler is its rather high consumption of auxiliary power. This is mainly due to the fan system, as it is the most power consuming system in a CFB boiler island. Important thing to be noted is that fan configurations are not standardized, for example one CFB boiler island can have two PA fans, where other might only have one. This is important when reviewing literature from different sources, as they do not always explicitly express for example, if they are representing information of a single PA fan or the overall PA fan system. Another case where this important to notice is, when comparing auxiliary power consumption levels of fans and pumps, that this comparison need to be done case by case and it is good to know the exact system configuration, as otherwise the information gained by this comparison might be misleading, since the number of pumps and fans can vary from one boiler island to another.

Overall auxiliary power consumption of a CFB boiler island is similar order of magnitude as in PC, but higher than in BFB. This is due to the fact, that FB boilers do not need power hungry fuel handling devices such as mills, which power consumption is only slightly less than the high-head PA fan in a CFB boiler. BFB boilers do not need either such high head PA fans or pulverizing mills so their auxiliary power consumption is the lowest of these three types. The comparison of typical auxiliary powers consumption of different units between CFB and PC boilers can be found in table 2.1. [1]

Table 2.1 Comparison of Auxiliary Power Consumption in the Boiler Island of a Typical 210-MWe Coal-Fired Thermal Power Plant. Adapted from Basu [1]

Equipment	PC (%)	CFB (%)
PA Fan	0.46	1.75
SA Fan	0.28	0.58
Ball mills	1.53	-
Coal feed	-	0.05
Others including loop-seal blower	1.17	1.52
Total boiler island consumption	3.44	3.90

After the fan system the highest power consuming unit in a CFB boiler are the feed water pumps. Other sources of auxiliary power consumption are the circulation pump and fuel feeding system, but they are rather insignificant compared to the fan system and the feed-water pumps.

A study about the reduction of auxiliary powers of a CFB boiler island was concluded in 2015 by Ahlqvist. This thesis studied and compared six different methods and their combinations for auxiliary power reduction. Results of that study showed that combinations of those methods can reduce the auxiliary power consumption by 2.1-10.9 %. From those methods, three were related to the operation of the boiler and the rest were related to the design of the boiler or were testing new types of boiler parts. Only methods related to the operation of the boiler are relevant for this thesis. From those three operation related methods two were found to be significant and they were air coefficient and primary/secondary -air ratio. Results of this study concluded, that both the reduction of the air coefficient and the PA/SA -ratio would lead to noticeable rises in carbon monoxide levels.[13]

Even though there are proven methods, that can reduce the auxiliary power consumption of a CFB boiler, they can cause changes elsewhere in the process. If these methods were applied to optimize the cost structure, further study about the impacts of these methods should be made, as it is possible that the economic benefits gained from auxiliary power reduction could be lost elsewhere.

2.3.3 Soot-blowing

The need for soot-blowing in the back-pass and especially the interval of how often to perform it is a major factor in the cost structure of a CFB boiler. This is especially relevant for boilers that fire difficult fuels, such as biomass or low-grade coal, as fouling is much prominent in these boilers and thus the need for soot-blowing is greater.

The mechanism how soot-blowing affects to cost structure of a CFB boiler is relatively straightforward; every time the furnace or other heat exchange surfaces are cleaned with soot-blowing, the power plant loses steam from the main steam flow, but afterwards heat transferring in the cleaned surfaces is greater which improves the energy coefficient of the boiler or the heat transfer in heat transfer surfaces thus leading to higher plant level efficiency. Soot-blowing can also prevent corrosion and erosion in heat transfer surfaces thus leading to a longer lifetime of the boiler and lowering downtime due to maintenance. One downside of soot-blowing is, that it increases flue gas losses temporarily as during soot blowing cycle the mass flow of flue gases increases by the amount of soot-blowing steam and removed ashes. All these beforementioned mechanisms offer interesting options for cost optimization.

Power plants operate based on desired electricity output and every time a soot blowing cycle is initiated there is less steam available in the main steam-flow, which means in theory that during soot-blowing cycle the power plant would produce less electricity. Since this is not a desired output, during soot-blowing cycle the lost steam flow to turbine is compensated with increased fuel mass flow to boiler, which lead to the plants electricity output during soot-blowing cycle remaining constant. With this information the price for a single soot blowing cycle can be calculated from equation:

$$C_{sb} = \dot{m}_{fuel} * \ C_{fuel,unit} * t_{sb} \tag{7}$$

where

$\dot{m}_{fuel}$ is the mass flow of the fuel needed to compensate the lost steam flow during a single soot-blowing cycle [kg/s], C_{fuel} is the price of the fuel [€/kg], t_{sb} is the duration of the soot blowing cycle [s]. The fuel flow is dependent on the design of the utilized soot-blowers and it can be defined from process data or design values.

The place in the process configuration from which the steam flow used for soot-blowing is taken can vary from plant to plant, but the cost for soot-blowing is always more practical to define as increased fuel consumption during soot-blowing cycle. Important thing to notice is that mass flow of steam used during a single soot-blowing cycle is usually constant and it is a parameter that is decided during design phase of the boiler according to the fouling tendencies of the designed fuel.

In large utility scale power plants with larger boilers, the effect that a soot-blowing cycle has on the main steam flow is proportionally less significant, than in a smaller power plants. This leads to a situation that in smaller power plants a soot-blowing cycle can cause fluctuation in electricity output due to control delay of the system. This also means, that in large scale boilers, the soot-blowing cycle has a minimal effect to the combustion process and the overall operation of the boiler, as the soot-blowing steam is typically in the order of magnitude of few percent’s of the main steam flow.

Even though soot-blowing is mostly a function with positive outcomes for the operation of the boiler, and its cost effect is relatively straight forward to define as seen from previous chapter, excessive soot-blowing should still be avoided. The reason for this is not only because every soot-blowing cycle uses valuable resources in form of increased fuel consumption, but also because excessive soot-blowing can lead to corrosion related issues with certain types of corrosive fuels and these issues can cause significant unexpected costs. The issue described is known as chlorine corrosion cycle and it is illustrated in Figure 20.

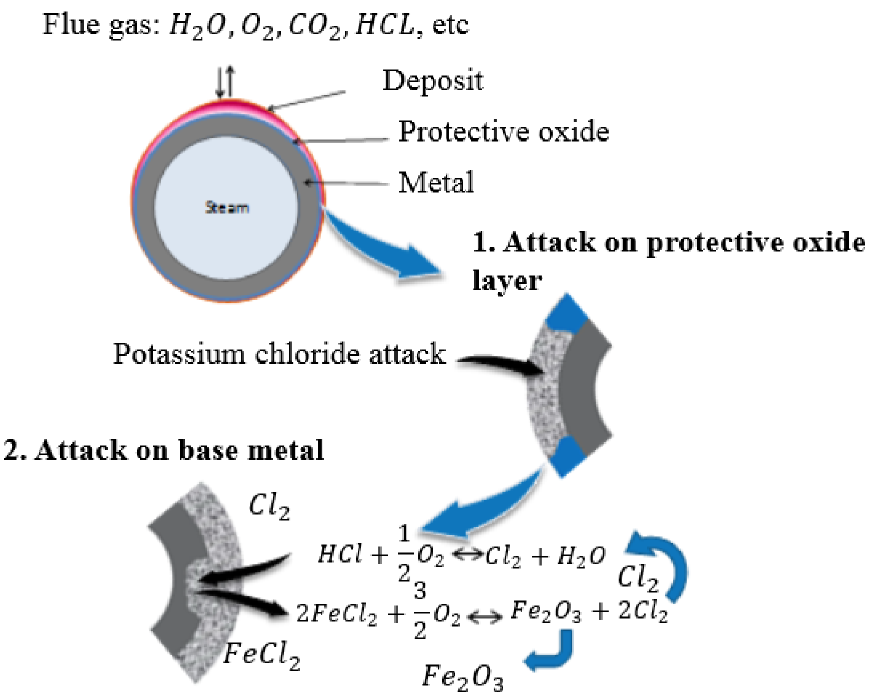


Figure 20. *Chlorine corrosion cycle. Modified by author based on a presentation by Sumitomo SHI FW.*

When removing the unwanted deposit layer, the soot-blowing steam also removes parts of the protective oxide layer. If the flue gases then include corrosive components, that also attack the protective oxide layer, excessive soot-blowing can lead to severe decrease in life-cycle of the heat transfer surfaces. This problem can be avoided by proper material choices and fuel analyses. This problem is an example, that even though when a problem is optimized from one point of view, as in this case soot-blowing is optimized from steam consumption point of view, the optimization problem should still be considered as a part of a bigger picture.[20]

2.3.4 Emissions

Emissions and how they affect the operation of the boiler from a cost point of view is a rather complicated question, since every country or economical area, such as EU, can have their own limits and regulations for certain emissions and have their own officials that supervise these regulations. This in why the effect that emission have to operation of the boiler should be revised case by case. A common trend is, that in areas that apply emission taxing, CO_2 is the only emission, that is controlled by taxing and other emission, such as NO_x and SO_x, have limits that the power plant must meet in order to have license to operate. Some exceptions to this trend can be found and they are presented later in this chapter.

The cost effect of emissions is realized in two typical manners. First very typical situation is, that at design phase of the power plant or after some time of operation is noticed that due to the plant not being able to meet the required emission limits, post combustion flue gas cleaning equipment, such as scrubbers, is needed. This situation occurs usually when the composition or quality of the fuel changes from the design or when emission limits become stricter compared to design phase of the boiler. The cost of this situation is a combination of fixed costs and variable cost, as the acquisition and installation of the equipment is a single payment fixed cost and the operation of the cleaning equipment is a variable cost. The operational cost of the flue gas cleaning equipment forms mostly from the price of used sorbents, such as limestone, and it can vary greatly depending on the area of location and availability of the used sorbent. The overall effect, that these flue gas cleaning systems have on the operational cost structure of the boiler should hence be revised case by case, as results may vary depending on many variables.[24]

The other typical case, where cost effects of emissions are realized, is for the countries, that use some form of taxing or fees as a mean to limit emissions. This is the case for example in Finland and Sweden. In Finland the only taxed emission is CO_2, and the tax is included in the price of the fuel and hence it can be seen as a variable cost. Since it is included in the price of the fuel, there are possibilities for optimization, as fuel consumption can be limited by having more efficient process. In some cases, boiler designs also have a margin to change fuel composition to some degree without decreasing the efficiency or causing unexpected problems. As fuel composition is strongly correlated to emissions, there are possibilities for optimization also by adjusting for example the ratio of coal and biomass used as fuel. Applications of biomass co-firing as a mean for emission reduction is discussed in more detail for example in a study concluded in 2011 by Basu et al.[25]

In Figures 21-23. some case examples of tax rates and commissions from Finland and Sweden are presented.

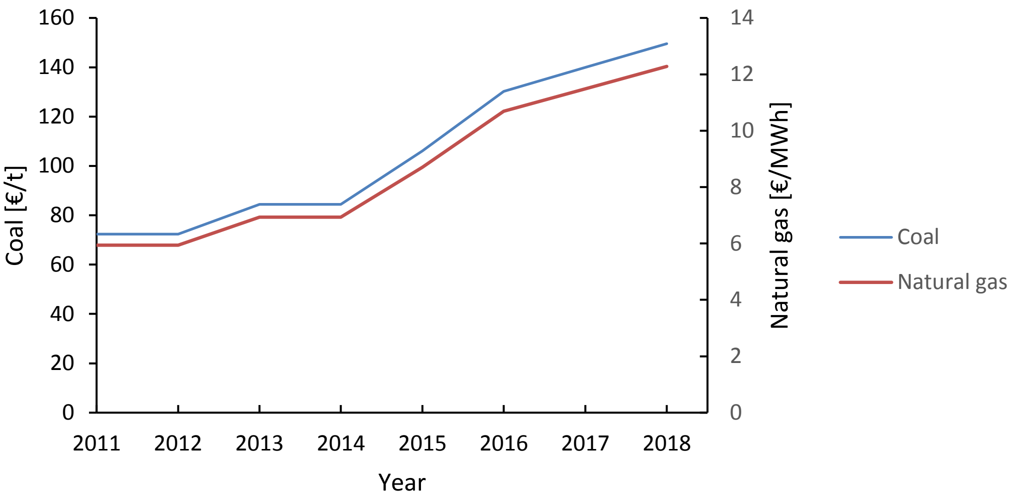


Figure 21. CO_2 tax in Finland for coal and natural gas in 2011-2018. Source: Statistics Finland [26]

Figure 21. presents trends how CO_2 tax has evolved in Finland during recent years. Even though natural gas is not used as a fuel in CFB boilers, it is presented here as a reference point, as the second most important fuel of CFB boilers is biomass and it is considered carbon neutral fuel and hence the CO_2 tax in not applied do it.

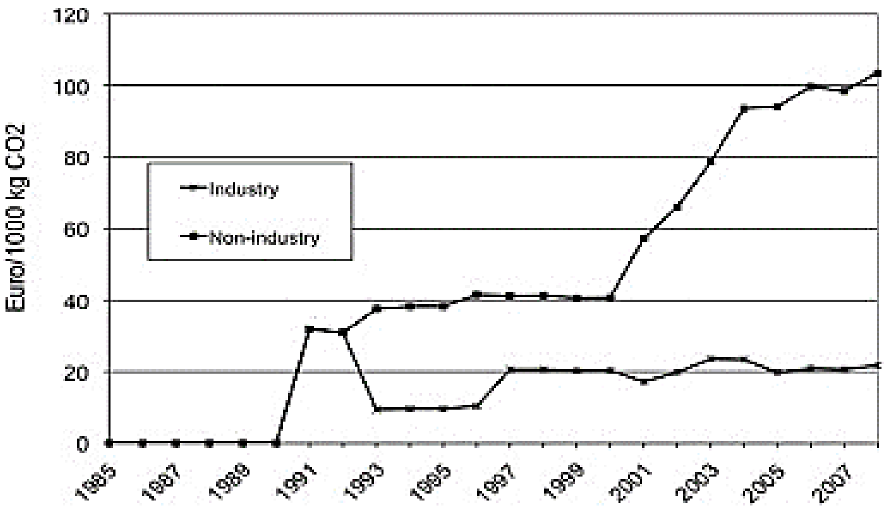


***Figure 22.** CO_2 tax rates in Sweden during 1985-2007. Taken from a study by Brännlund et al [27]*

Sweden also applies CO_2 taxing and the trend of the tax rates overtime can be seen in Figure 22. In Sweden there is also commissions for NO_xemissions. The way that Sweden has applied NO_x commissioning is rather unique; NO_x is commissioned with standard price per weight unit, which was 40 SKR/kg until 2008 and after that 50 SKR/kg. The amount of NO_x emissions is then divided with produced power output to ensure that plant size in not the deciding factor. Power plants that pollute more than the average of the country must pay the difference between their pollution rate and the average rate to those power plants that pollute less than the average. NO_x commissioning in Sweden can then be seen as a zero-sum method, that encourages power plants to compete with lower NO_x emissions. The effect of NO_x commissioning in Sweden is illustrated in Figure 23, where the NO_x emission amounts are presented over time.

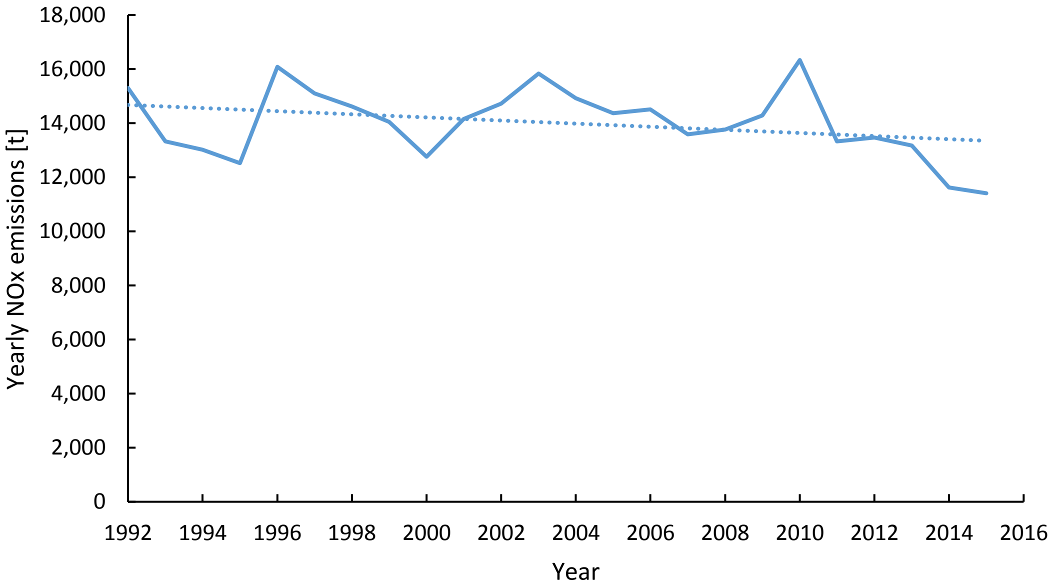


Figure 23. *NO_x emission in Sweden over time. Commission was increased in 2008. Based on data produced by Swedish Environmental Protection Agency.[28]*

NO_x emissions are also more feasible to control from a process points of view compared to CO_2. NO_x emissions can be limited for example by feeding ammonia to the furnace. Ammonia then reduces the NO_x to N_2 through chemical reactions and these reactions can also be enhanced with catalytic substances. Other possible ways for NO_x reduction are related to adjusting air coefficient or PA/SA ratio, but these adjustments can create changes elsewhere in the process, that might negate the gained monetary benefits.[24]

Even though emission taxing has good intentions, the consensus about the effectivity of taxing in emission reduction is still contradictory. A study by Brännlund et al [27] in 2014 concluded that during 1991-2004 the Swedish manufacturing industry managed to reduce CO_2 emission by 10 percent while increasing production by 35 percent. This study stated that CO_2 taxing is a significant factor for this positive development. A study regarding the econometric assessment of the carbon and energy taxation scheme in Sweden concluded in 2018 by Shmelev et al [29] stated that taken in isolation CO_2 was not a big enough of factor to drive down the emissions. Results of the study showed that there are other equally significant factors, such as rising of oil price, development of hydro and nuclear power and electricity import from other countries.

2.3.5 Additives

The cumulative effect of using additives, such as limestone for sulfur capture, have on the cost structure of a CFB boiler on a yearly level can be quite substantial. This is the case especially for utility level power plants, that have very high yearly operating time and it is something to be considered on every power plant. The yearly cost of using a certain additive can be calculated from the following equation:

$$C_y = \dot{m}_f * c * t_y \tag{8}$$

where C_y is the total yearly cost of the additive under inspection [€], $\dot{m}_f$ is the average mass flow of the additive into the boiler, c is the price of the additive [€/kg] and t_y is the early operating time of the boiler [h].

Example prices for some additives commonly used in a CFB boiler can be found on table 2.2.

***Table 2.2**. Example prices of some commonly used additives. Based on internal material of Sumitomo SHI FW.*

Additive	Unit price [€/ton]
Sand	46
PC Ash	50
Sorbacal	248.5
Sodiumbicarbonate	350
Limestone	68.25
Sulfur	400
Quicklime	171
Hydrated lime	177.5
Ammonia	785
Active carbon	1690
Kaolinite	135

These prices are examples based on average values over certain times on Nordic area and additive prices vary greatly depending on geographical location, as for example limestone is locally available in some regions and therefore the price can be very low, but in some areas, it has to be imported, which increases the price significantly. The amount of additive usage also varies greatly depending on the fuel composition. It can still be seen from these unit prices presented in table 2.2, that additives are rather expensive and even small improvements, such as 2-3 percent can lead to substantial savings on a yearly level. Purely from cost point of view the usage of different additives is a very tempting object to be minimized, but great care needs to be taken. These additives are a crucial part of certain sub processes, such as emission control, and they must be used to a certain degree to do their functions properly.

