

**The influence of co-firing of biomass on heating surfaces  
in coal fired boilers in PGE Energia Ciepła S.A. Power Plant  
in Kraków**

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**Energy Engineering and Management**

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## **ABSTRACT**

This work describes the slagging and fouling problem in boiler OP-380 related to biomass co-combustion in PGE Energia Ciepła Power Plant in Kraków. Examination period last 206 days and starts on 19.06.2014 till 23.01.2015. Biomass was co-fired on average level of 23 % by weight, and fuel was mix of agro-biomass: pellet from sunflower husk (87%) and pellet from herbaceous residues (13%). The main parameter which have been analyzed to determine progress of slagging and fouling process was heat load of boiler OP-380 parts. Following elements were examined: first, second and third level of primary and secondary steam superheaters, evaporator and feed-water preheater. Furthermore, temperature and pressure of flue gases were analyzed. Work consist photography of damages on heated surfaces. Final result indicate that most damages (90%) done during biomass co-firing are caused by steel oxidation (overheat) of pipes material. Rest of damages are result of aggressive compounds in flue gases from coal as well as from biomass. Moreover, investigation pointed out that co-burning biomass on level 15-20% (W/W) do not have direct influence on corrosion damages of superheaters. However, increasing share of biomass in feedstock up to 40% provoke occurrence of corrosion damages on wider scale.

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## **ACRONYMS AND ABBREVIATIONS**

TWh - Terawatt hours

Btu – British thermal units

GHG – Greenhouse Gas Emission

RED – Renewable Energy Directive

7EAP – Seventh Environment Action Programme

SRC – Short Rotation Coppice

NCV – Net Calorific Value

GCV – Gross Calorific Value

DB – Dry Basis

CFB - Circulating Fluidized Bed

PC – Pulverized Coal

OFA – Over Fire Air

PSS – Primary Steam Superheater

SSS – Secondary Steam Superheater

FWH – Feed Water Heater

EVP – Evaporator



## INTRODUCTION AND AIM OF THE WORK

One of the main sources of energy used for electricity generation is coal which is responsible for approximately 40% of the total power produced globally. Moreover, as it is well known, coal-fired power plants are major sources of CO<sub>2</sub> emission that contribute to anthropogenic climate change. Is there any option to replace production of 9538 (TWh/year) [1] of energy from coal by another renewable source in nearest future? It is hardly to imagine source of power so huge to cover those needs. All types of renewable technology have their limits and disadvantages. To be more precise, electricity generation from renewable sources nowadays is on the level of 21.1% in which 16% is hydro energy (excludes electricity generation from pumped storage). However, capacity of energy produced from water is on minor level. Other renewables include geothermal, solar, wind, tide/wave/ocean, biofuels, waste and heat combined together giving 7.1% of worldwide electricity generation. Electricity is moreover produced from natural gas (22.9%), nuclear power (10.6%) and oil (4.1%) [1].

Nothing indicates drastic changes in terms of fuel usage for power generation. Renewable energy sources are extremely eco-friendly but from economical point of view they appear much worse. Most of the existing power plants were built to produce electricity from anthracite or lignite. Furthermore coal is very well distributed on our planet which allows many countries to be producers and users simultaneously. It is also energy safety guarantor. Coal can deliver energy at a cost of between \$1 and \$2 per MMBtu compared to 6 to 12 per MMBtu for natural gas and oil [2] which gives the first place for cheapest energy source. Especially United States, China and India have enormous coal reserves. Is it possible to co-fire biomass with those huge amounts of coal on global scale? What are advantages, disadvantages and why people are interested in co-combustion of biomass?

Industrial co-combustion of biomass is gaining importance and is the object of intensive researches. Aims for those investigations are reducing CO<sub>2</sub> emission and diversification of fuel source. However, knowledge about biomass usage in power plants is still insufficient. Particular aspects of biomass combustion need to be better understood for instance greater utilization of agricultural biomass fuels, improvement of power plant efficiencies and solutions to the ash related problems to certain type of biomass [3], [4].

It is assumed that with binding law regulation in Poland, prices of electricity and financial mechanisms the most favored sources of renewable energy is biomass. Mainly residual wood from wood industry, but also cultivation of fast growing energy crops, agricultural or food industry residuals or biogas [5]. Biomass is seen as a highly flexible resource which can increase energy source diversification. Furthermore already existing power plants are suitable for burning biomass and those which are not, can be easily adapted for it.