2.3.6 Boiler operating efficiency

As can be seen from Section 2.2, the current trend is that boilers are becoming larger in terms of power output, which means that all volumes that go through the whole process also grow larger at the same rate. This leads to a situation, that the operating efficiency becomes even more crucial from a cost point of view, as even small improvements in efficiency mean even more savings in the costs for larger boilers.

It needs to be noted, that efficiency of a power plant may refer to either the efficiency of the boiler of the efficiency of the whole plant, depending on what source of information is used, and these are not the same thing. Boiler manufactures use boiler efficiency in their references as it is normal that a certain company only manufactures boiler for a power plant and the rest of the equipment, such as the turbine, is manufactured by other companies. In such a case, the boiler efficiency is the best reference to describe the quality of work of the boiler manufacturer. Hence the boiler efficiency is used and other efficiencies, such as turbine and generator efficiencies are not taken into consideration.

Another important thing to be noted is, that boiler efficiencies according to different standards are calculated in slightly different manner. Most significant difference is that some standards use lower heat value (LHV) for fuel and other use higher heat value (HHV). Difference between these two heating values for dry fuel is, that LHV does not include the latent heat for water and thus is lower than HHV. [17] Boiler manufacturers also have their own methods for defining the boiler efficiency. These methods are based on standards, manufacturers own experience and good engineering practices. [30]

According to the DIN 1942-Feb94 standard, that utilizes LHV, boiler efficiency is calculated from equation:

$$\eta_{boiler} = 1 - \frac{\varphi_{totalloss}}{\varphi_{totalheatinput}} - \eta_{manufmarginloss} - \eta_{unaccountedloss} \tag{9}$$

According to SHI FW method, that also utilizes LHV, boiler efficiency is calculated from equation:

$$\eta_{boiler} = 100 - L_{total} \tag{10}$$

Total losses with SHI FW method are the calculated from equation

$$\begin{aligned} L_{total} = {} & L_{UBC} + L_{bottom\ ash} + L_{fly\ ash} + L_{limestonereactions} + L_{wet\ flues\ gas} + \\ & L_{H_2O\ limestonelatent} + L_{leakeage} + L_{manufacturermargin} + L_{unaccounted} + \\ & L_{H_2O\ ashcoolerduty} + L_{H_2O\ ashcoolerspraylatent} + L_{H_2O\ waterinjectionlatent} + \\ & L_{radiation} \end{aligned} \tag{11}$$

As can be seen from equation 9 and 10 the increasing flue gas losses decrease the boiler efficiency. Flue gas losses is one of the inspected parameters in the computational part of this thesis.

2.3.7 Life cycle cost analysis

Optimal operating performance can have a great impact on both the variable and fixed cost structure of the power plant during its lifecycle and this Section takes a closer look on the fixed cost structure. Fixed cost structure includes costs that are not dependent on volume or performance of the operation such as salary of the personnel, rent of the building ground, planned yearly maintenance costs, annuity payment of the original investment etc. In theory optimal operating performance can affect the fixed cost structure of a power plant in two ways; by minimizing unexpected costs and by prolonging the life time of the power plant. In practice the latter is relatively insignificant, since energy market is changing at very a high rate and new and more efficient technologies and better designs of current ones are constantly developed. This leads to a situation, that at the end of the lifecycle of a power plant, which typically is around 25 years, the chances are, that prolonging the use of that power plant for a few years is no longer economically feasible due to better and more efficient current technologies or even possible due to stricter emission limits.

A good case example of this situation is Germany in recent years, who has launched a campaign called Energiewende, which purpose is to cut greenhouse gas emission by 80 percent into 95 percent by year 2050. One of the main methods this campaign is planning to achieve these goals is to slowly stop using any form of coal as energy source.[15, 31] Another good example that demonstrates the changing landscape of the current energy production industry can be found in Finland. In 2013 the largest non-nuclear based power plant in Finland, a coal-based power plant owned by Fortum in Inkoo, was shut down, but it was still maintained ready for operation for a few years, until it was finally decided to be demolished. This decision was made, even though huge amounts of capital is tied to the plant, because the plant produces electricity and the price of electricity in Finland has lowered to a level, that it no longer covers the productions costs.[31]

The minimization of unexpected costs on the other hand is in practice extremely relevant, as mentioned earlier in Section 2.3.1 during downtime the power plant is not producing anything and hence it is one of the biggest cost items of the power plant. Hence any problems that might prolong the planned yearly maintenance or at the worst-case scenario cause unexpected shutdown of the power plant become extremely expensive. The total cost of these problems is formed as a combination of lost power output and increased material and personnel costs. These problems have a tendency of forming as a cause of suboptimal operating performance and that is one of the biggest reasons why optimizing the operating performance of the power plant is extremely important purely from a cost point of view.[20]

2.4 Control variables of CFB boilers

This Section demonstrates the control variables of a CFB boiler, with focus on their thermodynamically significant properties and governing equations. Section 2.3 is focused on the cost structure of a CFB boiler and there the cost effects of different control variables are demonstrated. Here also some typical adjustable control parameters of different subprocesses are introduced on a general level.

Typical control system of a CFB boiler is divided into three master level control loops, that control other loops lower in the hierarchy. Typical master level control loops are boiler master loop, fuel master loop and air master loop. Highest in the hierarchy is boiler master loop, which controls the boilers steam production and steam pressure according to the steam consumption, that is determined by the demanded power output. Boiler master control loop dictates the operation of fuel and air master loops. The fuel master loop provides a single point of control for all solid fuel feeders and its objective is to match the heating value compensated solid fuel flow to the solid fuel firing demand. The air master control loop is a central point of control for all the air flows and is responsible for maintaining the total air flow rate according the demand by the boiler master.[32]

2.4.1 Fuel

The fuel feed system of a CFB boiler can be found in Figure 6. and it consists mainly of fuel silos, fuel feeding screws and conveyer belt.

The most typical fuels fired in CFB boilers include coal, biomass and refuse derived fuels (RDF). In theory every CFB boiler is capable of firing all fuel types, but in practice the design of the boiler varies greatly from fuel type to another. Especially modern CFB boilers are flexible at firing different fuel types, but this is something that should be considered at design phase. For example, if a boiler designed for coal starts firing biomass with similar heating value can lead to severe corrosion problems in heat transfer surfaces.[20]

Fuel types, their availabilities and hence prices vary greatly depending on geographical location and socio-economic structure of the area, where the power plant is located. This leads to a situation, where fuel type is one of biggest deciding factors when a new power plant project is considered. This also in many cases means, that the operator of the power plant has very little control over the type and the quality of the fuel. This is even more relevant issue in cases of biomass and wastes as the quality of the fuel can vary depending on the original source of the fuel of the harvesting time. Also, in case of coals there is quality variation to a certain degree. In many cases with biomass or coal it is not economically feasible to obtain higher graded fuels. In case of boilers that are designed to fire a combination of fuels, for example 20 percent of coal and 80 percent of biomass, the design usually allows to adjust the fuel composition to some degree, but this is something that need to be done with great care and good understanding of the overall process, since overshooting this chance can lead to severe problems for example with corrosion on heat transfer surfaces or with rising emission contents. [20]

The most important characteristics of fuels are price, heating value, ash content, chemical composition and to some extent particle size. Fuel prices and how the total price of the fuel for the operator of the plant is formed is discussed at Section 2.4.1. Power plants are designed for certain desired power outputs and steam parameters and since fuels are the source of energy, the heating value of the fuel is the most relevant characteristic.[17]

Other important characteristic, especially relevant for CFB boilers, is the ash content of the fuel. Reasoning for this is, that in many cases the ash is used as bed material and if the ash content of the fuel if not on a high enough level for bed formation, make-up material, such as sand, is needed. The price of the make-up material adds another cost item and the material itself also requires its own handling and feeding system. Another problem that might occur is, that in certain areas it can be hard and expensive to obtain high enough amounts of suitable make-up material.

Chemical composition of the fuel is a relevant characteristic because it indicates agglomeration, slacking, fouling and emission composition of flue gases. [17]

2.4.2 Air

Functional air system is a very crucial part of a CFB boiler as it is at the same time the highest source of auxiliary power consumption and responsible for providing air for combustion and the solid circulation. In a typical CFB boiler there are four types of fans and their locations are demonstrated at Figure 6. and they are the following:

1. Primary air fan
2. Secondary air fan
3. ID fan
4. Loop-seal air fan or blower

ID fan differs from PA and SA fans in that sense, that is used for suction and is located at the end of the flue gas duct as shown in Figure 1. This fan is responsible for creating enough suction so that flue gases exit the boiler and enter the possible dust- or emission control equipment. The power consumption of the ID fan is therefore dependent on the volume of flue gas flow.[1]

Type of fan used for loop-seal air system varies from power plant to another. There are typically one or two loop seal air fans, but if HP blowers are used instead the amount can vary from 3-8. From power consumption point of view the loop-seal air system is significantly smaller than PA, SA and ID fans[1].

Typical adjustable control parameters of the air system of a CFB boiler are for example PA/SA ratio, bed pressure and excess-air. They are adjusted according to fuel feed and this adjustment is done with inlet vanes or by PA/ SA fans rotation speed frequency converter.[33]

2.4.3 Feed water

The water and steam circulation system of a CFB boiler is similar compared to the systems in other types on thermal power plants. The newer CFB boilers tend to be supercritical once-through (OTU) boilers, as this design allows higher steam temperature and pressure and hence higher amount of electricity production. The term OTU refers to the absence of a steam drum, where normally water and steam are separated, but instead in OTU design the evaporation from water into steam takes place in one pass through the boiler. The OTU design is illustrated in Figure 7.[1]

Typical adjustable control parameters in the steam and water circulation system of a CFB boiler are for example steam temperature and pressure. They are adjusted according to the demanded power output.[33]

2.4.4 Additives

Sorbents such as limestone ($\mathrm{CaCO_3}$) and dolomite ($\mathrm{CaCO_3} \cdot \mathrm{MgCO_3}$) are used in CFB boilers for sulfur capture. These sorbents are fed into the furnace and they capture sulfur by absorbing it. This sulfur capture occurs in two stages; calcination and sulfation. Calcination in the one occurring first, and it is the reaction where limestone decomposes into CaO and $\mathrm{CO_2}$. This reaction in endothermic, meaning that it binds heat from its surrounding environment. The second stage is called sulfation, where calcium oxide absorbs sulfur dioxide forming calcium sulfite. This reaction is exothermic, meaning it releases heat into its surrounding environment. The formed calcium sulfite can afterwards be disposed easily as it is rather inert and stable solid.[1]

Other additives that are commonly used in CFB boilers are bed materials that are used when firing fuels, that have low ash content is, such as certain types of biomass, and these bed materials help in bed formation and stabilizing the bed. Term used in industry for these bed materials is make-up and typical examples of make-up material is sand or gravel, which is often used when firing bio-mass.

Sometimes, when firing biomass, chemicals such as elementary sulfur are used in the boiler to prevent agglomeration. Sulfur can be fed into the boiler for example in form of ash from a PC boiler. The amount of sulfur used to prevent agglomeration is small and the sulfur is bonded with alkalis and removed from the CFB boiler in the ash, so feeding sulfur in such way does not increase sulfur levels in the flue gases.

3. KEY PERFORMANCE INDICATORS

In this thesis the approach to cost optimization was done by identifying Key Performance Indicators of the CFB process and evaluating which ones of these KPIs are most relevant from a cost point of view and which ones can be optimized with feasible means. This chapter introduces references about the state of the art of KPI monitoring in industry applications and the KPIs of CFB boiler island. This section also aims to answer to the second research question: *What are the most critical Key performance indicators of a CFB boiler from operational cost point of view?*

Key performance indicators on a general level can be defined as specific measures of performances of an individual, team or department [34]. In industry, or as in this thesis in power plant environment, KPIs refer to performances of specific parts of the process or process-components rather than the performance of people. KPIs can be used for example for benchmarking with KPIs from similar facilities and then evaluate efficiencies of certain components or sub processes and by doing so determine possible potential for improvement. It is also possible to measure different types of performances with KPIs, for example such as energy or raw-material.[35]

3.1 Key performance indicators in industry applications - State of the Art

Several papers and studies can be found where KPIs were used in different industry applications and good practical results were achieved. This Section demonstrates some of those studies.

For instance, a very practical approach to the usage of KPIs was in a study in 2016 by Chioua et al.[36], where KPIs were used for plant-wide root cause identification with application to a paper machine. In that study a plant operating in the pulp and paper industry was used as a case example and the authors compared their proposed top-down method to the formerly more used down-top method for root-cause identification. This proposed top-down method used KPIs as a starting point to identify and highlight the section that was performing sub optimally and then control variables that affect that section the most could be identified. After identifying the sector, that was the possible root-cause for the oscillation of the measured KPI, the method was to identify measurements that have similar oscillation rate as the KPI. The used top-down approach is illustrated in a schematic manner in Figure 24. The approach is divided into two steps in a manner described earlier.

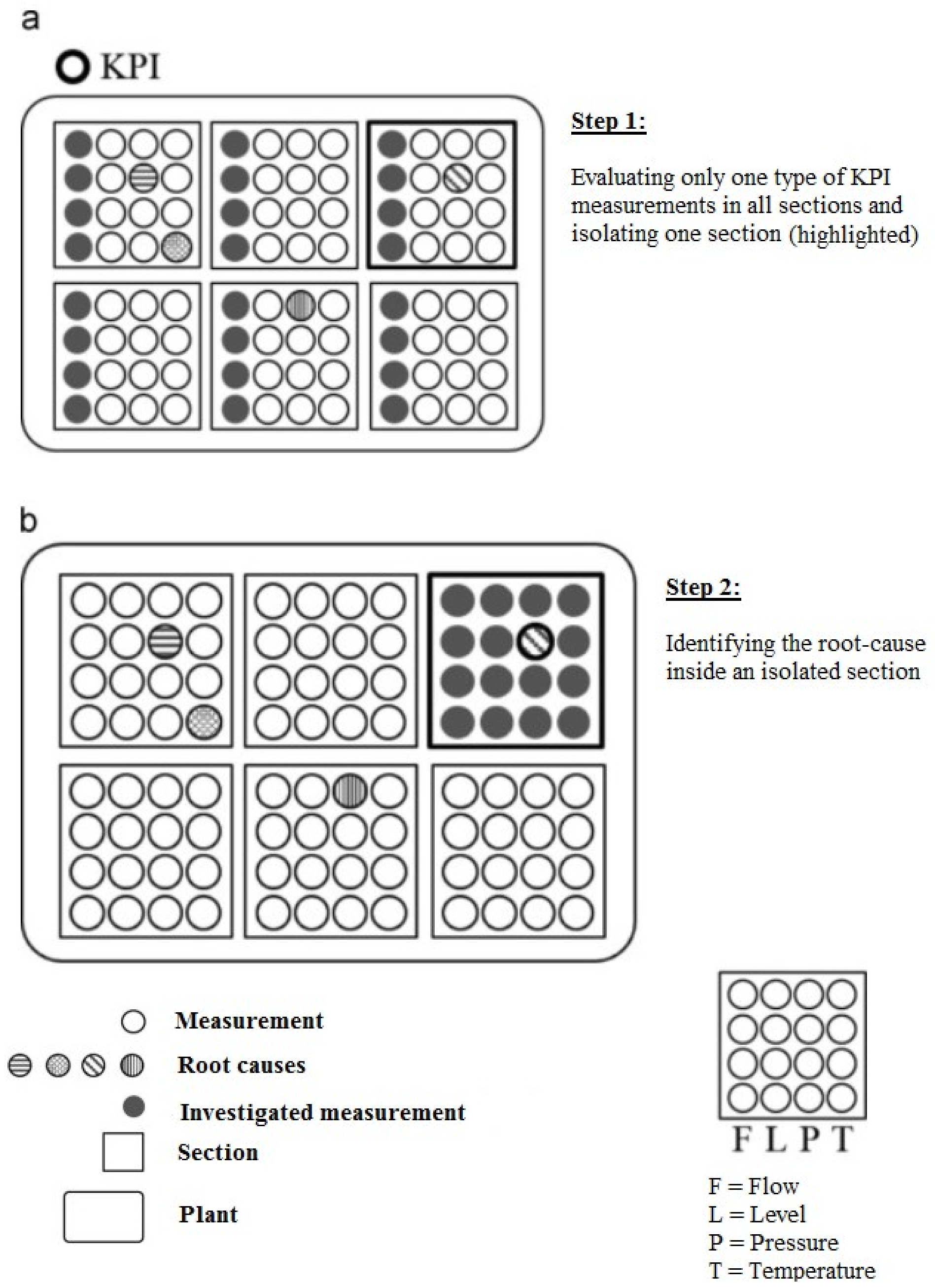


Figure 24. *Schematic illustration of top-down approach for root cause identification in two steps. Modified by author based on the original study by Chioua et al [36]*

The suggested method managed to reduce the original data set of 7000 measurements to 112 and could also highlight the dryer section earlier in the process as a possible area for the source of the problem. Further analysis of that area did manage to identify the root-cause and proper means for fixing the problem could then be made. Methods and results presented in this study suggest, that KPI monitoring could be a useful tool for fault diagnostics also in a CFB based power plant environment.

Another interesting study related to KPIs and industrial performance was concluded in 2015 by Lindberg et al.[35] First this study took a broader look into KPIs and listed what types of KPIs could possibly be identified in industrial environment. The paper suggested the following list as a list to draw inspiration from: energy KPIs, raw-material KPIs, operation KPIs, control performance KPIs, maintenance KPIs, planning KPIs, inventory and buffer utilization KPIs and equipment KPIs. Authors noted that this is not a conclusive list and different industry sectors can have their own types of KPIs. It was also noted, that the unit of the KPI is important to keep track of, is KPI monitoring is used for benchmarking, but if it used to track trends, then the unit of the KPI will become insignificant. After this the paper presented a case study, where KPI monitoring was done on a combined heat and power (CHP) plant and methodology that was used.

The study suggested a method as an alternative to benchmarking. The suggested method was to identify process signals that correlate the strongest to the chosen KPI and then to change these signals in such direction, that the measured KPI would improve. The method suggested to use historical data from a long enough period and for enough process signals, maybe even all, if limitations to the scope can't be done with certainty. In this case data from a six-month period was used to identify the correlated signals. It was also suggested to remove signals with zero standard deviation and to remove data in all signals for time periods when the plant is shut down or is working under abnormal conditions. Then the KPI of interest can be calculated from this modified historical data, and correlations with process signals and the chosen KPI can be identified and different combinations of changes can be tested to improve the KPI. The case study presented a CHP plant firing municipal solid waste and the boiler efficiency was chose as measured KPI. The boiler efficiency KPI was defined as ratio of flow rate of main steam [kg/s] and power in fuel [MW]. The correlations between the chosen KPI and the control variables are presented in Figure 25.