Usage of the biomass as energy carrier in modern energy policy already started. However reaching the sufficient level is still in front of World energy industry. European Union set 20% of renewable energy source share for every Country Member till 2020. Furthermore, European Deputies agreed that till 2030 the renewable energy share will reach at least 35%. For countries without natural sources of renewable energy (wind energy, solar energy, ocean energy) that level will be hard to achieve. However, biomass could be used as fuel in countries without predisposition to other renewable energy sources. Poland have been used biomass for that reason in high amount. Obviously, this kind of fuel need more examinations and experience of it effectively usage. There are many difficulties in burning biomass in power plants, which were initially designed for burning coal. Below the issue related with co-firing, coal and biomass, will be discussed.

Generally biomass may be converted applying different conversion routes in order to produce electricity, heat and liquid fuels. Electricity and heat are produced by burning biomass or biogas in variety of installations. From limited domestic-scale stoves to industrial size power plants. It is possible to burn solid biomass in traditional unit together with fossil fuels. This technique is called co-firing and to adapt already existing coal plants for it, only slight adjustments need to be done.

This work will focus on the problem of slagging and fouling of heated surfaces in biomass co-burning. In next chapters I want to describe problem of slagging and fouling of equipment used for biomass co-firing and recommend possible best way to avoid those difficulties. The main objective of this work is to study slagging and fouling process during biomass co-fire in boiler OP-380 installed in PGE Energia Ciepła S.A. Power Plant in Kraków (Fig. 1) and find solution to avoid this issue.



Figure 1. PGE Energia Ciepła S.A. Power Plant in Kraków, adapted from [6]

# 1. MODERN ENERGY POLICY

European Union is very strict about energy policy. Emission of greenhouse gases should be gradually decreased to minimize impact of the global warming. Regulations have impact on many aspects of citizens life. Legislation includes rules for energy sector as well as architecture, transport, agriculture and food industry.

In 2009 the Renewable Energy Directive set policy frameworks for biomass usage. Established mandatory 20% share of renewable energy sources in the European Union final energy mix by 2020. However renewable energy sources are not only wind power, hydropower, solar or geothermal energy but also bio energy. In other words, biomass was listed as a renewable energy source to increase mobilization of existing timber reserves. It mandates Member States to set conversion efficiency thresholds above which Member may promote bioenergy technologies [6]. Furthermore it obliges EU countries to schedule national renewable energy action plans. Conversion capability change according to the conversion pathway. For every source there is different yields of conversion efficiency. For example, for biomass the minimum conversion efficiency is set at 70% for industrial applications and 85% for residential and commercial applications [6]. European Environment Agency in 2013 delivered report which suggests that only three conversion routes meet these criteria:

- Combustion to produce only heat (efficiency of at least 85%)
- Solid biomass cogeneration (efficiency between 65% and 85%)
- Biogas/biomethane (efficiency between 50% and 85%) [6]

Greenhouse gas emissions (GHG) under the European Union's and the global regulatory framework are not included in the energy sector when associated with biomass combustion. Based on the assumption about re-absorbing of released carbon dioxide by plants. On the other hand, changes that are resulted in a carbon stock have impact on the forestry, agriculture and other land use sectors.

Relative recently, European Parliament and Council set definition about accounting rules for GHG from land use, land - change and forestry. This is the first step to include those activities in the European Union emissions-reduction commitment.

Biomass as a fuel feedstock is not strict defined, the RED (Renewable Energy Directive) does not specified exact parameters (however for biofuels there are lot of precise regulations). In year 2010, the European Commission set criteria regarding biomass quality for heating and electricity generation. Criteria mentioned above where suggested and recommended to adopt by every of EU Member State. Nevertheless, those regulations were not consistent<sup>1</sup> and some stakeholders have reported concerns, that various sustainability criteria for each European Country could be an obstacle to trade biomass

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<sup>1</sup> Half of the Member States adopted regulations promoting higher efficiency in energy production, however only a few have introduced Green House Gases saving criteria, some have implemented forest management criteria, and a number have implemented regulations addressing competition with other biomass uses [6].

between Member States [6]. However, there is a list of sustainability schemes related to biomass, for instance: norm and criteria for sustainable forest management established by intergovernmental institution Forest Europe, schemes for silviculture products (like FSC and PEFC)<sup>2</sup>, and industry initiatives (e.g. the ENplus certification for wood pellets or the sustainable biomass partnership). Moreover, in 2013 the European Commission accepted a new EU forest strategy, suggesting the increasing use of forests for a different purposes, inclusive with bioenergy. The aim is to guarantee that all European Union forests are well managed and meet the sustainable forest management standards by 2020.

## **1.1. ENERGY POLICY ABOUT RENEWABLE ENERGY SOURCES IN EUROPEAN UNION**

The long term objective is to reduce overall environmental impact due to usage of natural resources in Europe. Raw materials are fundamental for our existence, however people need to learn how to use the efficient and sustainable. Furthermore, using natural resources more efficiently provide economic profits, for instance increased productivity, reduced costs and boost competitiveness.

First strategy on the sustainable use of natural resources was proposed on December 21<sup>st</sup> 2005 by the European Commission. Later, in 2010 European Union developed initiative “a resource-efficient Europe” as one of 7 flagship initiatives for a sustainable growth of the Europe. To guide policy developments to 2020, number of roadmaps for initiative coordination were presented. The Roadmap is the proper document to monitor efficient use of resources across the European Union by a set of indicators.

The framework of the European environmental policy include Seventh Environment Action Programme (7EAP). Generally, the core ideas from the Roadmap were expanded in 7EAP. Moreover it sets out main objectives for European Union environment policy up to 2020. Nevertheless 7EAP present where it wants the EU to be by 2050. There are three priorities of the 7EAP:

- To turn the European Union into a resource efficient, green and competitive low-carbon economy;
- To protect, conserve and enhance the Union’s natural capital;
- To safeguard the Union’s citizens from environment-related pressures and risk to health and wellbeing.

Strategy for Europe 2020 is moving towards a circular economy. In December 2015 the European Commission adopted a new Circular Economy Package. It helps to stimulate Europe’s economy transition towards this direction. Looping production and recycling sector bring a lot of benefits, to

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<sup>2</sup> FSC - Forest Stewardship Council, PEFC - The Programme for the Endorsement of Forest Certification.

mention only few: increasing competitiveness, generate new jobs and promotion of sustainable economic growth. Diagram below present concept of linear and circular economy (Fig. 2).

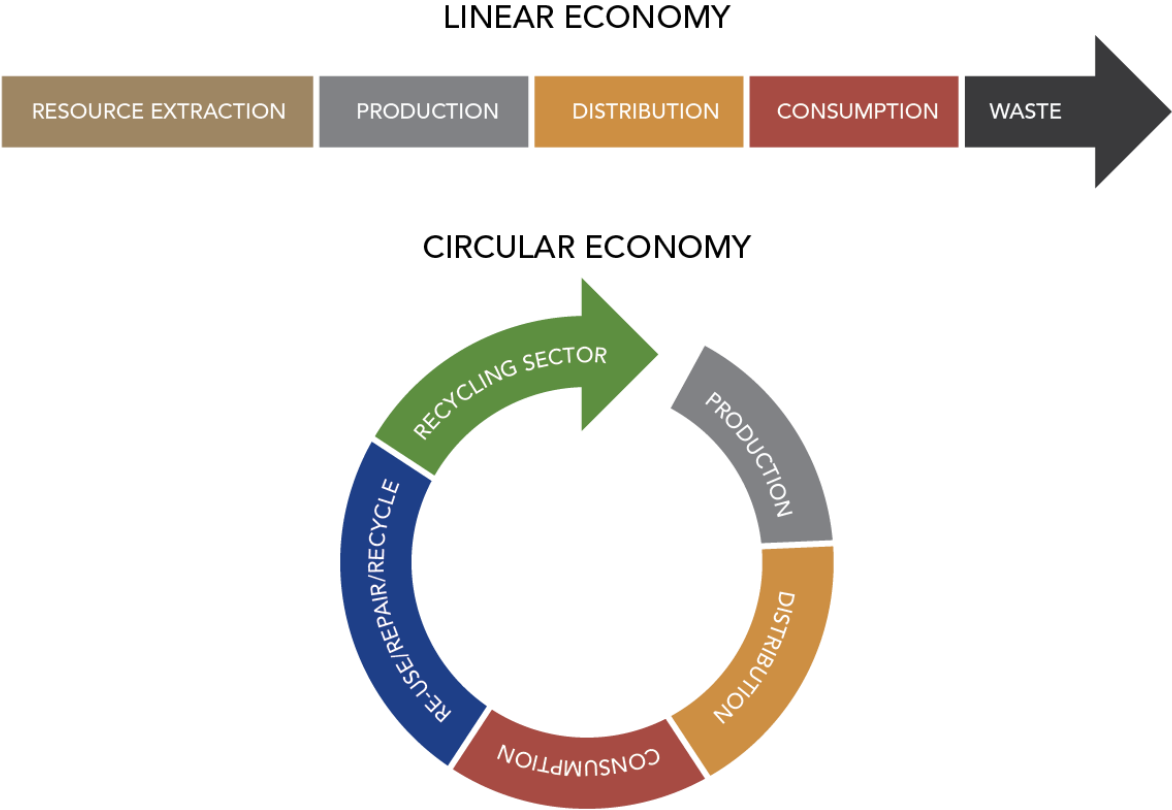


Figure 2. Concept of linear and circular economy, adapted from [7]