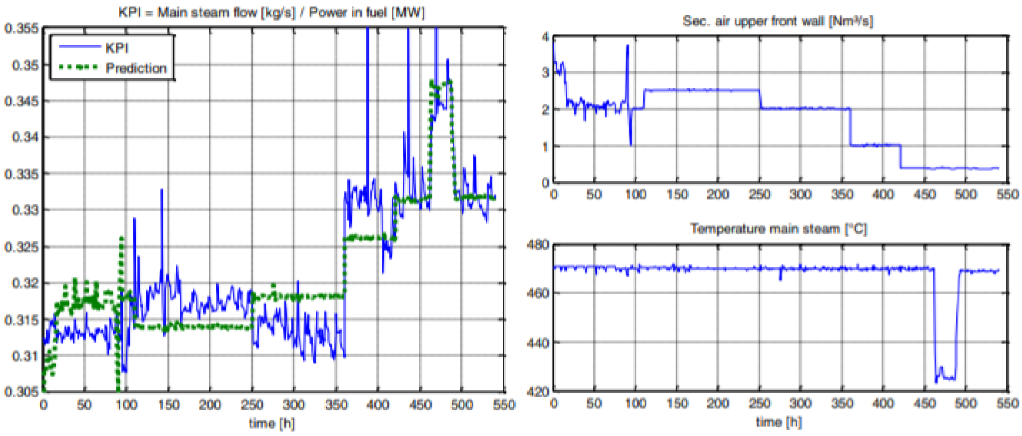


__Figure 25.__ KPI measurements in relation to chosen variables. Taken from the original study by Lindberg et al [35]

The study then found SA in upper front wall and main steam temperature to correlate the most to the chose KPI and concluded that only the former is a process signal that is possible to be changed. This study in an excellent representation of how KPI monitoring can be applied to power plant environment and how it can lead to practical solutions.

A study concluded by May et al. in 2013 [37] aimed to provide a method for manufacturing companies from varying industry sectors to identify their energy related KPIs (e-KPI). The functionality of these identified e-KPIs is to help and guide decision making towards more energy efficient operation. The highlight in this study was, that traditional types of KPIs, such as energy consumption per year or per product are not sufficient enough to aid decision making. According to the study, these types of KPIs are only valuable in describing the current status regarding energy efficiency. The authors then proposed company specific e-KPIs, that are tailored according to each companies' operating fields and production systems. The proposed e-KPI system is able to identify each companies' energy drivers and make their energy portfolio more transparent. Another benefit of the proposed method is the ability to identify causalities and to prepare actions for improvement measures.

The authors identified two possible major problems. These problems are common in methods that are designed to aid decision making and they are the following: 1) the approach is scientifically valid, but difficult to apply in practice (the practice gap) or 2) the approach is applicable in practice but scientifically not underpinned (the research gap). The seven-step method developed in the study was designed to avoid these two major concerns. The case example of this study included five companies from all over Europe. These companies' sizes varied from 3500 employees to 400,000 employees and their sectors varies from harvesting machines to integrated digital technology products and to industrial automation systems and services. The e-KPIs produced with this method were then evaluated in an energy consumption matrix presented in Figure 26. This matrix has time and power as variables and it is designed to evaluate the e-KPIs in order to aid the decision-making process.

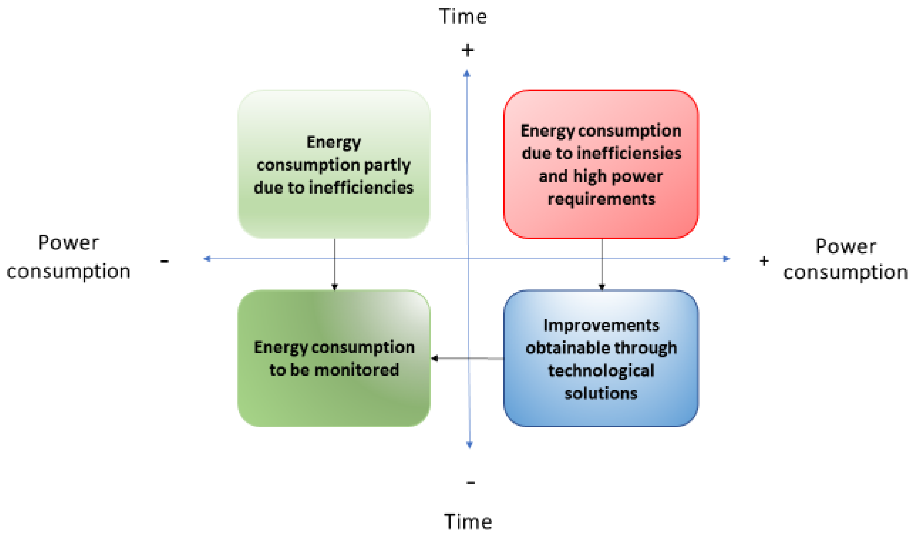


Figure 26. *Energy consumption matrix for evaluation of Energy key performance indicators. Modified by author based on the original study by May et al. [37]*

The horizontal axis called Power and it represents the magnitude of individual energy consumption of an e-KPI. The vertical axis is called Time and it represents the time that the inspected e-KPI is monitored to consume the energy presented in vertical axis. Therefore, this matrix aims to evaluate the e-KPIs in relation to how much energy they consume and for how long of a time period they consume the energy. This way the most critical e-KPIs can be identified and possible suggestion for improvements can be made. In the matrix there are also guidelines for typical actions to improve the e-KPI and as can be seen form the arrows between the fields of matrix the aim is to direct the e-KPIs to the bottom right corner field of the matrix, which is the least critical area as both consumed power and time used to consume power are at lowest rate there.

The methodology presented in this study proved to be useful for manufacturing companies from such varying sectors, that it is safe to assume that this type of KPI monitoring designed to help decision making could be useful to some degree also in a CFB based power plant environment.

A study concluded in 2016 by Alhajaj et al [38] used KPIs in a different manner. The approach in this study was to use so called non-monetized KPIs to examine the overall effects of key operating parameters to the overall system behavior. The system behavior refers to the developed model in this study, which was a model of an amine-based post combustion CO_2 capture plant and CO_2 compression. The benefit of including such non-monetized KPIs to process monitoring according to this study is the explicit consideration of the trade-offs between capital and operating costs, and environmental impacts. The non-monetized KPIs used in this study can be found from Table 3.1.

Table 3.1 *KPIs used in the study by Alhajaj et al [38].*

Non-monetized KPI	**Unit**
Reboiler duty	MJ/ton CO_2
Cooling duty	MJ/ton CO_2
Volume of packing	m^3/ton h-1
Ancillary power consumption	kWh/ton CO_2
Amine slippage	kg/ton CO_2
Solvent flow rate	m^3/ton CO_2

This study managed to reach its research goals, and the used methodology and results demonstrate the feasibility of KPIs in a techno-economic study, with the ability to consider additional aspects such as environmental impacts. This study implicates, that similar methodology could prove to be useful also in a CFB-based power plant environment.

A very traditional way of using KPIs was used in a study by Cabeza et al in 2015[39]. In this study authors aimed to identify KPIs for thermal energy storage (TES) systems. TES applications can be varying from technical point of view and up to day only KPIs for TES systems in solar power plants and buildings were found in literature. Goal of the study was to find KPIs common for more types of TES systems, so benchmarking and financial and environmental comparison between different types of TES systems would become easier in the future. Lack of this type of comparisons was found to be hindering the progress of TES applications. This study demonstrates well, how KPIs can be used for benchmarking and evaluating technical solutions from multiple points of views.

Other interesting studies related to KPI monitoring are for example: a study by Personal et al. that used KPIs as a tool to asses Smart Grid goals [40], a study by González-Gil et al. that used KPIs for energy management of urban rail systems [41] and a study by Hanak et al. that used KPIs for probabilistic performance assessment of a coal-fired power plant [42].

3.2 Key performance indicators of a CFB boiler island

The process of burning solid fuel in a CFB boiler for superheated steam production is a complicated process consisting or several different sub-processes and technical solutions and devices. Modern methods and technologies allow gathering of large amounts of measurements, even in challenging environment such as a CFB boiler. Hence monitoring of such complicated process can become at the same time more accessible and challenging as more and more data is available for the user. Therefore, detecting KPIs and evaluating them becomes very valuable, as this allows the user to detect the most valuable information from large amounts of accessible data.

There are a few possible ways to categorize these KPIs into different subcategories. One way is to divide them into directly measurable ones and computational ones; temperatures and pressure differences would belong to the former category and efficiency coefficients would belong to the latter. Other way would be to categorize KPIs under the sub-process or component that they refer to, for example label all boiler related KPIs under the tag boiler and so on. There are no fixed rules or ways to measure which way is the best and it is up to the user to decide how to process information.[43]

Typical KPIs of a CFB power plant are for example: temperatures and pressures both in steam circulation system and on the flue gas side, pressure drops over certain areas or components, efficiency coefficients for certain sub-processes or components, emission levels and flue gas compositions and mass flow rate of flue gases. The identification and evaluation of these KPIs requires solid expertise and knowledge, not only about the overall CFB process, but also about the specific power plant project at hand and its customer's needs. This is due to the fact, that every power plant project is unique and is designed to its customers' needs and hence its KPIs and their relative importance may vary from case to case. For example, emission levels might be much more relevant factor for a power plant that is operating in a country with strict emission limits, than it is to a similar power plant located elsewhere with looser emission limits.[43]

One thing common for every CFB power plant is, that its main purpose is to produce superheated steam to its customers' needs. Hence certain trends in importance of KPIs can be identified, that also have straightforward connections to the cost structure of the boiler and power plant. Two topics of major importance can be found, the ability to produce steam and the avoiding of unavailability. Therefore, KPIs that indicate the boilers ability to meet its production needs or indicate possible failures, that in worst case can lead to shutdown of the power plant, should be prioritized in every CFB power plant. These are also the most important KPIs from a cost point of view as the connection to cost structure if extremely important and straightforward; during downtime the power plants output is zero and it should be avoided at all costs. An example of a such critical KPI is maximum temperature difference in the bed as this KPI can indicate sintering of bed material, which can in the worst-case lead to shut down of the boiler.[33] How these identified KPIs are located in CFB boiler is illustrated in Figure 27.

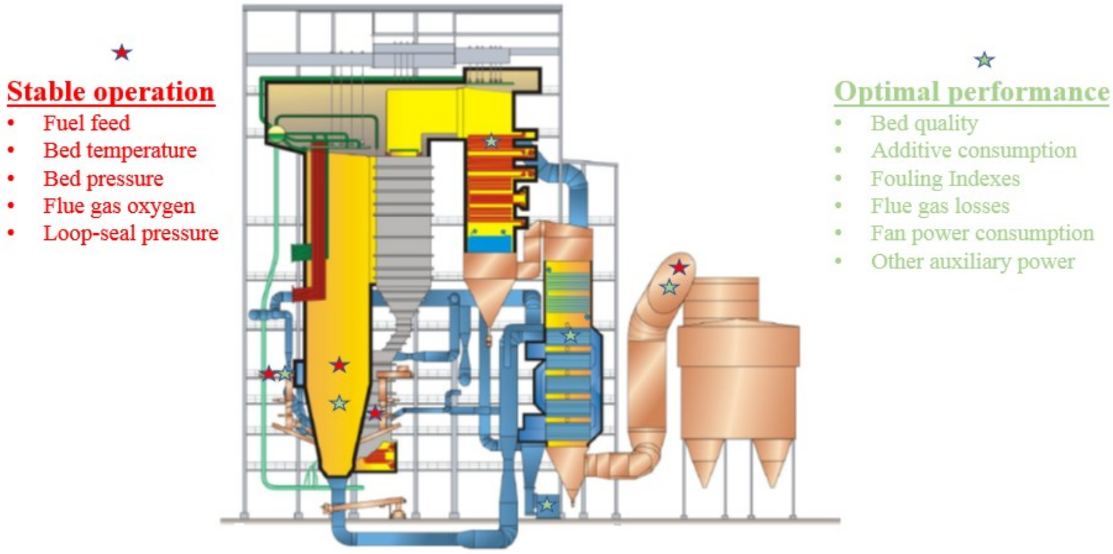


Figure 27. *Key performance indicators of CFB boiler. Produced by author.*

The optimal performance is the next most important thing, but it can only be a matter of importance after the boilers solid base operation is secured. This is due the fact, that the improvements gained by optimal performance are typically in the order of magnitude of percent’s. With such small scale gains it takes a long time to catch up the losses of an unexpected shutdown. During normal operation, when optimal performance can be a priority, the most important KPIs from a cost point of view are those, that are correlated with the cost structure of the CFB boiler, that is presented in chapter 2.3. Examples of most relevant from these KPIs are power consumption levels of fans as they correlate to auxiliary power consumption, flue gas temperature and mass flow as they correlate to flue gas losses and boiler efficiency and bed quality as it correlates to mass flows of additives and make-up material. [33]

As a conclusion can be said, that from cost point of view KPIs of a CFB boiler and therefore also power plant should be monitored in a two-layered structure. Firstly, normal and stable operation of the boiler should be secured and KPIs that correlate to this should be prioritized. Secondly comes the optimal performance during normal operation and KPIs that correlate to this should be monitored with secondary priority.[33] Author suggests a similar method for KPI monitoring and evaluation for cost point of view as was the used in the study by May et al, which is illustrated in Figure 26. The exception being, that variables in this cost effect evaluation matrix are availability and optimal performance. This suggested method is illustrated in Figure 28.

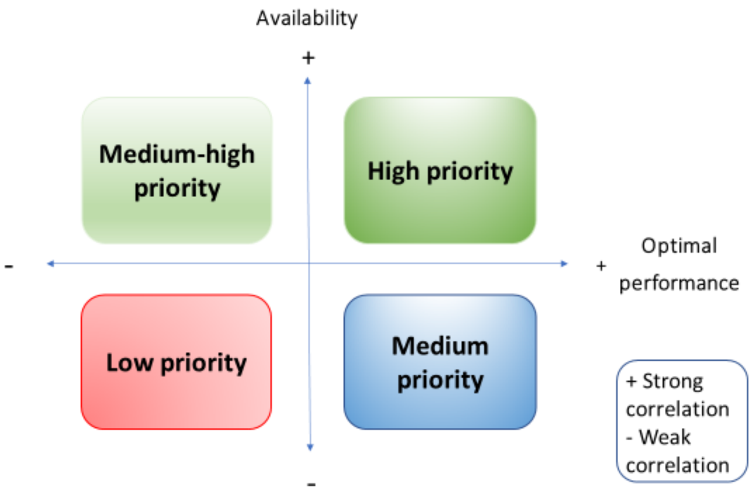


Figure 28. *Cost effect evaluation matrix for Key performance indicator monitoring in CFB boilers proposed by author.*

The choice of soot-blowing cycle as an optimization problem was done based on KPI monitoring method where all KPIs of a CFB boiler island are identified and then evaluated with scale that indicates relative importance to output of the boiler. The identification and evaluation of the KPIs of the CFB boiler island was done as a groundwork for this thesis and the author does not claim to be a contributor for that groundwork. Over 100 KPIs with varying relative importance were identified. [43]

4. OPTIMIZATION METHODS AND TOOLS

In this thesis the problem of the most cost-efficient soot blowing cycle in the back-pass of a CFB boiler was solved by forming a time-variant cost function that describes the problem at hand in a realistic way. Then mathematical tools were used to find the moment of time where this cost function reaches the price of a single soot-blowing cycle. Even though this problem was chosen as topic of interest in this thesis, other options for cost-optimization also do exist. In the future the scope should be broadened from a single optimization problem to whole boiler island and power plant level optimization. Therefore, to provide insight on broader scale optimization problems and methods, references of different optimization methods and problems are demonstrated in this Section. Also, a literature review regarding state of the art soot-blowing optimization was concluded and the results are presented in Section 4.1.1. The chosen mathematical tools and software that were used to solve the optimization problem in the computational part of this thesis are also introduced shortly.

4.1 References of different optimization methods

In this Section examples of methods to solve optimization problems are presented. This thesis aims to be groundwork for whole plant level optimization and as such references regarding research done for whole plant level optimization are presented in chapter 4.1.1. Also, as the scope for actual optimization done in this thesis was chosen to be soot-blowing, references regarding soot-blowing optimization are presented in chapter 4.2.2.

4.1.1 Power plant level optimization problems and methods

A study by Zhang et al. [44] aimed to optimize a novel CHP-system, that is based on ground source thermal heat pump (GSHP) and partial biomass gasification. The system configuration is illustrated in Figure 29.

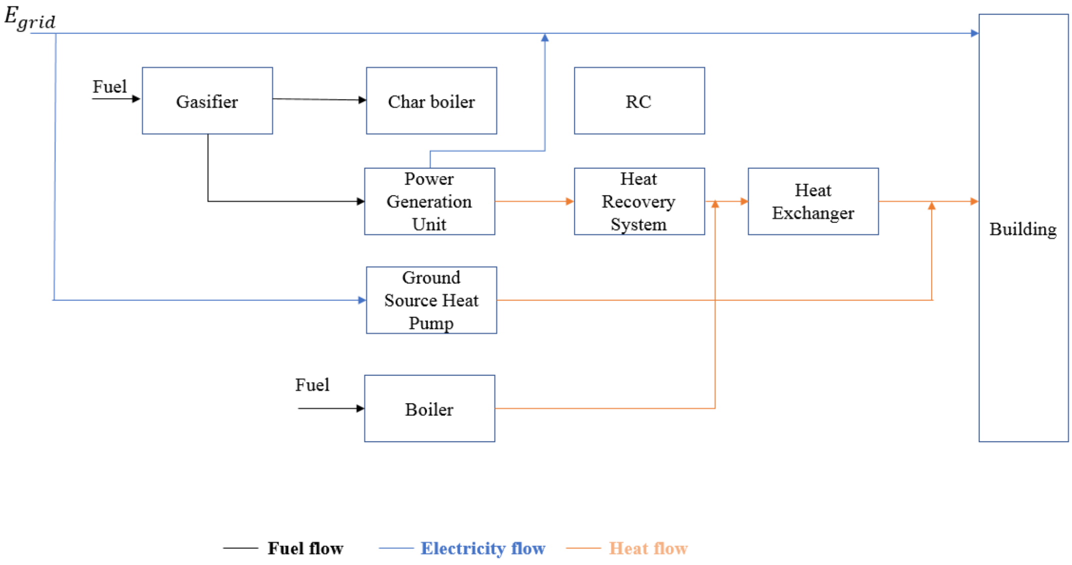


Figure 29. *Simplified configuration of the optimized CHP-system. Modified by author based on the original study by Zhang et al [44]*

The different components of the proposed system and their functionalities are explained in detail in the following chapter. Electricity is created with Rankine cycle (RC) and power generating unit (PGU). The gasifier uses biomass as input fuel and provides fuel for both the PGU and char boiler as its output. The char boiler then produces heat for the RC. Generated electricity in the used both for powering the GSHP and to provide power for the needs of the building. The thermal energy needs of the building are produced with the GSHP and a combination of heat recovery system and heat exchanger, which utilize the heat from the hot flue gases of the PGU. The auxiliary boilers only function is to provide thermal energy when the thermal energy demand of the building is higher than the production capacity of the proposed system. If the proposed system can't produce enough electricity, the building utilizes the utility grid for the missing portions of its capacity.