## 1.2. ROLE OF BIOMASS AS A RENEWABLE ENERGY SOURCE

What is the definition of biomass? The Eurostat [8] defines biomass in the following way: “Biomass - organic material of non-fossil origin, including organic waste - can be converted into bioenergy through combustion, either directly or via derived products.” [9] What is also important, in 2015 nearly 64% of total primary renewable energy production comes from biomass. What are derived products? Those can be produced by conversion of waste oil into biodiesel, organic household waste and animal manure into biogas and plant o plant waste into biofuel. To generate bio-energy the following materials may be used:

- Wood and wood waste;
- The organic part of industrial and municipal solid waste;
- Sewage;
- Manure;
- Crop plants and waste from food production.

To generate electricity and/or heat, particularly woody biomass can be combusted directly. Considering that plant matter has absorbed CO<sub>2</sub> as it grows, during combustion it releases almost equal amount of carbon back into the atmosphere generating energy in the same time. However, not every assumption include into balance harvesting, transportation and handling issues of biomass which are main disadvantages of this fuel.

### **Environment and human health**

The fact is that higher use of biomass for energy generation may have harmful impacts on air quality. Wood burning, especially, emits detrimental compounds. For example benzene, benzo(a)pyrene (BaP), particular matter (PM) and others, with serious effects on human health (ex. Respiratory diseases or asthma). Collected data allowed European Commission to make estimation, that solid fuels combustion (including biomass) for households purposes is responsible for nearly one third of all PM emissions. Those are suspect to cause 430 00 deaths a year in the European Union.

Interference in management of wood waste and removal all tree residues (usually braches, tree tops, stumps and roots) can significant impact on soil properties in the future. Forest residues have a very high nutrient concentration. Extracting it may affect soil quality, impede regeneration and limit future, natural production potential. Removing straw on cropland, may increase soil erosion and decrease water retention. Moreover it can lead to limitation of soil temperature (however in some areas it may be favorable). Because carbon element is mainly stored in soils rather than in above-ground biomass, amount of carbon store in temperate forests may be reduced by forest harvesting. Furthermore extraction of the biomass may also affect biodiversity, especially through deforestation or exchange of natural forests to tree plantations. Species which lives off biomass residues like a crop roots or dead wood may be affected by forest residue harvesting. On the other hand, if forests will be better managed and when pest will be removed biodiversity will gain positive impact.

## **1.3. DATA REVIEW**

In this chapter I will present basic information about production of energy in chosen European Union countries<sup>3</sup>. For transparency, material is shown in graphic form. All data is collected from Eurostat webpage and comes from year 2015. In graphs below I gathered numbers about primary production of

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<sup>3</sup> Czech Republic, Germany Italy, Norway, Poland, Portugal, Spain.

energy by resource (all products) (Fig. 3), primary production of energy by resource (renewable energy source) (Fig. 4) and primary production of renewable energy by type (Fig. 5).

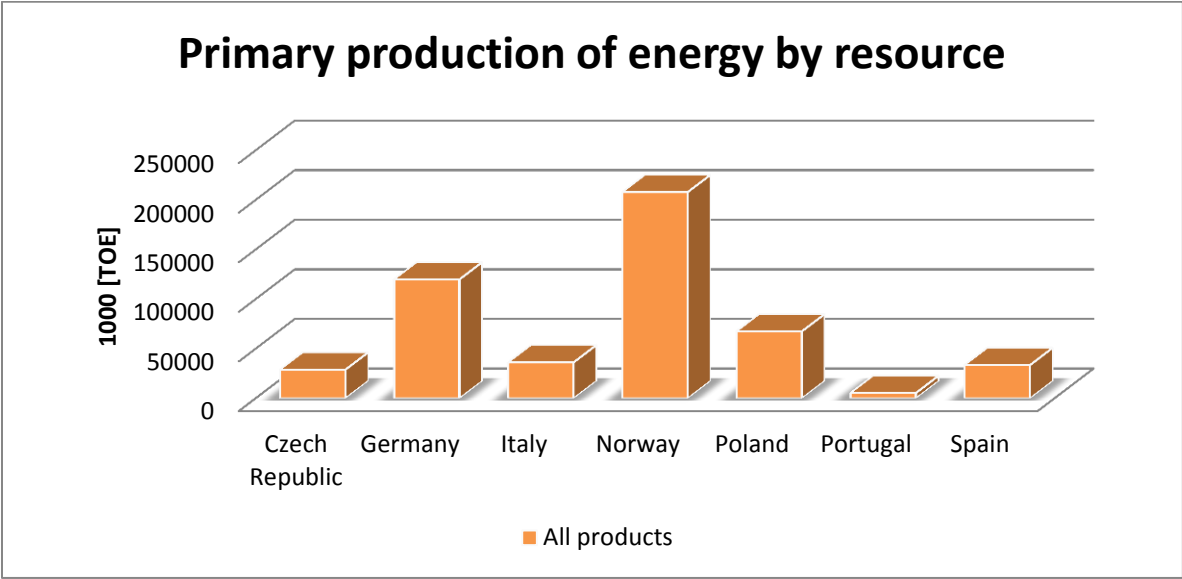


Figure 3. Primary production of energy by resource, chosen EU countries, adapted from [9]

Primary production is any kind of extraction of energy products from natural sources to a usable form. Primary production takes place when the natural sources are exploited, for example in coal mines, crude oil fields, hydro power plants or fabrication of biofuels. Transformation of energy from one form to another, like electricity or heat generation in thermal power plants or coke production in coke ovens is not primary production [9]. Fig. 2 show that from compared countries Norway have largest primary production of energy from all products.

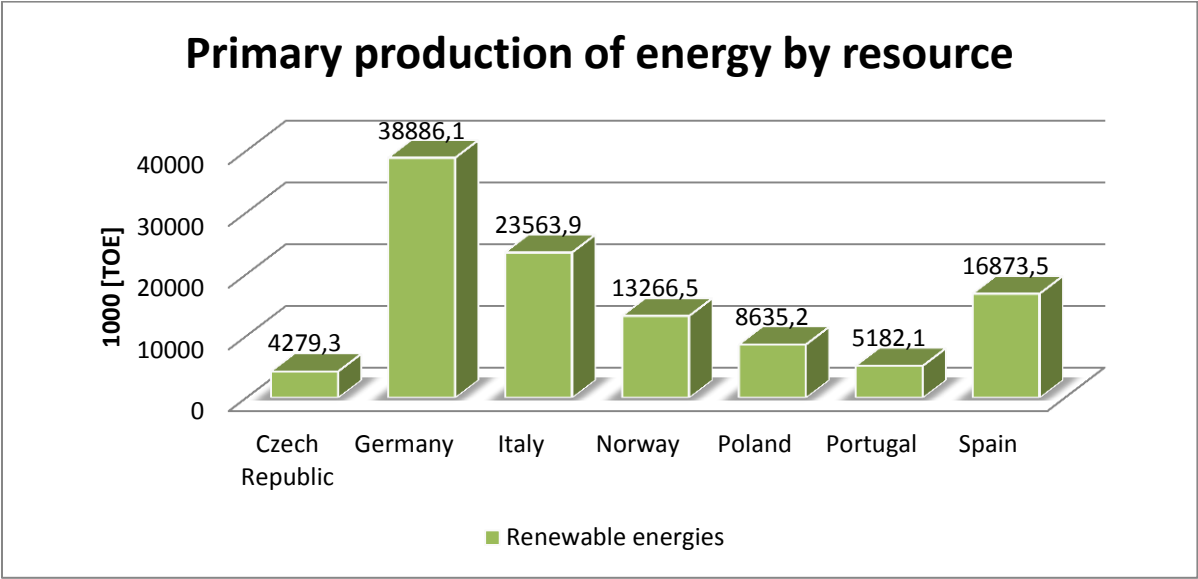


Figure 4. Primary production of energy by resource, chosen EU countries (All renewable energies), adapted from [9]