The goal of the study was to optimize the system from energy, economic and environmental aspects. The authors opted to use Genetic Algorithm (GA) to solve this multi-objective optimization problem. The optimized parameters were defined to be the following: primary energy saving ratio (PESR), annual total cost saving ration (ATCST) and CO2 emission reduction ratio (CO2ERR). The optimized multi-objective function, named as performance indicator (PI), was then defined as follows

$$PI = \omega_1 \times PESR + \omega_2 \times ATCST + \omega_3 \times CO2ERR \tag{12}$$

were coefficients ω_n are weights describing the relative importance of each factor. GA was chosen as an optimization algorithm in this study, since it is widely known to be suitable for similar optimization problems as it has fine global search capability. A specified case study of a hypothetical building demand was then used to test the model performance.

Another study regarding multi-objective optimization of a CHP system was concluded by Bracco et el [45] in 2013. The optimized system was a distributed CHP based system located in urban area. The goal was to optimize this system from both economic and environmental aspects as the developed model aimed to minimize both capital and operation costs and carbon dioxide emissions. The optimization model in this study was developed using mixed-integer linear programming.

A study concluded in 2017 by Li et al [14] aimed to develop a method for whole plant level optimization under full working conditions. This means that model was designed to work on full range of operation, when the more typical approach is that a model is only valid for example during base load time or peak load time. The suggested method is based on operation data and dominant factor modelling. The whole plant was divided into four different zones that were inspected separately. The zones were pipes, stages of turbine, heat exchangers and pumps. The method suggested in this study managed to gain 0,2 percent increase in thermal efficiency on the 330 MWe power unit used in the case study.

Another study regarding optimization of CHP plants was concluded by Savola et al in 2005.[46] This study was focused on small scale biomass based CHP plants with a range varying from 1 to 20 MWe. The aim was to optimize the power output of the power plants. The authors used mixed integer non-linear programming for the optimization model development and results from this model showed to be very promising.

4.1.2 Soot blowing optimization methods

A journal article by Piboomtum et al [8] demonstrates a commercially available soot-blowing optimization system. The model used in this study uses furnace exit gas temperature (FEGT) for determining the cleanliness rate of the boiler. FEGT is also used as a starting value for the soot blowing optimization system named Powerclean. This Powerclean system is able to control the water and steam spray systems that are used for cleaning the heat-transfer surfaces. The Powerclean system can also monitor boiler operation and provide a comparison of actual performance compared to the expected performance over different varying load ranges. This monitoring allows to gather information about how well the soot-blowing optimization is performing and gives insight whether the surfaces are over- or under cleaned.

Another existing commercial system for soot-blowing optimization was developed in China in a government-funded program by Li et al. and it is presented in a paper.[9] The boiler used in as a case example in this study was a 900 MWe PC boiler. This study clearly demonstrates, that soot-blowing optimization systems can be applied regardless of boiler capacity or type.

In a report in 2004 Rhode [47] presented a Neural Network based intelligent soot blowing (NN-ISB) system module. Instead of using timeframes or general rule-based protocols, for example the fouling rate, for determining the optimal soot blowing cycle, this presented method uses a more sophisticated approach. The NN-ISB system can modify the sequence of soot blowing according to occurrences or conditions in the boiler in a proactive or on-line manner. This creates a major advantage to the typical retrospective monitoring systems. This method was tested for a PC boiler in the study and the results showed to be promising. This study clearly demonstrates the power of neural networks for solving the soot-blowing optimization problem.

Study by Pattanayak et al [10] suggested a method based on similar parameters as used in this thesis for soot-blowing optimization. The method includes defining the cleanliness factor, which is defined as the ratio of the actual heat flux to the heat flux in a clean state. The method used in this thesis uses similar approach to fouling monitoring. The method suggested in this study differs from the one used in this thesis, as neural network approach is not applied to solve the optimization problem in this thesis. The structure of the optimization model is illustrated in Figure 30.

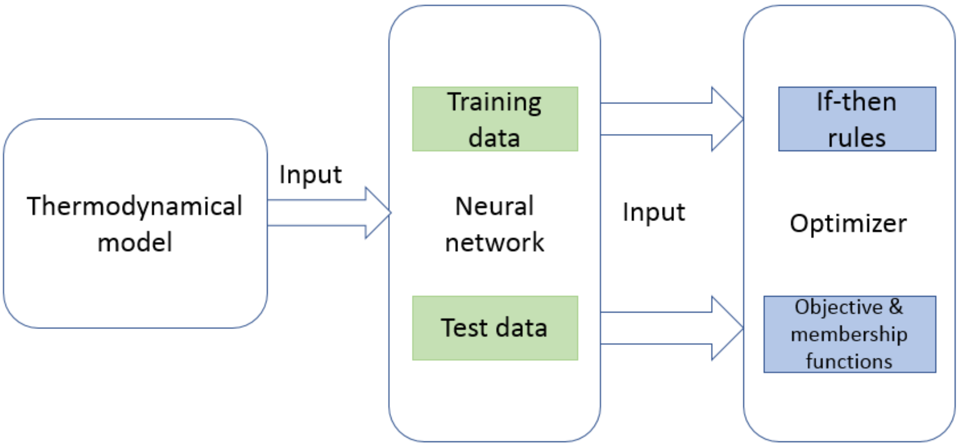


Figure 30. *The soot-blowing optimization model. Modified by author based on the original study by Pattanayk et al[10]*

Use of similar parameters in a more complex method in an independent study and the results of that study indicate, that method chosen for this thesis is appropriate for solving the chosen soot-blowing optimization problem.

Peña et al suggested using soft-computing models for soot-blowing optimization in coal-fired utility boilers in a study concluded in 2011. [11] The suggested method aims to develop a probabilistic model to predict the effectiveness of soot-blowing. The method is a hybrid system based on two different kinds of models; Artificial Neural Networks and Adaptive Neuro-Fuzzy Inference Systems (ANFIS). The main goals of this study were the following. Firstly to improve the fouling prediction model that was developed by one of the authors in a previous study [6]. Secondly to systematically evaluate how much value the predictive model can create to the operator staff as an advisory tool. Finally, to demonstrate the quality and functionality of the suggested method, a comparison of ANN and ANFIS models was concluded. Figure 31 demonstrates the topology of the ANFIS models.

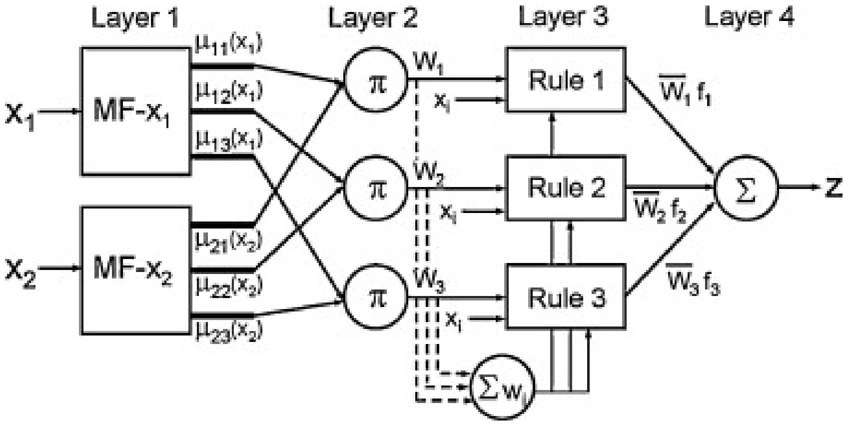


Figure 31. *Type-3 ANFIS topology with two inputs and three rules. Taken from the original study by Peña et al [11]*

The results of the study lead to a conclusion, that techniques give similar results, but predictions made by the ANN model were slightly more accurate.

Another state of the art hybrid system for fouling control was suggested by Romeo et al in 2006 [12]. This suggested hybrid system combines neural networks (NN) with Fuzzy-Logic Expert System (FLES). The system aims to select the moment for activating a soot-blowing cycle in boiler firing biomass. The benefits of the suggested system are minimizing energy efficiency losses in the boiler and improved fouling control. The suggested system is comprised of several sets of NN, that each have their own purpose. The NN are responsible for boiler monitoring, fouling forecasting and predicting the boiler behavior and cleaning effect if the soot-blowing cycle was activated. The system is completed with a FLES application, that makes the decision of soot-blowing cycle activation based on the prediction of the NNs. The structure and functions of the suggested hybrid system are illustrated in Figure 32.

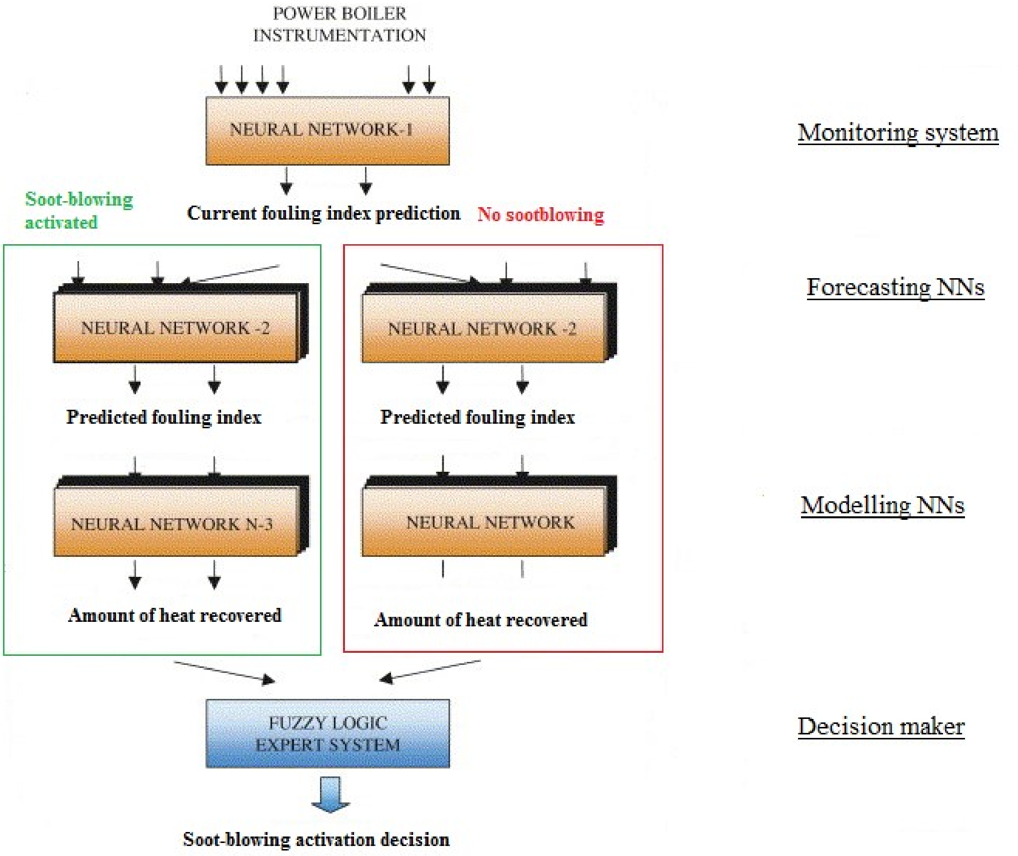


Figure 32. *Hybrid system for soot-blowing optimization. Modified by author based on the original study by Romeo et al [12]*

The suggested NN structure functions as follows: The thermal monitoring system is based on boiler simulation and it is responsible for managing historic and on-line data, calculating boiler fouling indexes and selecting objective variables. It also prepares the data for the training of the following NN. The following parallel boiler fouling evaluation NNs predict fouling indexes with and without soot-blowing based on the outputs of the previous NN. After that the following parallel NNs are used to evaluate the thermal response of the boiler in both cases. The forecast the energy responses to know the hourly energy improvements in both scenarios. The relations between input variables and outputs of the monitoring and forecasting NNs are illustrated in Figures 33 and 34.

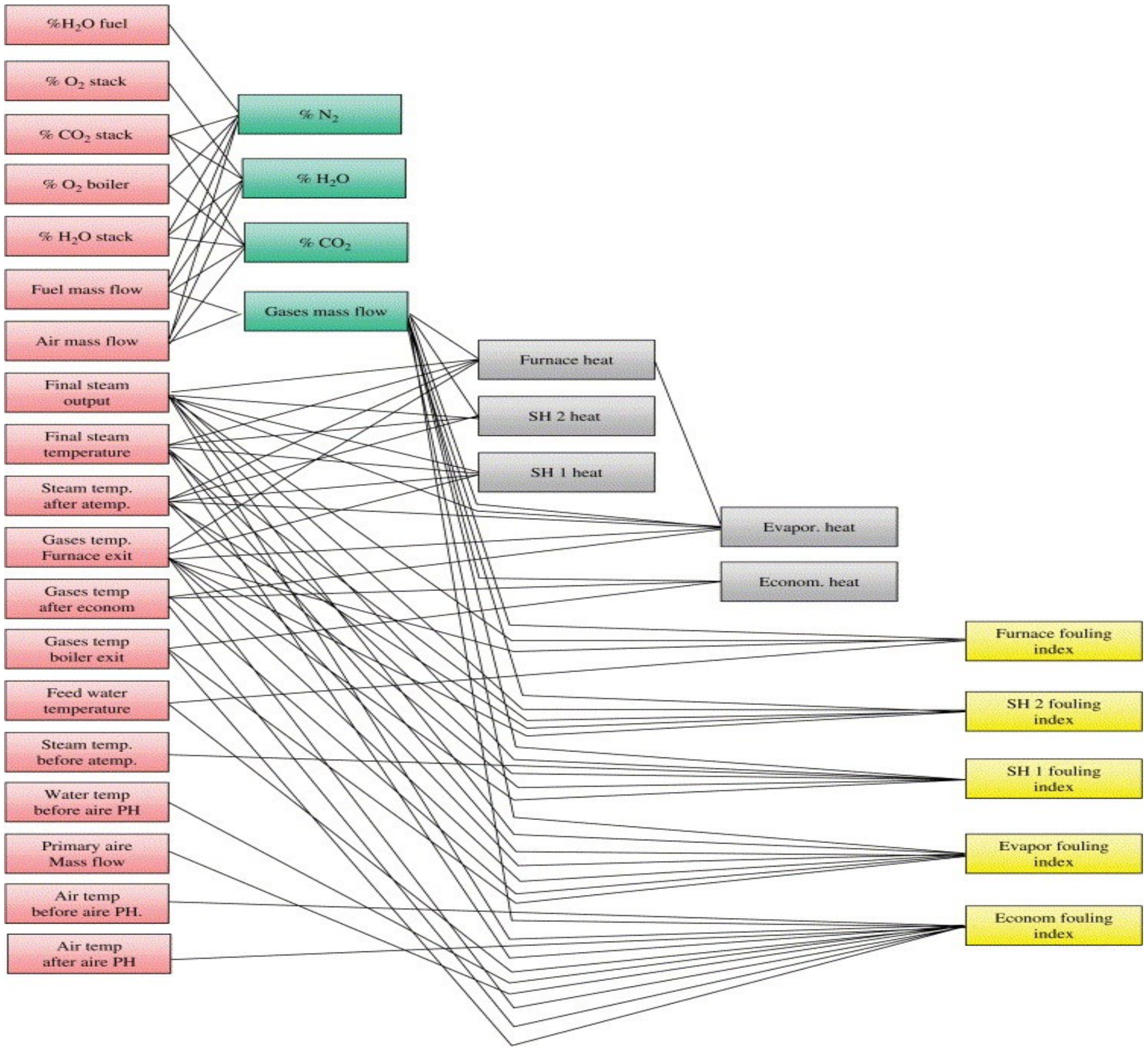


Figure 33. *Relation between variables of the three monitoring neural network sets. Taken from Romeo et al [12]*

As can be seen from Figure 33. the monitoring NN system is structured in a 3-layered manner, where the outputs of previous NNs are used as inputs for the following NNs. The final output parameters of this monitoring system are the fouling indexes.

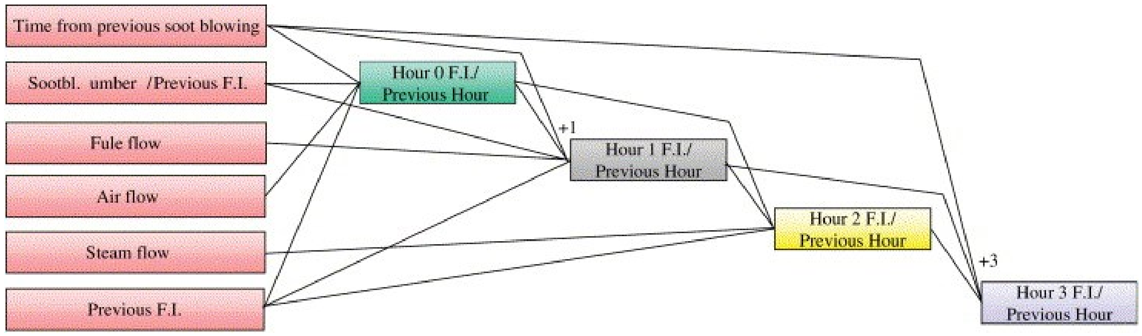


Figure 34. *Relation between variables of the fouling forecasting neural network sets. Taken Romeo et al [12]*

As can be seen from Figure 34. the forecasting NN system aims to predict the fouling behavior of the boiler after certain times based on the FIs produced by the previous monitoring NN systems and few other process parameters. The output value is the passed on to the fuzzy logic-based expert system as presented in Figure 32.

The hybrid system is finished with a soot-blowing decision maker that takes the predictions on previous NN as input and uses a FLES application to decide the right time for activation and chooses the right type of a soot-blowing cycle. The functionality and structure of the FLES applications is illustrated in Figure 35.

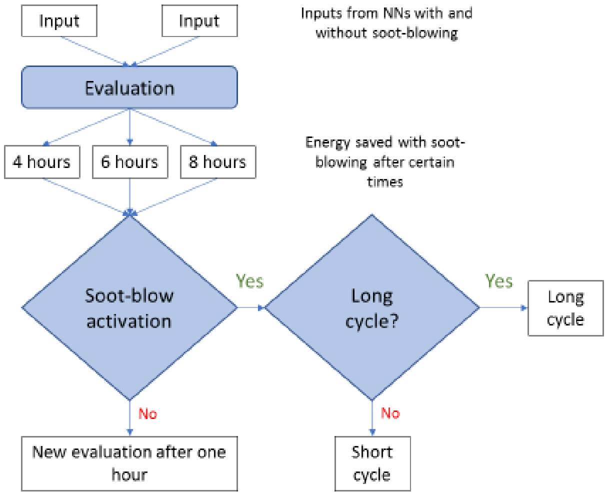


Figure 35. *Fuzzy-Logic Expert System design for decision making regarding soot-blowing activation. Modified by author based on the original study by Romeo et al [12]*

The suggested hybrid system managed to improve the power output the case study boiler by impressive 3.5 percent. This state of the art study demonstrates the power of sophisticated artificial intelligence-based optimization systems and clearly proves they are applicable to soot-blowing optimization. Downsides of this type of systems are their rather complex nature and the need for excessive amounts of training data.

As can be seen from previously presented studies regarding soot-blowing optimization, fouling modelling and monitoring functions as a baseline for many soot blowing optimization methods. A few examples of studies regarding fouling monitoring are the following studies by Afgan et al in 1996 [5] and by Teruel et al in 2005 [6] and they are presented in more detail earlier in chapter 2.2.3. Current state of the art regarding soot-blowing optimization systems is, that many sophisticated systems that use artificial intelligence are available. This implicates that there is room for improvement and future development work regarding the more simpler approach that is applied in this thesis. This should be considered when more resources, such as sufficient neural network tools and sufficient amounts or validated data for training are available for the development work. Even though the presented studies demonstrate that the method applied in this thesis is a solid approach and works also as a baseline for future development work.