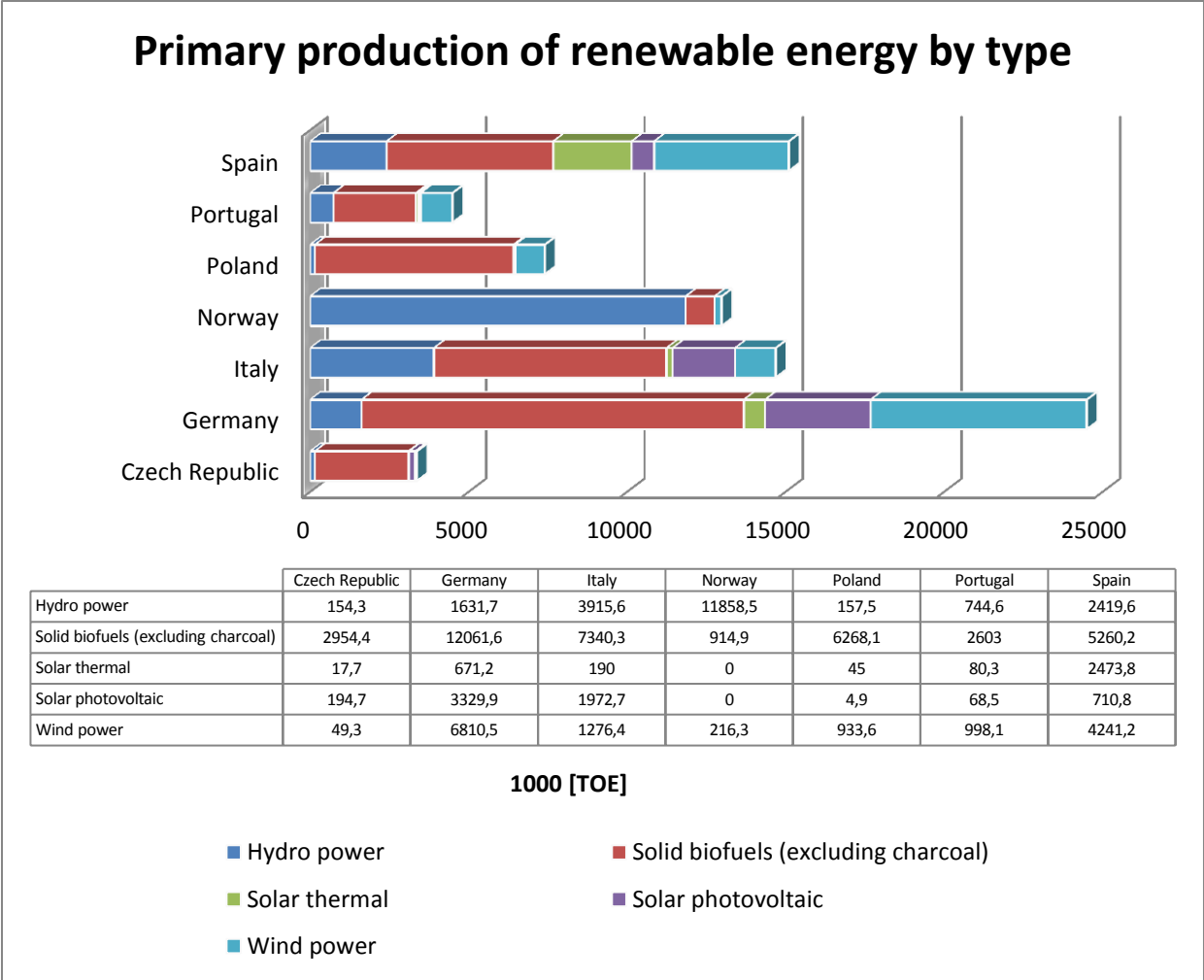


Figure 5. Primary production of renewable energy by type, chosen EU countries, adapted from [9]

Figure 5 represent graph of primary production of renewable energy in chosen EU countries. Renewables are divided into five categories: hydro power, solid biofuels (excluding charcoal), solar thermal, solar photovoltaic and wind power. Germany have largest primary production of renewable energy in total and also biggest share of solid biofuels and wind power. In Norway bulk share of primary production of energy comes from hydro power, whereas Spain use solar thermal and wind power in relative large quantities.

### 1.4. BIOMASS AS A FUEL IN ENERGY SYTEMS

This chapter presents the basic data about properties of biomass. Various types of biomass fuel burned in power plants are presented. Furthermore, coal and biomass properties are compared and later, characteristics of biomass feedstock related to co-firing are listed.



As it commonly known, biomass is created via photosynthesis process in which carbon dioxide from the atmosphere is converted to carbohydrates. The released by-product of this reaction is atmospheric oxygen. Different plant species perform photosynthesis in different way, however the first step is always the same. Green chlorophyll pigments which are called reaction centers absorbing solar energy from light. Next, energy is used to reduce atmospheric carbon dioxide into hexoses through biological process with water [10]. The solar energy is converted into chemical energy and stored in the chemical bonds of carbohydrate compounds like cellulose, hemicelluloses and lignin. Polysaccharides like hemicellulose and cellulose are made from glucose (polymers of glucose). Hemicellulose can be easier hydrolyzed to mono-sugars and other products because less ordered structure in comparison to cellulose. Lignin polymer is responsible for creating structure of the plants.