4.2 Matlab and Excel based tools

The modelling and optimization work in this thesis was done using Matlab and Excel software and Sumitomo SHI FWs data acquisition system called Smartboiler. Smartboiler is local server-based system, that gathers all the measured data from the power plant and performs process calculations to calculate values and indexes, that cannot be gained with straight measurements. For example, the FI and flue gas loss values, that are used in the research part for optimizing the soot-blowing cycle, are values that the Smartboiler calculates based on process measurements. Typical values that such system can collect with straight measurements are temperatures, pressures and flow rates. Values such as flue gas loss and boiler efficiency are then calculated from the measurements based on balance calculations and process models. These models typically have some error margin due to boundary assumptions, but this error is rather insignificant compared to the error margin of the measurements done in a challenging environment, such as CFB boiler.

Excel was used mainly for handling the process data, that was retrieved from the studied power plants using the Smartboiler data collection system. The visual presentations of the results were also done using Excel.

Matlab was used for modelling and optimization calculations. The engineering fits used in this thesis for flue gas loss and fouling index modelling were done by the curve fitting toolbox in Matlab. All optimization and process calculation, that were needed to calculate the most cost optimal soot-blowing cycle, were done with symbolic toolbox in Matlab.

5. OPTIMIZATION TOOL DEVELOPMENT

The soot blowing cycle in the back-pass was chosen as the target for optimization in this thesis. This decision was made for multiple reasons; firstly, as can be seen from market trends presented in Section 2.2, the share of biomass as fuel has increased in recent years and it is expected to keep on increasing in the near future and fouling is a topic of major importance concerning boilers that fire biomass. Hence this type of an optimization tool will be very useful already in the current market situation and will become even more relevant as the portion of boilers that fire biomass keeps increasing. Second most important reason for this particular choice of scope was its simplicity and straightforward correlations to the cost structure of the boiler. As many real-life processes are, the CFB boiler island is a complex process with many feedback connections. This leads to a situation, that optimizing the whole boiler island or power plant will become a very complex problem, as changes made in certain parts of the process can change the sub-processes before it and thus can nullify the gained savings. When approaching such large and complex problem, it is often practical to start from the simplest parts and try to obtain solid results there and then start to broaden the scope of problem part by part. The development of this tool therefor aims to answer the third research question*: Can soot-blowing optimization be proven to be suitable for cost optimization?*

Six different power plants were chosen for inspection in this thesis. These specific power plants were chosen, because they fire different types of fuels and they operate on varying modes. By choosing different types of power plants, it is possible to identify possibilities and problems regarding the soot blowing optimization. These power plants operate with CFB boilers, but as discussed in Chapter 2.2.3 the differences between CFB and BFB boilers regarding ash-related issues are not very significant. The most significant difference is, that in certain cases the amount of fine fly-ash can be higher in BFB boilers. This can lead to a situation, that soot-blowing cycles for BFB boilers might need to shorten on average compared to CFB boilers. The presented optimization method is based on such parameters that are independent of boiler type and therefore is suitable for both CFB and BFB boilers.

5.1 Optimization problem

As stated earlier in this thesis, power plants typically operate according to the desired electricity output and operation is designed to keep the output on a desired and stable level. After a soot-blowing cycle has ended the heat transfer surfaces of the boiler begin to foul and its operating efficiency starts to weaken due to the increasing flue gas losses. After a certain point, this fouling begins to either decrease the electricity output, which will then cause a need for additional fuel flow to keep the output on the desired level or requires additional fuel to keep the same level of desired output. The next soot-blowing cycle is typically initiated before this point to prevent fluctuations in the process. The concept of soot-blowing is illustrated in Figure 36. with all related energy/cost flows.

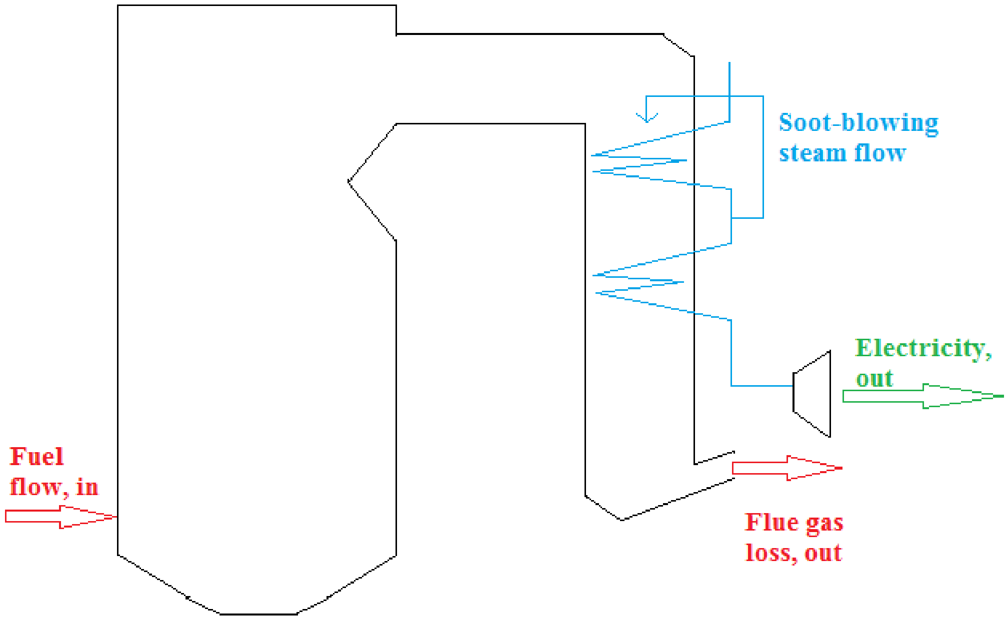


Figure 36. *Energy/cost flows related to the soot-blowing optimization. Produced by author.*

As can be seen from Figure 36 the steam used for soot-blowing is taken from the process and during the soot-blowing cycle this steam needs to be compensated with additional fuel flow in order to keep the electricity output on the desired level even during the soot-blowing cycle. The amount of steam needed for a single cycle is approximately a constant value, as it is defined by the design of the soot-blowers. Hence the operational cost of a single cycle is a constant value. The optimization problem can then be defined as finding the time when the increasing flue gas losses between soot-blowing cycles have reached the price of a single soot-blowing cycle. This problem is illustrated in Figure 37 on a schematic level.

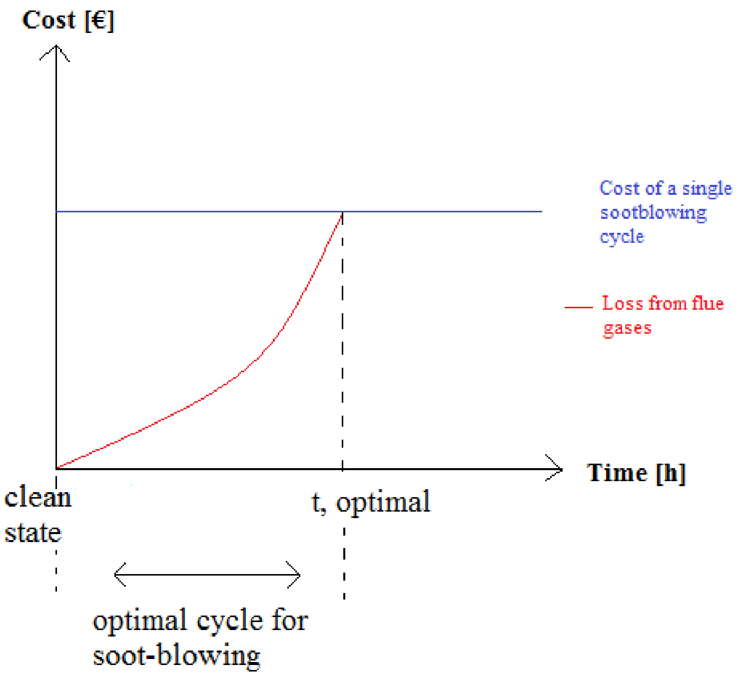


Figure 37. *Schematic illustration of the process of defining the most cost-efficient soot-blowing cycle. Produced by author.*

As can be seen from Figure 37, at a certain time point the cost from the flue gas losses reach the price of a soot-blowing cycle and this is theoretically the most cost-efficient sequence for soot-blowing from operational point of view. Mathematically this optimization can be seen as solving the following equation:

$$Cost_{FGloss}(t) = Cost_{Sbcycle} \tag{13}$$

The equation for flue gas losses over time was modelled for each inspected power plant separately from operational process data and this is explained in more detail in chapter 5.4. The developed method for soot-blowing optimization is illustrated as simplified flowchart in Figure 38.

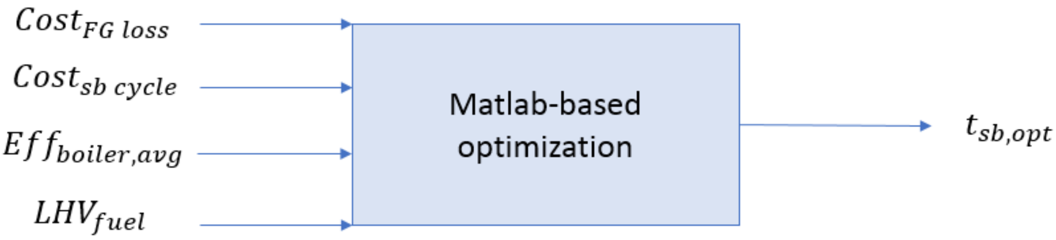


***Figure 38**. Simplified flowchart for soot-blowing optimization.*

It needs to be noted, that soot-blowing is performed not only from an operational point of view, but also as a maintenance action to prevent corrosion related problems in heat-transfer surfaces and to prevent excessive maintenance needs during yearly maintenance stoppages. These factors form the technical framework for soot-blowing optimization and this is discussed in more detail in chapter 5.3.

5.2 Case study power plants

Five power plants with varying nominal power outputs and fuel types were chosen under inspection for this thesis. These power plants represent the most typical fuels fired in CFB boilers and are of varying operating types. By choosing such varying power plants, more profound analysis regarding the gained results can be concluded. Especially the veracity and reliability of the results can be assessed in more precise manner as there are known facts about the fouling tendencies of certain fuel types. The analysis of gained results in comparison to expectations based on previous knowledge is concluded in detail in chapter 6. The properties of the power plants under inspection in this thesis are presented in Table 5.1

Table 5.1 *Properties of the case-study power plants*

Power plant	Type	Fuel	Steam capacity [MWe]	Main steam flow [ton/h]
PP A	CHP	Demolition wood	27	101
PP B	Power	Biomass-wood	55	215
PP C	Power	Peat	100	280
PP D	CHP	Peat & biomass-wood	200	576
PP E	Power	Biomass-wood & crop waste	205	569
PP F	Power	Coal-bituminous	460	1298

These power plants represent typical CFB boilers from fuel and design point of view. Exceptions are, that power plant F is once-through boiler with super-critical steam parameters, which is somewhat rare for CFB boilers. This design is illustrated in theoretical part in Figure 7.

Power plant A is also slightly different design, as it is a relatively small-scale boiler and it fires demolition wood, which is somewhat challenging fuel compared to for example clean wood, which is more typical biomass fuel. This design difference between demolition wood and typical biomass CFB boilers is illustrated in theoretical part in Figure 8. As can be seen from Figure 8, the most significant difference in the convective part of the boiler is, that in case of demolition wood design hanger type superheater surfaces are utilized and they are located on the horizontal pass, whereas in case of typical biomass design all heat-transfer surfaces are located on the vertical pass.

Even though these power plants have different boiler designs and fire different fuels, the same methodology can be applied to all these power plants.

5.3 Technical framework for soot-blowing optimization

As presented earlier in theoretical part, soot-blowers are cleaning devices, that utilize process steam to remove deposit layers from heat transfer surfaces. There are also other technical solutions for soot-blowers, but all power plants presented in this thesis utilize steam-based soot-blowers. In the scope of this thesis soot-blowing is treated as a cycle, that cleans all the heat transfer surfaces during one cycle but depending on the soot-blowing manufacturer and soot-blower type, configurations where only individual soot-blowers are activated for specified surfaces is also possible. This is discussed in more detail for future development work in section six.

Soot-blowing is done mainly to improve heat transfer and to return the process to clean state operation, but also to reduce corrosion risk in heat transfer surfaces and to prevent blocking up of the tube packages due to excessive deposit layer formation. These risks set the end boundary for soot-blowing cycle optimization as they are severe risks that would lead to prolonged yearly maintenance breaks or could lead to shutdown of the power plant in the worst-case scenario. Evaluation of these risk as an exact mathematical time variant function is extremely difficult and it not considered is this thesis more thoroughly, but it is treated as a limiting factor, that is evaluated based on former knowledge regarding the operation of the power plants.

Another important technical solution regarding soot-blowing operation is so-called desuperheaters. These are technical solutions that are used to control steam temperature by spraying water into the steam flow. Desuperheaters are typically located before superheaters so that they can be used to adjust steam temperatures before the superheater and can react both to rising and falling steam temperatures. Typical situation where desuperheaters are used to lower steam temperatures is when the heat-transfer surface is fully cleaned, and superheater is operating at its peak. In such situations there is risk that material temperatures in the superheater surface can rise too high and hence the steam temperatures are lowered by fully opening the desuperheater valve. Typical situation where desuperheaters are used to raise steam temperatures is, when the heat-transfer surface becomes foul and superheater performance starts to lower. In such case the desuperheater flow is decreased to compensate the lowering steam temperatures. Typical structure of a desuperheater is illustrated on a schematic level in Figure 39.

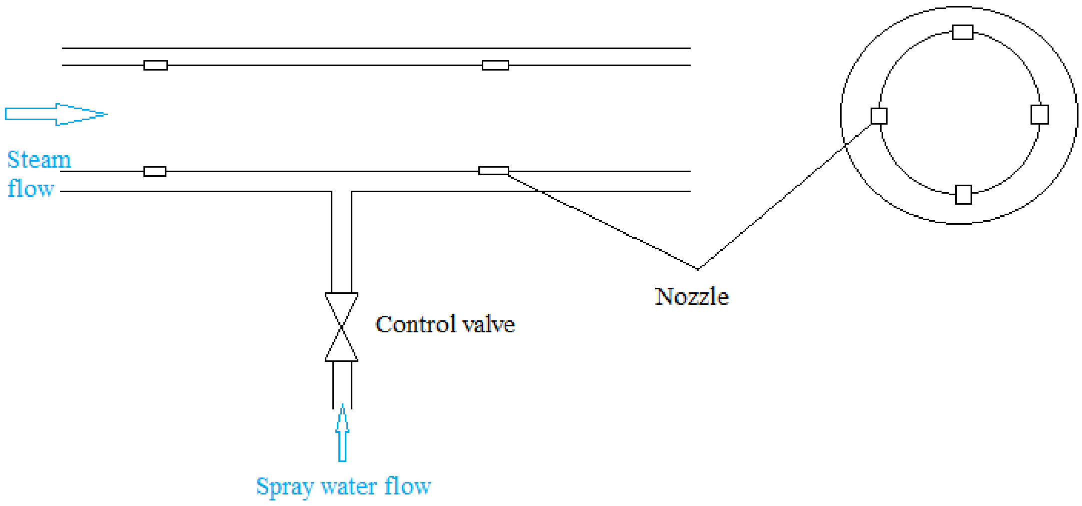


__Figure 39.__ Schematic illustration of a desuperheater

As can be seen from Figure 39, desuperheater controls the steam temperature by adjusting the amount of water that is sprayed into the steam. During the peak performance of a superheater, which is right after the soot-blowing cycle is initiated and the heat transfer surface is clean, the spray water flow is at is maximum and it starts to decrease until the control valve is fully closed. If the power plant is operating at varying loads new soot-blowing cycle should be initiated before the spray water control valves are fully closed, so that the steam temperatures have margin for adjustments according to the load demand. During stable load operation the importance of spray water flows becomes less significant. The relations between soot-blowing steam flow and spray water flow is illustrated in Figure 40.

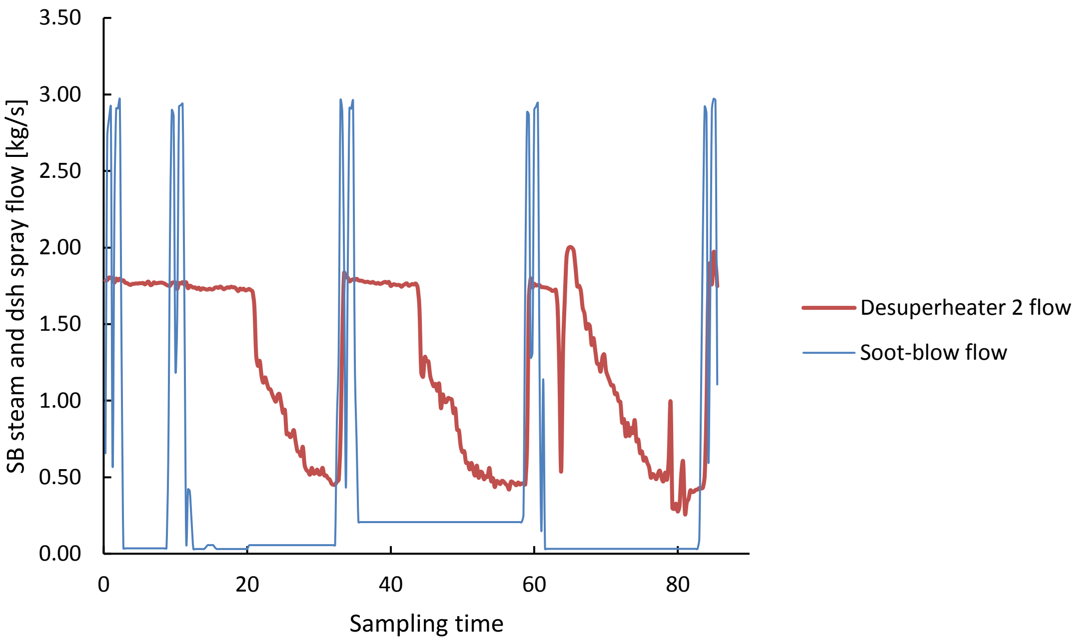


Figure 40. Relation between soot-blowing steam flow and desuperheater spray flow. From one of the case study power plants.

As can be seen from Figure 40, during short soot-blowing cycles, when fouling is minimal, the spray water flow barely changes but as the soot-blowing cycle is prolonged the spray water flow starts to decrease. Desuperheaters are a multifunctional solution as they allow adjusting the steam temperature during load changes and compensate small scale fouling without needing for additional fuel flow. This is explained and illustrated in more detail in chapter 5.4 and Figure 45.

5.4 Fouling and flue gas loss modelling

First attempt at modelling the losses between soot-blowing cycles was done by modelling the fouling indexes for each heat-transfer surface and calculating the total losses as a sum of all individual surfaces. Fouling index describes the performance of a heat transfer surface and it can be calculated with equation 5. This approach did not lead to realistic results due to various reasons. First of all, using six different engineering fits, which all have their own error margins leads to unacceptable cumulative error. The second problem can be seen from Figure 41, where the fouling indexes of most clean and most fouled surfaces from one of the case-study power plants are presented over time during few soot-blowing cycles.