Biomass used as a fuel in energy industry can be sort into dedicated energy crops and residues from various processes. Biomass is generally obtained from:

- Crop residues (wheat straw, corn stalks, nut shells, orchard pruning's, vineyard stakes, sugar cane bagasse, etc.)
- Forest residues (forest thinning, slash)
- Urban wood waste (construction residues, grass clipping and backyard pruning's)
- Energy crops (Miscanthus, SRC, etc.) [6]

Presently, co-firing systems may be fed by various types of biomass. Co-burning practice includes: wood wastes, agricultural residues and biomasses in processed form such as pellets (really popular in Netherlands and the Denmark). There are already exist plants which are grown especially for electricity generation. Example of the energy crops are perennial crops (such as Muscanthus, switch grass, reed canary grass) or Short Rotation Coppice (SRC). However, practice showed us that energy crops cannot be presently produced in sufficient amount to satisfy large power plants (over 50 [MWth]) demands regarding co-firing [11]. More often biomass for co-combustion is imported as dried and pelletized wood from Russia, Scandinavia, North European countries or North America [11]. Moreover in countries with large olive oil production (Portugal, Spain, Greece, Italy, Turkey and Tunisia) olive processing wastes are produced in large quantities, in form of dry granulated material. Eventually from far eastern countries (Malaysia, Thailand) there is possibility to import resides of the palm oil industry in solid form in large quantities [11]. Residues form industry production of oil, sugar or starch may be used for production of high-energy value liquid fuels (biodiesel, bio-ethanol) which are better alternative that utilization in power plants.

Table below presents types of biomass which are used as a fuel for energy purposes. Moreover supply sectors are listed, as well as examples of biomass (Table 1).

Table 1. Types of biomass feedstocks used for energy purposes, adapted from [12], [13]

SUPPLY SECTOR	TYPE	EXAMPLE
Agricultural residues	Dry lignocellulosic agricultural residues	Straw (maize, cereal, rice) Sugar beet leaves Residue flows from bulb sector
	Livestock waste	Solid manure (chicken manure) Liquid manure (cattle, pigs, sheep manure)
Dedicated energy crops	Dry lignocellulosic woody energy crops	SRC - poplar
	Dry lignocellulosic herbaceous energy crops	Miscanthus Switch grass Common reed Reed canary grass Giant reed
	Oil energy crops	Rapeseed Sunflower seeds Soybean Olive-kernel
	Sugar energy crops	Sugar beet Cane beet Sugar millet
	Starch energy crops	Wheat Potatoes Maize Barley Corn (cob)
	Others	Flax (Linum) Hemp (Cannabis) Tobacco stems Aquatic plants (lipids from algae) Cotton stalks
Forestry	Forestry by-products	Bark Wood blocks, wood chips from tops and branches Wood chips from thinning Logs from thinning
Industry	Wood industry residues	Industrial waste wood from sawmills and Industrial waste wood from timber mills (bark, sawdust, wood chips, slabs, off-cuts)

		Fibrous vegetable waste from virgin pulp production and from production of paper from pulp, including black liquor
	Food industry residues	Wet cellulosic material (beet root tails) Fats (used cooking oils) Tallow, yellow grease Proteins (slaughter house waste)
	Industrial products	Pellets from sawdust and shavings Briquettes from sawdust and shavings Bio-oil (pyrolysis oil) Ethanol Bio-diesel
Parks and Gardens	Herbaceous	Grass
	Woody	Pruning
Waste	Contaminated waste	Demolition wood
		Biodegradable municipal waste
		Sewage sludge
		Landfill gas
		Sewage gas
Others	Roadside hay	Grass/hay
	Husks/Shells	Almond Olive Walnut Palm pit (imported) Cacao (imported)

Normally biomass has approximately 20% of fixed carbon (ash free and moisture free basis) and 80% of volatile matter. In contrary group-one bituminous coal has just 20-30% of volatile matter and up to 80% of fixed carbon [14]. As shown in Table 1, the chemical composition of coal is different from various types of biomasses. Mainly regarding ash content and moisture. Table below (Table 2) present comparison of basic properties of chosen solid fuels.