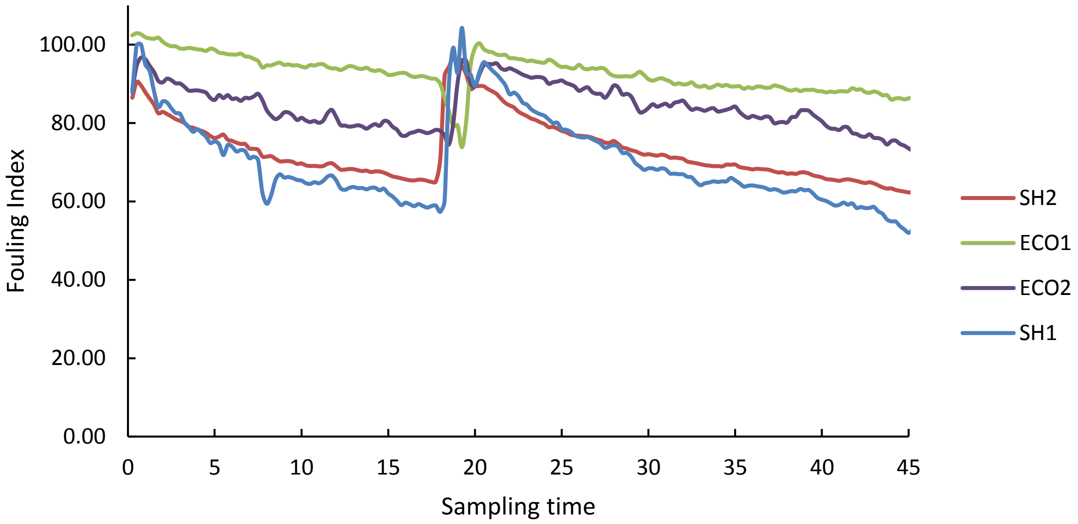


Figure 41. *Fouling indexes of superheaters and economizers over time.*

As can be seen from Figure 41, the fouling indexes of individual heat-transfer surfaces do not reduce in a unison cycle, but the peaks performance of the economizers, which are the last surfaces in the back-pass typically, is reached later than the peak performance of superheaters. This is partly due to the fact, that the duration of the soot-blowing sequence is several hours in large utility level boilers and partly due to fact, that when the first surfaces foul, the flue gases enter the next surfaces hotter than before, increasing the heat-transfer rate of the latter surfaces to some degree. This approach to cost modelling was then discarded, and the flue gas losses were chosen as a modelled parameter. Fouling indexes of individual heat-transfer surfaces still hold value as a monitoring tool for soot-blowing performance, but from a cost point of view the fuel gas losses are a more reasonable parameter to be modelled and used in calculations.

The flue gas losses were modelled using several time series between soot-blowing cycles. This approach is demonstrated in Figure 42.

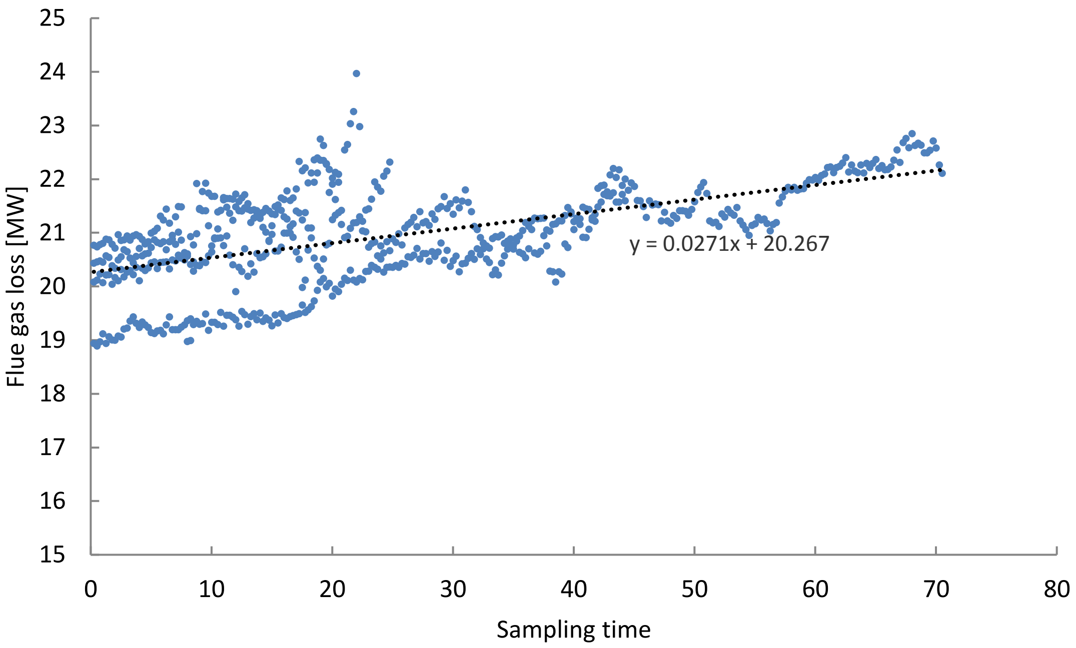


Figure 42. *Flue gas losses over time during soot-blowing cycles. From one of case-study power plants.*

The flue gas loss is a realistic parameter to describe the increasing cost between soot-blowing cycles as it is heat produced with the boiler system, that is not utilized within the process, but is lost outside of the process with the flue gas flow. There are some problems regarding the usage of flue gas losses as a parameter for soot-blowing optimization. Flue gas losses is a dynamic variable that is dependent on multiple variables, such as fuel mixture and load level. Especially fuel mixture is a difficult parameter, as the exact composition of the fuel is in many cases unknown. The dynamic nature of flue gas losses is presented in Figures 43 and 44. These figures present flue gas loss behavior between soot-blowing cycles in power plant E, which fires a varying mixture of biomass and crop waste. The fuel composition varies over seasons as the availability of such fuels is seasonal and this power plant has also utilized soot-blowing cycles with different lengths during different seasons.

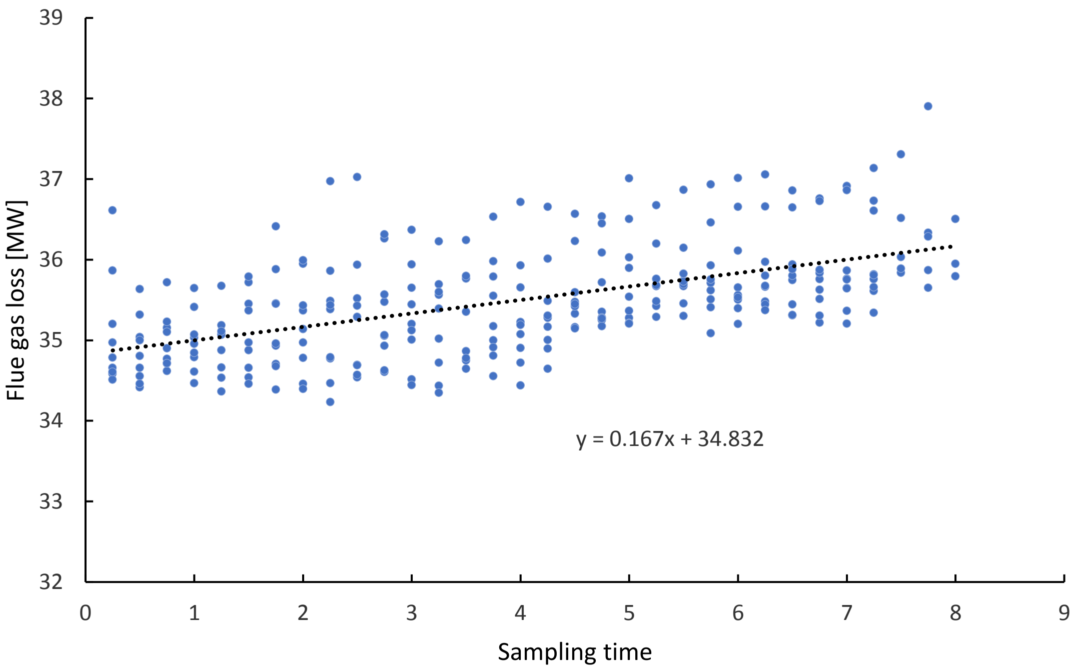


***Figure 43.** Flue gas losses between soot-blowing cycles in power plant E during springtime and with short soot-blowing cycles.*

As can be seen from Figure 43. during springtime and with shorter soot-blowing cycles the coefficient for flue gas losses is 0.167, which implicates that flue gas losses in this plant begin to rise fast after a soot-blowing cycle.

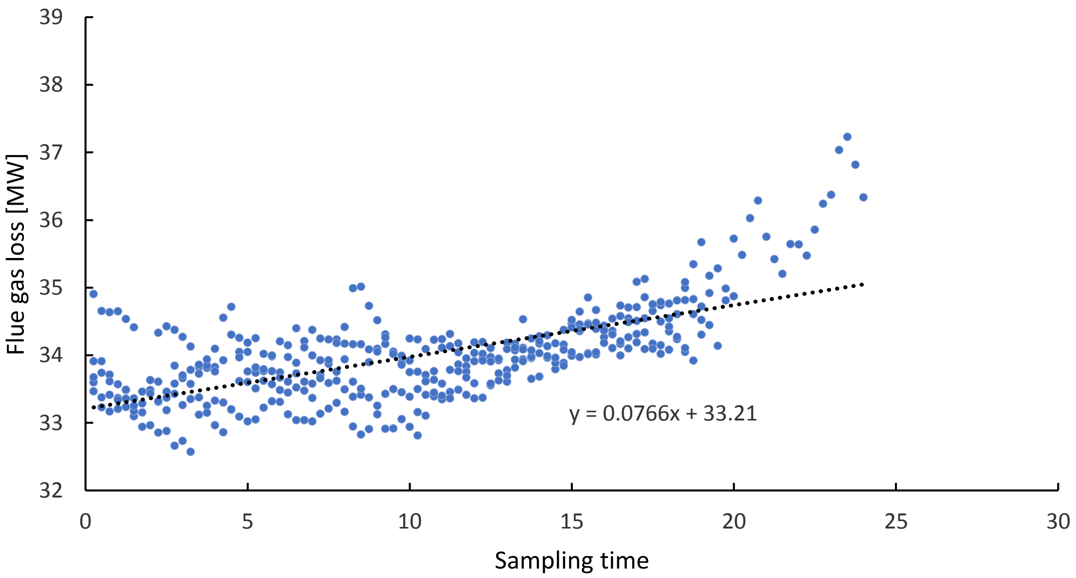


***Figure 44.** Flue gas losses between soot-blowing cycles in power plant E during summertime and with long soot-blowing cycles.*

As can be seen from Figure 44 during summertime and with longer soot-blowing cycles the coefficient for flue gas losses is now lower. It is uncertain whether this difference is due to changed fuel mixture or the behavior due to longer soot-blowing cycles. Taking into account both the fouling index behavior over time presented in Figure 41 and this phenomenon, it is safe to assume, that an accurate model should include both long and short soot-blowing cycles. In this manner over- or undershooting, when extrapolating with too high or low a coefficient, can be avoided.

The relation between flue gas loss, soot-blowing steam flow and fuel mass flow during few soot-blowing cycles is presented more closely in Figure 45.

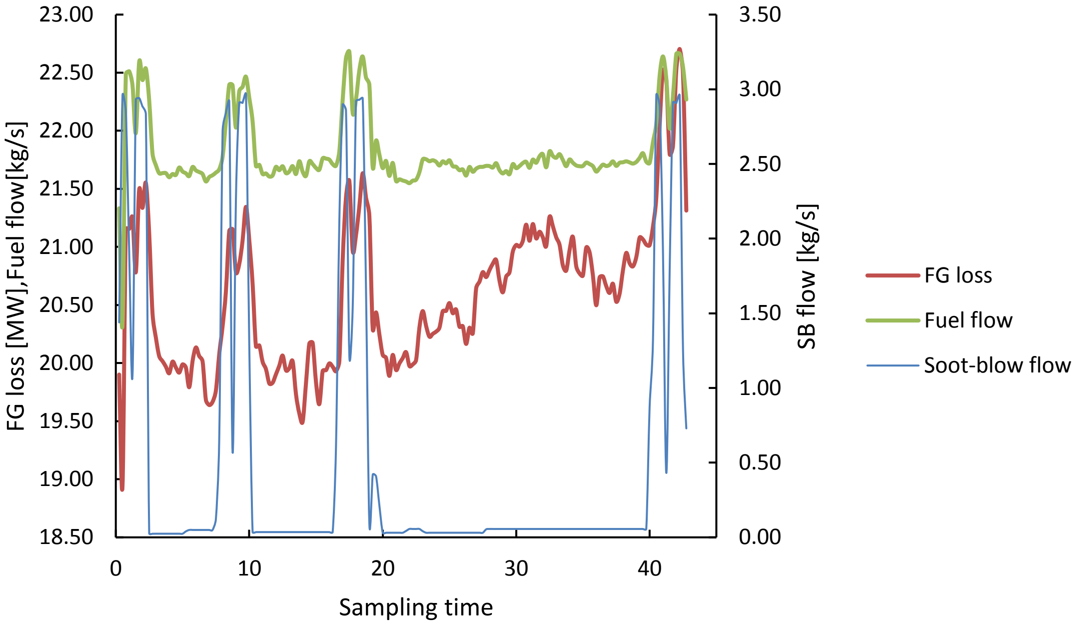


Figure 45. *Relations between fuel flow, soot-blowing steam flow and flue gas losses during few soot-blowing cycles. From one of the case study power plants.*

As can be seen from Figure 45, during short soot-blowing cycles the flue gas losses stay on a stable level, but when the cycle is prolonged the losses start to increase. The peak that the flue gas losses have during the soot-blowing cycle is due to the soot-blowing steam flow as it is sprayed to the back-pass as presented in Figure 33 increasing the flue gas steam flow during the cycle, hence increasing the flue gas losses as lost power. It can be seen from Figure 46, that even though the soot-blowing cycle is prolonged, the fuel mass flow does not start to increase significantly. This phenomenon is due to spray water flow as explained in Chapter 5.3. and also somewhat due the inaccuracy of the measurements.

5.5 Optimization of the soot-blowing cycle

In order to be able to optimize the soot-blowing cycle the cost of a single cycle needs to be defined. There are two typical operation modes in power plants regarding soot-blowing and the cost of a soot-blowing cycle is defined in a different manner for both modes. The identified operational modes are demonstrated in Figures 46 and 47.

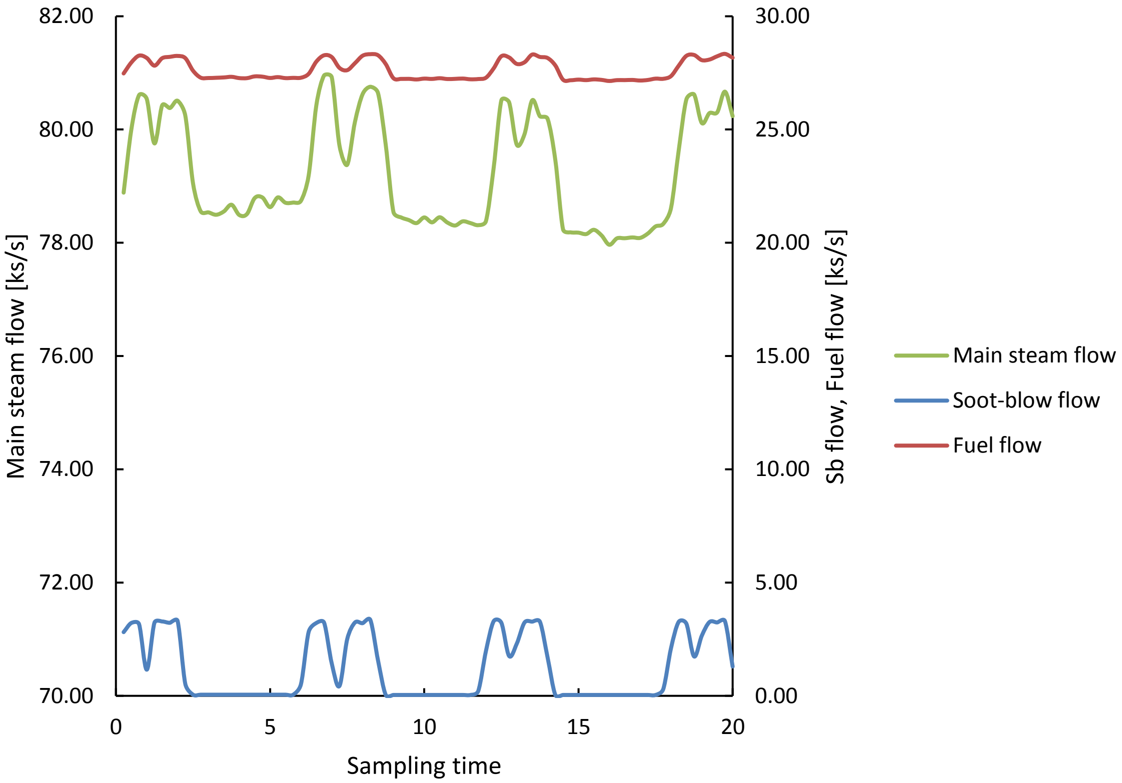


Figure 46. *Operation mode where soot-blowing steam is compensated with additional steam production and added fuel flow. From one of the case study power plants.*

The first and more common mode is, where during soot-blowing cycle the power plant produces additional steam, that can then be used for soot-blowing. This operational mode allows the turbine power output to remain constant during the cycle, but additional fuel flow is needed to produce the additional steam. In this mode the price for a soot-blowing cycle is defined merely by the additional fuel flow and fuel price. This mode is more common, since typically in most areas and during most seasons electricity is more expensive than fuel prices and hence it is more economically viable to keep electricity production in a constant level and realize the cost with fuel flow. Also, most power plants have production agreements with power grid companies and power plants are not always allowed to lower their electricity output. In this operation mode all changes are done inside the power plant process and the power grid does not experience load changes.

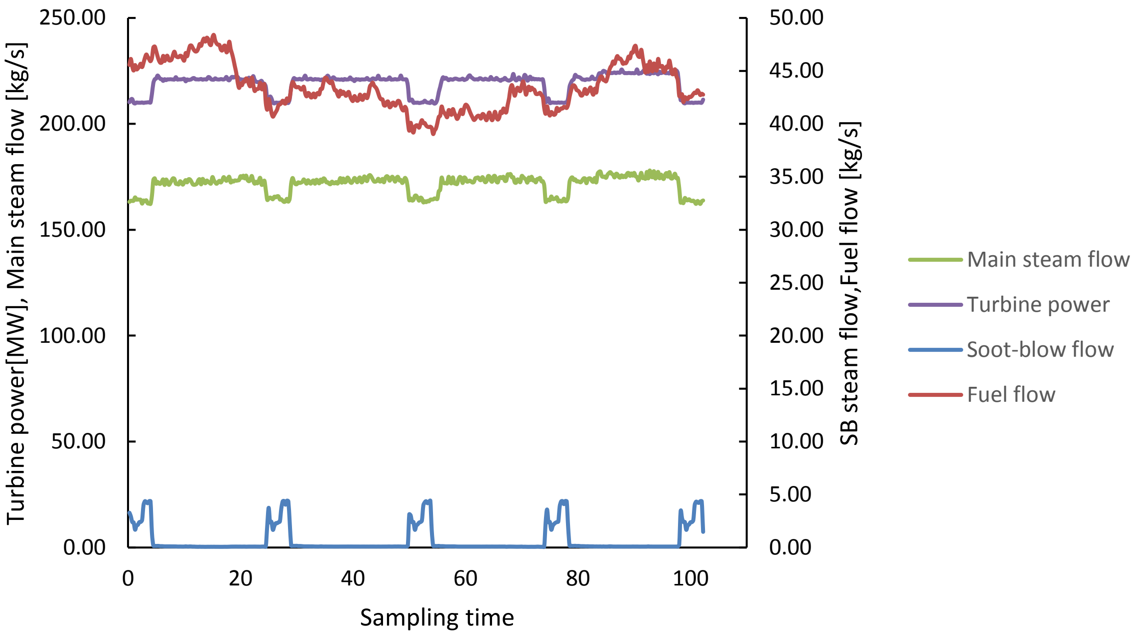


Figure 47. *Operation mode where during the soot-blowing cycle the turbine produces less electricity and main steam flow is smaller. From one of the case study power plants.*

The second most typical, but rarer than the first, operation mode is, where during the soot-blowing cycle the turbine produces less electricity and the main steam flow is also smaller. This mode is illustrated in Figure 47. The cost of a soot-blowing cycle on this mode is defined by the lost electricity output and therefore from the current price of electricity. The fuel flow shows some instability in Figure 47. and this is due the fact, that this powerplant fires a mix of biomasses and hence the overall fuel flow has some fluctuation due to varying fuel composition. It can still be seen, that is this operation mode during the soot-blowing cycle the fuel flow is on a lower level that during normal operation before and after the cycle and naturally this is due to the lower production rate of steam during the soot-blowing cycle. This operation mode is used by power plants that are allowed to alter their electricity output during times when the price of electricity is low.

Typical examples of timeframes for this operation mode is summertime and early autumn, when there is lot of hydro power available and the need for heating is at its lowest rates due to warm outside temperatures. These factors drive the market price for electricity to be at its lowest, and hence the electricity production is not feasible as it is normally in combustion-based power plants. It is then economically viable to realize the cost of soot-blowing with lower electricity output. As explained in earlier chapter, not all power plants have the possibility to choose this operation mode, even though it would be more economically viable, due to production agreements with power grid companies. Typically, power plants that are owned by a company that has multiple power plants can choose this mode, as such agreements usually are related to the overall electricity output of all power plants of the company and hence the company can optimize the production between its power plants as it best suits the company interests.

As the two different ways for defining the cost of a soot-blowing cycle were identified, the actual optimization calculations could be performed. As explained earlier in chapter 5.1 the optimization was done by solving the equation 13 for each case study power plant respectively. The flue gas losses were modelled for all power plants respectively and the cost function was defined as an integral function for the modelled flue gas loss functions. The prices for soot-blowing cycles were calculated from process data as an average of several realized soot-blowing cycles. The prices for single soot-blowing cycle as mass of fuel and their values related to typical daily fuel consumption without soot-blowing for all the case study power plants are presented in Table 5.2. This is done to give the impression of the order of magnitude related to the actual operational price of soot-blowing.

Table 5.2 *Soot-blowing fuel consumption*

Power plant	**Fuel used for one soot-blowing cycle [t]**	**Daily fuel consumption without soot-blowing [t]**	**Soot-blowing fuel/normal daily fuel consumption [%]**
PP A	1.025	464.430	0.221
PP B	3.958	1496.356	0.264
PP C	6.353	2091.562	0.304
PP D	5.321	4233.486	0.126
PP E	14.021	3716.206	0.377
PP F	36.902	7037.723	0.524

As can be seen from table 5.2, the price of soot-blowing is a significant operational cost and is therefore safe to say, that even small optimization in this area can lead to significant yearly savings for the power plant. In conclusion can be said, that soot-blowing optimization is a feasible way for cost-optimization in CFB boilers.

6. RESULTS AND DISCUSSION

In chapter five the method for calculating optimal soot-blowing cycles was presented. The calculated results and analysis regarding them is presented in this Chapter. Therefore, this chapter answers to the final research question: *How large monetary savings can be achieved with soot-blowing optimization?*

In Chapter 4.1.2 reference methods from scientific articles were presented. Method utilized in this thesis is somewhat simpler than some of the reference methods, but results are still realistic. The simplicity is also a benefit, as this presented method only requires basic measurements from power plants and a simple data acquisition system with process calculations to function. There is for example no need for large amounts of training data and time and this is a distinct benefit compared to some of the refenced neural network-based optimization systems. There is also no added error from prediction accuracy, as there would be in neural network-based systems. In conclusion this presented method is simple and robust, it can be rather easily applied as an optimization tool for digital platform and its accuracy is only dependent on the accuracy of the measurement and process calculations.

6.1 Calculated results

These results are calculated purely based on the operational cost-point of view and it is possible, that technical framework, such as desuperheaters or flue gas fan operation, sets the boundary limit for soot-blowing cycle, that can be shorter than the cost-optimal cycle. The method included modelling the behavior of flue gas losses between soot-blowing cycles as presented in Figure 42. The coefficient of flue gas losses is an indicator of the fouling rate of the fuel as faster fouling rate would mean that flue gas losses rise faster, and the coefficient would therefore be higher. Comparison between the model and measurement for few soot-blowing cycles is presented in Figures 48 and 49.

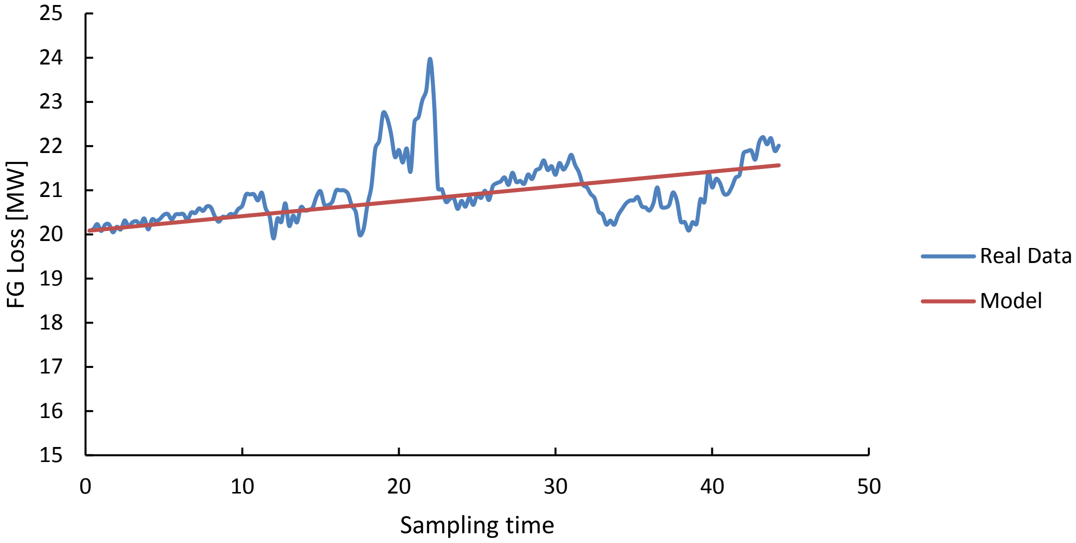


Figure 48. *Model and real data comparison for long soot-blowing cycle.*

As can be seen from Figure 48, the measurements fluctuate somewhat due to dynamic nature of the measurements in power plant process, but is these abnormal spikes are ignored, the model is accurate.

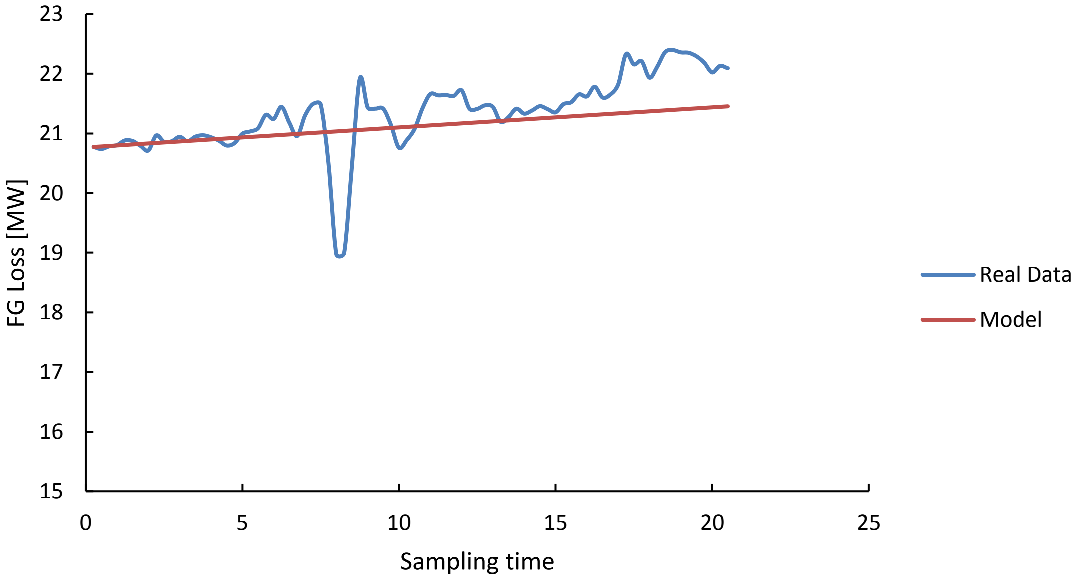


Figure 49. *Model and real data comparison for short soot-blowing cycle.*

Same behavior can be observed also with shorter cycle as can be seen from Figure 49. In conclusion it can be observed that model seem to be very accurate right after the previous soot-blowing cycle and loses some accuracy after longer periods of time.

The modelled flue gas loss coefficients for all case-study power plants are presented in table 6.1

Table 6.1 *Modelled flue gas loss coefficients*

Power plant	**Coefficient**	**Max soot-blowing cycle duration in model [h]**
PP A	0.0352	15
PP B	0.031	21
PP C	0.0336	70
PP D	0.0526	5
PP E	0.0766	24
PP F	0.0851	21

It is important to notice, that the data that was used for these models in some cases, for example in case of power plant C, only includes short soot-blowing cycles. In these cases, the coefficient only presents the behavior of flue gas losses shortly after a soot-blowing cycle, and during that time the flue gas losses rise faster and after some time it starts to settle. This leads to a situation that the coefficient of modelled with such data is higher than it would be if modelled from data that would include also longer soot-blowing cycles. Therefore, when interpolating with this coefficient to higher than the actual used soot-blowing cycles the results become somewhat inaccurate. This phenomenon was demonstrated in chapter 5.4 in Figures 43 and 44, where two different cases from power plant E are compared.

Considering this phenomenon, it is safe to assume that the coefficient for power plant D is most likely higher than it should be. Power plant D fires a combination of peat and woody biomass and it is therefore arguable, that the coefficient should actually be closer to power plants B and C.

It needs also needs to be noted regarding power plant F, that there was little data available where the load level was stable during soot-blowing cycles and therefore the model for power plant F is based on significantly less data than the other power plants. This can lead to an inaccurate model, so the error margin in results of power plant F is higher than in other cases.

The optimal soot-blowing cycles were then calculated with Matlab based on the fuel consumption during soot-blowing cycle presented in table 5.2 and the flue gas loss coefficients presented in table 6.1. The relation how soot-blowing operation cost develops between real data and optimized model is illustrated in Figure 50.

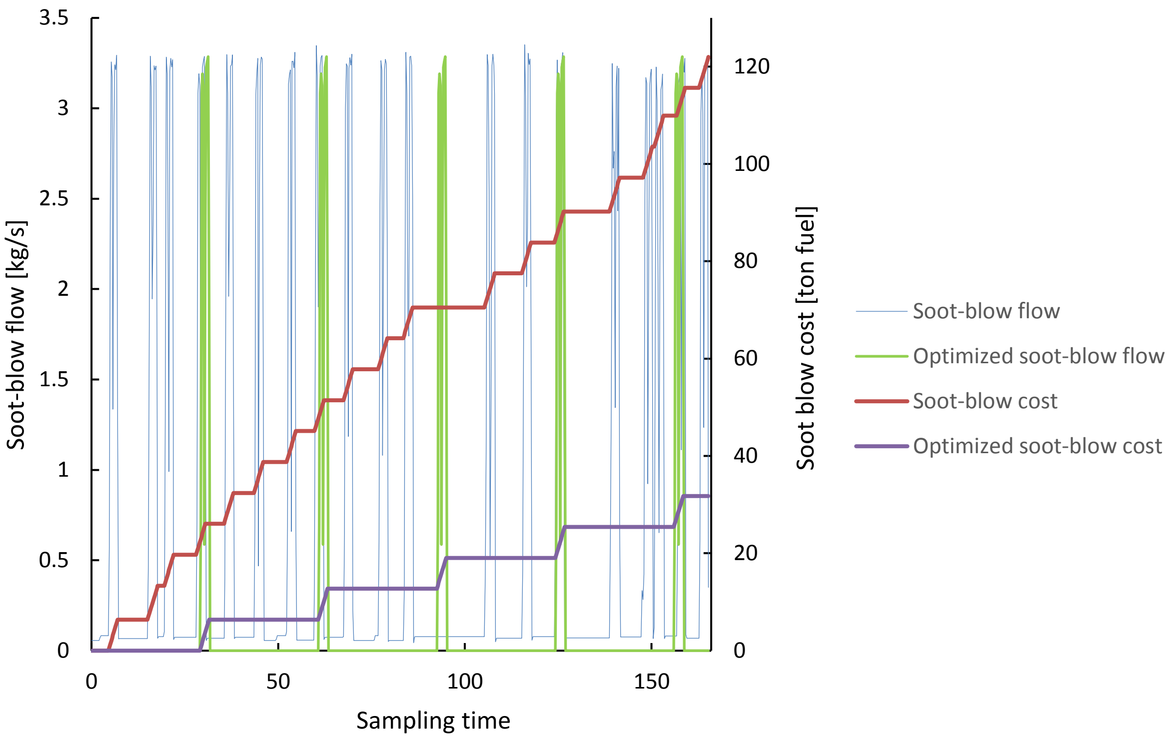


Figure 50. *Soot-blowing operational cost comparison between real data and optimized results.*

As can be seen from Figure 50 in this example comparison from power plant C, during one week of normal stable operation the utilized soot-blowing cycle duration varies a little, but for the most part it is quite consistent. If this is compared to the optimized soot-blowing cycle duration, it can be seen that even during one week of operation the amount of saved fuel is significant. At this stage of development, the model does not consider technical boundary limitations, that are presented earlier in this thesis and it is possible that in some cases the cost optimal soot-blowing is too long for technical limits. These calculated savings can therefore be seen as the upper computational limit for potential savings and they do not necessarily reflect reality in a fully exact manner, but they do clearly demonstrate the order of magnitude and potential of soot-blowing optimization for cost optimization.

In table 6.2. the calculated results and potential savings as tons of fuels are presented. These results are calculated with assumption that yearly operation hours of 8250, which is typical for utility level power plants. These results are also calculated based on operation mode presented in Figure 46, in which the soot-blowing steam is compensated with additional steam production and therefore price for the soot-blowing cycle is defined by additional fuel consumption. This choice was done to keep the results consistent and comparable, as the operation mode presented in Figure 47, where during soot-blowing the turbine produces less electricity, was not utilized in all the case-study power plants. Adding this alternative operation mode to the model and optimizing soot-blowing operation between these two operation modes remains as a future development work.

***Table 6.2** Optimal soot-blowing cycles and potential yearly savings*

Power plant	Used soot-blowing cycles [h]	Calculated optimal soot-blowing cycles [h]	Potential yearly savings [ton fuel]
PP A	5.0-14.75	13.3	1055.93
PP B	20.25-20.75	23.5	222.99
PP C	8.0-75.0	29.1	4750.63
PP D	4.0-4.75	27.5	9377.66
PP E	18.25-24.0	31.7	2689.33
PP F	16.25-20.75	51.7	12846.30

The second column in table 6.2 refers to the actual duration of soot-blowing cycles, that were used in these power plants during the timeline when data was gathered. In third column the calculated optimal soot-blowing cycles are presented. In final column the potential yearly savings are presented as amount of fuel and this value is calculated as the difference between the most typically utilized soot-blowing cycle and the optimal soot-blowing cycle on a yearly level. This potential savings therefore demonstrates the difference between normal year of stable operation with a typical soot-blowing cycle and stable operation with optimized soot-blowing cycle. As stated earlier, this can be seen as computational upper limit and it is safe to assume, that when this model is utilized in normal power plant operation with many varying factors, this amount of savings will most likely not be gained to full extend.

To demonstrate what this amount of saved fuel means from operational point of view, it can be calculated for example for power plant F, that the amount of fuel that could be saved with soot-blowing optimization in one year corresponds to full two days of normal operation of the power plant. If the latest yearly average price of Indonesian coal presented in Figure 19, which is 54.16 €/t, is used as a reference the potential yearly savings in case of power plant F could be as high as 696,000 €. As soot-blowing optimization reduces excessive fuel consumption it is naturally economical, but also environmental benefit, as the saved fuel corresponds to smaller yearly CO_2 emissions. This is extremely important factor for power plant operators to keep in mind, as in the light of recent climate policy studies, the future the emission limits will most likely be stricter than ever.

6.2 Discussion

It can be noted regarding the results, that the calculated optimal soot-blowing cycles are longer than the utilized cycles throughout all the case-study power plants. One exception being power plant C, in which the longest utilized cycle was 75 hours. Data from power plant C was taken during time, when soot-blowing was tested in that power plant and this exceptionally long soot-blowing cycle was before shutdown of the plant and it does not correspond to normal operation. The consistency of these results indicates that power plant operators seem to operate soot-blowing in a cautious manner and there is most definitely margin for cost optimization. If these results are compared to results reported in state of the art research articles same trends and same order of magnitude can be found. For example NN-based soot-blowing optimization model developed by Pattanayak et al was reported to optimize soot-blowing cycle in a 500 MWe coal-fired power plant from twice in 36 hours to once in 36 hours [10].

There are certain risks regarding soot-blowing optimization that this cost optimization method ignores, and the most severe risk is reduction of soot-blowing efficiency if soot-blowing cycle is prolonged. In practice this means, that if the ash-deposit layer stays in contact with the heat-transfer surface for excessive amount of time due to longer soot-blowing cycle, there is a risk that it not anymore fully removed by the next soot-blowing cycle. As stated earlier this risk is hard to model in an explicit manner by equations, but it is easily detectable by observing FIs of individual heat-transfer surfaces and pressure drops over the tube packages. Lowered FI and increased pressure drops are both indicators of increased deposit layer on the surface and if such indicators are noticed due to soot-blowing frequency optimization corrective measures needs to be taken. Implementing these corrective functionalities remains as future development work.

The longer contact time that ash will have with the tube surface when soot-blowing cycle is prolonged can potentially shorten the life-cycle of the tube bundle, as the longer contact time might in some circumstances promote corrosion. On the other hand, this risk is most evident with fuels that have high alkali content, such as waste derived fuels. The life-cycle of tube bundles is already significantly shorter with these fuel types compared to coal, so increased corrosion risk due to longer soot-blowing cycle is not that significant in these boilers, as the tube bundles need to be changed quite frequently in any case. The corrosion comparison between waste derived fuels and coal is demonstrated in Figure 15, and as can be seen with coal the surfaces are in good condition even after 10 years, compared to waste derived fuel, where already after one year there is clear signs of corrosion.

As presented in Figure 20 excessive soot-blowing can cause issues such as promote corrosion by removing not only the ash deposit layer but also protective oxide layer from the tube surface. It is therefore reasonable to assume, that in some cases prolonging the soot-blowing cycle could also add additional benefits as it might reduce corrosion risk.

Total error of this presented method is composed of the error of measurements in the power plant environment, error of the process calculations and the model error of the flue gas loss coefficient. CFB boiler is challenging environment due to high temperatures, high fluid velocities and high pressures and therefore there will always be some error margin in the process measurements and this will reflect to the process calculations that utilize those measurements. The process calculations themselves also add some inaccuracy due to boundary limits and assumptions for example for timely averaged values, but typically during stable operation this is rather insignificant compared to the inaccuracy of the measurements. Typically, these fluctuations will average out in the long run and this can be seen for example in Figures 49 and 50, where the value of flue gas losses, which is a value produced by process calculations, fluctuates momentarily, but evens out as time passes on. From these Figures it can also be seen, that the model is quite accurate, and it is therefore safe to assume, that error that utilizing such model creates is quite insignificant compared to the error of the measurements from the power plant process. In conclusion it is therefore safe to assume, that the overall accuracy is mostly dependent on the accuracy of the measurements.

For the calculations for potential savings there are also assumptions such as typical yearly operation time and median soot-blowing cycle duration, which will create some inaccuracy compared to real operation of the power plant. As stated earlier these calculated potential saving should therefore be seen as upper limit to demonstrate potential of soot-blowing optimization.

In conclusion can be stated that optimizing the soot-blowing cycle can create substantial savings for power plants, but there are certain risks and possibly some added benefits by reducing tube surface wear. It is therefore highly important to keep monitoring process signals that correlate to these risk and benefits after implementing this type of optimization method to the power plant process. This enables to detect possible risks early on and they can then possibly be fixed before they are fully realized. This way the created saving can be realized to the operator of the plant and they do not get lost for example to additional maintenance costs.

6.3 Future development work

The calculated results clearly indicate the potential of soot-blowing optimization as cost optimization method. There is possibly still even greater potential, for example by adding a method to calculate whether the soot-blowing steam is cheaper to produce by additional steam production or lower electricity production. There are also certain risks regarding the optimization of the soot-blowing cycle, for example risk that after prolonged soot-blowing cycle individual heat transfer surfaces do not get fully cleaned anymore. Adding monitoring function, that supervises the performance of individual heat transfer surfaces by monitoring their FIs for example, is the most important future development task. This function enables to detect possible risks early on and take corrective measures before the risk is realized. In this manner the savings gained by soot-blowing optimization can be realized to the operator of the power plant. This is also technically the easiest way to apply this presented method to real time power plant process in a safe manner.

Some of presented reference soot-blowing optimization methods, for example the soot-blowing optimization system presented in a journal article by Piboomtum et al [8], were focused on optimizing the soot-blowing steam consumption within one soot-blowing sequence. This approach is also interesting and could possibly be combined with the optimization of the soot-blowing cycle for even greater savings. This approach on the other hand has some technical drawbacks, as it might not be possible to do such optimization with all types of steam-based soot-blowers and their automated control systems. In any case this approach is interesting and should be studied more.

Other approach that was presented in referenced articles regarding soot-blowing optimization was to utilize modern more complex systems, such as neural networks and fuzzy-logic expert systems as was concluded in an article by Romeo et al [12]. With this approach a predictive element could be gained to soot-blowing optimization, which could help to detect for example changes in fuel mixture, that can possibly affect the most cost optimal soot-blowing cycle to some degree. These complex systems offer interesting opportunities, but their typical drawback is the need for large amounts of training data, computational needs and prediction accuracy. Nevertheless, these artificial intelligence methods have developed a lot in recent years and their feasibility for soot-blowing optimization should be studied more.

In conclusion the most important future development needs can be listed as the follows:

- Adding a function to calculate whether the cost of soot-blowing steam is more cost-efficient to realize as additional fuel consumption or lowered electricity production
- Adding corrective functionalities, that are based on process parameters such as desuperheater spray flows, FI and pressure drops over tube packages, to ensure that this cost-optimization based method does not cause significant disturbances to the overall process

Other future development needs are to study modern artificial intelligence-based methods and possibilities that they offer to soot-blowing optimization. Regarding the whole boiler island level cost optimization, the scope should be broadened little by little from one optimization problem eventually to whole plant level optimization.

7. CONCLUSIONS

Worlds demand for primary energy has steadily been increasing in the last decades and this trend will most likely keep on increasing in the future. In the boiler industry this trend can be observed as demand for larger scale and more efficient boilers. At the same time stricter emission limits must be met. This creates a situation where process optimization is a topic of utmost importance, as in large scale utility boilers even small improvements can mean great environmental and economic benefits. Accurate process optimization from cost point of view requires certain steps, such as identifying the operational cost structure and most critical key performance indicator from cost point of view. In this thesis the scope of focus was narrowed on soot-blowing optimization as from prior knowledge fouling of the boiler is known to be important problem to solve in CFB boilers.

Even though soot-blowing optimization was chosen as topic of interest, this thesis aims still to provide a solid techno-economic background for broadening the scope of interest in the future. This thesis is divided into theoretical and computational parts. The theoretical part answers to the first two research questions and the computational part, where a method for soot-blowing optimization is presented, answers to the third and fourth research questions.

The variable operational cost structure of a CFB boiler is mainly composed of price of the fuel, auxiliary power consumption, prices of different additives, soot-blowing steam consumption and emission taxation and penalties. From cost point of view the most critical key performance indicators (KPI) were identified to be such that correlate to the normal and stable operation of the boiler. This is due the fact, that forced shutdown is something to be avoided at all costs, as during shutdown the monetary output of the power plant is zero. It takes a very long time to gain back monetary loss of a forced shutdown with performance optimization. Typical KPIs that correspond to stable operation of the boiler are for example bed temperatures and oxygen levels in flue gases. After the stable operation of the boiler KPIs that reflect to optimal performance, such as fouling index and flue gas losses, can be prioritized and optimization methods can be applied as long as they do not risk the stable operation of the boiler.

In the computational part of this thesis a method for soot-blowing optimization was developed. The target was to develop as simple and robust a method as possible. The method was designed to utilize existing data acquisition system and process calculations as these were already existing tools. Simplicity was a target as one future goal is to apply this developed method as a tool for power plant operators in a digital platform and simplicity corresponds to usability and effectiveness in terms of needed computational capacity.

The most cost-optimal soot-blowing cycles were calculated for 6 different power plants utilizing the presented method. These power plants represent full spectrum of CFB boilers both in terms of utilized fuel and power capacity. The results calculated with this method represent the most cost-optimal soot-blowing cycle, but is a possibility that technical aspects, such as desuperheater flow or flue gas fan operation, might set a limit for soot-blowing cycle, that could shorter than the calculated most cost-optimal cycle. The presented results are calculated based on operation mode, where soot-blowing steam is compensated with additional steam-production and therefore additional fuel consumption. Other option is to allow the power plant produces less electricity during soot-blowing sequence, in which case turbine receives the amount of soot-blowing steam less than during normal operation. This operation mode is much rarer than the former and it was not utilized in all the case-study power plants, so for sake of consistency the former operation mode was chosen for the calculations.

The results are consistent between these 6 inspected power plants, excluding few exceptions. One of the case-study power plants had lower amount of usable data available than the other, so the error is most likely higher in case of that power plant. Also, other one of case-study power plants had historically only utilized very short soot-blowing cycles, therefore the model created based on this data is most likely less accurate than in other cases. Overall the results are reasonable and in line in terms of trend and order of magnitude with results presented in state of the art literature. The results clearly indicate, that power plant operators are cautious with soot-blowing operation, as the calculated optimal cycles were in all cases longer than the cycles that were used on average. The amount of fuel that could be saved on yearly level with soot-blowing optimization varied from 200 to 12,800 tons of fuel. These amounts were calculated with certain assumption regarding average operation of the power plant and they can be seen as computational upper limit for potential savings gained by soot-blowing optimization. This amount in best-case scenario corresponds to two days of normal operation of the power plant or as monetary savings to as high as 690,000 € on a yearly level. These results clearly indicate, that soot-blowing optimization is a feasible method for cost optimization in CFB boilers. There are certain future development needs, such as monitoring and correcting the optimization system, that need to be added so that these potential savings can be realized, and they do not get wasted for example to additional maintenance costs.

For future development work regarding soot-blowing optimization the main targets are developing a function to calculate whether the cost of soot-blowing steam is more cost-efficient to realize as additional fuel consumption or lowered electricity production and adding corrective functionalities based on process parameters to the model. These improvements will create added value as an optimization tool and secure safe operation of the tool making it more attractive from power plant operator point of view. Another future development goal is to broaden the optimization scope from a single problem first to whole boiler island and eventually to whole power plant level optimization.

REFERENCES

[1] B. Prabir, Combustion and Gasification in Fluidized Beds, 1st ed. CRC Press, Boca Raton, 2006, 496 p.

[2] Peltier, 11/01/2016 | Dr Robert Advanced CFB Technology Gains Global Market Share, https://www.powermag.com/advanced-cfb-technology-gains-global-market-share/.

[3] Transparency Market Research Circulating Fluidized Bed (CFB) Boilers Market - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2015 - 2023, Transparency Market Research, https://www.transparencymarketresearch.com/cfb-market.html.

[4] G. Yue, R. Cai, J. Lu, H. Zhang, From a CFB reactor to a CFB boiler – The review of R&D progress of CFB coal combustion technology in China, Powder Technology, Vol. 316, 2017, pp. 18-28. Available (accessed ID: 271376): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0032591016307550.

[5] N. Afgan, M.G. Carvalho, P. Coelho, Concept of expert system for boiler fouling assessment, Applied Thermal Engineering, Vol. 16, Iss. 10, 1996, pp. 835-844. Available (accessed ID: 271641): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/1359431195000828.

[6] E. Teruel, C. Cortés, L. Ignacio Díez, I. Arauzo, Monitoring and prediction of fouling in coal-fired utility boilers using neural networks, Chemical Engineering Science, Vol. 60, Iss. 18, 2005, pp. 5035-5048. Available (accessed ID: 271348): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0009250905003283.

[7] J. Tamminen, Heat Transfer Based Fouling Examination in Fluidized Bed Boilers, Tampere University of Technology, 2017, Available: http://URN.fi/URN:NBN:fi:tty-201711172171.

[8] Boiler modeling optimizes sootblowing - ProQuest, https://search-proquest-com.libproxy.tut.fi/docview/232491152?accountid=27303.

[9] D. Li, M. Yu, Y. Dai, P. Jun, G. Chen, The Sootblowing Optimization System for 900MW Supercritical Boilers, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 615-619.

[10] L. Pattanayak, S.P.K. Ayyagari, J.N. Sahu, Optimization of sootblowing frequency to improve boiler performance and reduce combustion pollution, Clean Technologies and Environmental Policy, Vol. 17, Iss. 7, 2015, pp. 1897-1906. Available (accessed ID: Pattanayak2015): https://doi.org/10.1007/s10098-015-0906-0.

[11] B. Peña, E. Teruel, L.I. Díez, Soft-computing models for soot-blowing optimization in coal-fired utility boilers, Applied Soft Computing, Vol. 11, Iss. 2, 2011, pp.

1657-1668. Available (accessed ID: 272229): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S156849461000102X.

[12] L.M. Romeo, R. Gareta, Hybrid System for fouling control in biomass boilers, Engineering Applications of Artificial Intelligence, Vol. 19, Iss. 8, 2006, pp. 915-925. Available (accessed ID: 271095): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0952197606000467.

[13] R. Ahlqvist, Reducing auxiliary power of a fluid bed boiler island, Lappeenranta University of Technology, 2015

[14] T. Li, P. Liu, Z. Li, Operation Data based Modelling and Optimization of Thermal Power Units under Full Working Conditions, Computer Aided Chemical Engineering, Vol. 40, 2017, pp. 2455-2460. Available (accessed ID: 276008): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/B9780444639653504116.

[15] C. Schrader, Can Germany engineer a coal exit? Science, Vol. 351, Iss. 6272, 2016, pp. 430. http://science.sciencemag.org/content/351/6272/430.abstract.

[16] CFB multifuel and biomass firing, Sumitomo SHI FW, Not publicly available, 2018

[17] Poltto ja palaminen, 2nd ed. Teknistieteelliset akatemiat, Helsinki, 2002

[18] T. Atkins, M. Escudier, cross-flow heat exchanger, in: Anonymous (ed.), A Dictionary of Mechanical Engineering, Oxford University Press, 2013

[19] A.F. Milss, Basic Heat and Mass Transfer, 2nd ed. Prentice Hall, New Jersey, 1999

[20] M. Sc. A. Rokka, Principal Engineer Process Concepts, Sumitomo SHI FW, Varkaus. Interview 10.7.2018, Original interview in Finnish, translated to English by author.

[21] Tilasto: Energian hinnat [verkkojulkaisu], Tilastokeskus, Helsinki, 2018, Available: http://www.stat.fi/til/ehi/2018/01/ehi_2018_01_2018-06-12_kuv_004_fi.html.

[22] Tilasto: Energian hinnat [verkkojulkaisu], Tilastokeskus, Helsinki, 2018, Available: http://www.stat.fi/til/ehi/2018/01/ehi_2018_01_2018-06-12_kuv_003_fi.html.

[23] Indonesia Investements Benchmark Coal Price of Indonesia Near Six-Year High in March 2018, Indonesia investements, https://www.indonesia-investments.com/news/todays-headlines/benchmark-coal-price-of-indonesia-near-six-year-high-in-march-2018/item8637?.

[24] M.Sc. M. Carvalho, Research and Development Engineer Emissions, Sumitomo SHI FW, Varkaus, Interview 9.8.2018

[25] P. Basu, J. Butler, M.A. Leon, Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants, Renewable Energy, Vol. 36, Iss. 1, 2011, pp. 282-288. Available (accessed ID: 271431): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0960148110003125.

[26] Tilasto: Energian hinnat [verkkojulkaisu], Tilastokeskus, Helsinki, 2018, Available: http://www.stat.fi/til/ehi/2018/01/ehi_2018_01_2018-06-12_tau_001_fi.html.

[27] R. Brännlund, T. Lundgren, P. Marklund, Carbon intensity in production and the effects of climate policy—Evidence from Swedish industry, Energy Policy, Vol. 67, 2014, pp. 844-857. Available (accessed ID: 271097): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0301421513012561.

[28] Swedish Environmental Protection Agency, Utkast miljöavgift på utsläpp av kväveoxider 2015 version 3, Swedish Environmental Protection Agency, 2015, 3 p. Available: https://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-sverige/energi/nox/nox-statistik-promemoria-2015.pdf.

[29] S.E. Shmelev, S.U. Speck, Green fiscal reform in Sweden: Econometric assessment of the carbon and energy taxation scheme, Renewable and Sustainable Energy Reviews, Vol. 90, 2018, pp. 969-981. Available (accessed ID: 271969): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S1364032118301047.

[30] Engineering manuals by SHI FW, Sumitomo SHI FW, Not publicly available, 2018

[31] P. Tiainen Suomen suurin purkutyömaa käyntiin Inkoossa – Hiilivoimalaan mahtuisi yhdeksän eduskuntataloa, Yle Uutiset, http://yle.fi/uutiset/3-9622097.

[32] Boiler Operation and Control Concept, Material by Sumitomo SHI FW not publicly available, Sumitomo SHI FW, 2017, 1-9 p.

[33] M. Sc. R. Parkkonen, Senior Technology Engineer, Sumitomo SHI FW, Varkaus, Interview 10.8.2018,

[34] J. Law, Key performance indicators, in: J. Law (ed.), A Dictionary of Business and Management, Oxford University Press, 2016,

[35] C. Lindberg, S. Tan, J. Yan, F. Starfelt, Key Performance Indicators Improve Industrial Performance, Energy Procedia, Vol. 75, 2015, pp. 1785-1790. Available (accessed ID: 277910): http://www.sciencedirect.com/science/article/pii/S1876610215012424.

[36] M. Chioua, M. Bauer, S. Chen, J.C. Schlake, G. Sand, W. Schmidt, N.F. Thornhill, Plant-wide root cause identification using plant key performance indicators (KPIs) with application to a paper machine, Control Engineering Practice, Vol. 49, 2016, pp. 149-158. Available (accessed ID: 271086): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0967066115300381.

[37] G. May, M. Taisch, V.V. Prabhu, I. Barletta, Energy Related Key Performance Indicators – State of the Art, Gaps and Industrial Needs, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 257-267.

[38] A. Alhajaj, N. Mac Dowell, N. Shah, A techno-economic analysis of post-combustion CO2 capture and compression applied to a combined cycle gas turbine: Part I. A parametric study of the key technical performance indicators, International Journal of Greenhouse Gas Control, Vol. 44, 2016, pp. 26-41. Available (accessed ID: 273596): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S1750583615301092.

[39] L.F. Cabeza, E. Galindo, C. Prieto, C. Barreneche, A. Inés Fernández, Key performance indicators in thermal energy storage: Survey and assessment, Renewable Energy, Vol. 83, 2015, pp. 820-827. Available (accessed ID: 271431): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0960148115003961.

[40] E. Personal, J.I. Guerrero, A. Garcia, M. PeÃ±a, C. Leon, Key performance indicators: A useful tool to assess Smart Grid goals, Energy, Vol. 76, 2014, pp. 976-988. Available (accessed ID: 271090): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0360544214010718.

[41] A. GonzÃ¡lez-Gil, R. Palacin, P. Batty, Optimal energy management of urban rail systems: Key performance indicators, Energy Conversion and Management, Vol. 90, 2015, pp. 282-291. Available (accessed ID: 271098): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0196890414009923.

[42] D.P. Hanak, A.J. Kolios, C. Biliyok, V. Manovic, Probabilistic performance assessment of a coal-fired power plant, Applied Energy, Vol. 139, 2015, pp. 350-364. Available (accessed ID: 271429): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0306261914011295.

[43] M. Sc. A. Kettunen, Manager Fluid Bed Processes, Sumitomo SHI FW, Varkaus. Interview 27.6.2018, Original interview in Finnish, translated to English by author.

[44] X. Zhang, H. Li, L. Liu, C. Bai, S. Wang, Q. Song, J. Zeng, X. Liu, G. Zhang, Optimization analysis of a novel combined heating and power system based on biomass partial gasification and ground source heat pump, Energy Conversion and Management, Vol. 163, 2018, pp. 355-370. Available (accessed ID: 271098): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0196890418301900.

[45] S. Bracco, G. Dentici, S. Siri, Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area, Energy, Vol. 55, 2013, pp. 1014-1024. Available (accessed ID: 271090): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S0360544213003046.

[46] T. Savola, C. Fogelholm, MINLP optimisation model for increased power production in small-scale CHP plants, Applied Thermal Engineering, Vol. 27, Iss. 1, 2007, pp. 89-99. Available (accessed ID: 271641): http://www.sciencedirect.com.libproxy.tut.fi/science/article/pii/S1359431106001736.

[47] M.A. Rhode, Tampa Electric Neural Network Sootblowing, Tampa Electric Company, 2004, Available: www.osti.gov/bridge/servlets/purl/900192-uB-MBCK/900192.pdf.