Table 2. Typical properties of different solid fuels, adapted from [15]

	Coal	Peat	Bark	Forest residues <sup>4</sup>	Willow	Straw	Olive residues	
Ash content db <sup>5</sup>	8.5-10.9	4.7	2-3	1-3	1.1-4	5	2-7	
Moisture content [w%]	6-10	40-55	45-65	50-60	50-60	17-25	60-70	
NCV [MJ/kg]	26-28.3	20-21.3	15.5-23	18.5-20	18.4-19.2	17.4	17.5-19	
C	%w dry basis	76-87	52-56	48-52	48-52	47.51	45-47	48-50
H		3.5-5	5-6.5	5.7-6.8	6-6.2	5.8-6.7	5.8-6	5.5-6.5
N		0.8-1.5	1-3	0.3-0.8	0.3-0.5	0.2-0.8	0.4-0.6	0.5-1.5
O		2.8-11.3	30-40	24.3-40.2	40-44	40-46	40-46	34
S		0.5-3.1	0.05-0.3	<0.05	<0.05	0.02-0.1	0.05-0.2	0.07-0.17
Cl		<0.1	0.02-0.06	0.01-0.03	0.01-0.04	0.01-0.05	0.14-0.97	0.1 (in ash)
K		0.003	0.8-5.8	0.1-0.4	0.1-0.4	0.2-0.5	0.69-1.3	30 (in ash)
Ca		4-12	0.05-0.1	0.02-0.08	0.2-0.9	0.2-0.7	0.1-0.6	No data

4 Coniferous tree with needles

5 db - dry basis

Biomass usually has low calorific value which is a result of high moisture content. Bituminous coals contains approximately 5% of moisture, when fresh wood typically content 50% of water by weight. Unfortunately, combustion of biomass is affected by high amount of moisture. Higher water content decrease the combustion temperature and rise the optimal residence time of feedstock in a combustion chamber. It causes feedstock coolness, incomplete combustion and finally emission increasing (volume of flue gases produced per energy unit) [13].

Generally, biomass contains less ashes than coal and the chemical composition is different. Biomass ash contains components required for plant growth, when coal ash include mostly mineralogical composition [16]. Similarly ash from biomass and from coal, is composed from forms which can be divided into four main groups [14]:

- Inorganic materials (sand, salt or clay);
- Minerals included into fuel structure;
- Inorganic elements occurring in organic matter of the biomass;
- Easily leachable salts.

Furthermore, biomass content high amount of alkaline metals which are responsible for fouling of heat exchange surfaces. Those elements are generally build salts or bound in the organic compounds, however in some cases for instant in peat it is different. In peat, inorganic matter is mostly located in silicates, which are resistant for high temperature. Compounds responsible for ash-melting behavior are chlorine, calcium, phosphorus, silicon and alkali metals. Even small dose of chlorine in feedstock could result in settling of harmful chlorine and alkaline deposit on boiler heat transfer surfaces [15]. Regarding to coal composition, biomass has less fixed carbon and sulphur, but more oxygen. Unfortunately, biomass has low bulk energy density. Moreover, biomass in contrary to coal is non-friable and hydrophilic. In table below (Table 3) there is presented characteristic of biomass divided on chemical and physical properties and their impact on co-firing.

**Table 3. Characteristic of solid biomass fuels and their most important effects, adapted from [17], [13], [14]**

	Characteristics	Effects
<b>PHYSICAL PROPERTIES</b>	Moisture content	Storage durability and dry-matter losses, NCV <sup>6</sup> , self-ignition, plant design
	NCV, GCV	Fuel utilization, plant design
	Volatiles	Thermal decomposition behavior
	Ash content	Dust emissions, ash manipulation, ash utilization/disposal, combustion technology
	Ash-sintering behavior	Operational safety, combustion technology, process control system, hard deposit formation

6 NCV – Net Calorific Value,

	Fungi	Health risks
	Bulk density	Fuel logistics (storage, transport, handling)
	Particle density	Thermal conductance, thermal decomposition
	Physical dimension, form, size distribution	Hoisting and conveying, combustion technology, bridging, operational safety, dying, dust formation
	Fine parts (wood pressings)	Storage volume, transport losses, dust formation
	Abrasion resistance (wood pressings)	Quality changes, segregation, fine parts
CHEMICAL PROPERTIES	Elements	
	Carbon C	GCV'
	Hydrogen H	GCV, NCV
	Oxygen O	GCV
	Chlorine Cl	HCl, PCDD/PCDF emissions, corrosion, lowering ash-melting temperature
	Nitrogen N	NO <sub>x</sub> , N <sub>2</sub> O emission
	Sulphur S	SO <sub>x</sub> emissions, corrosion
	Fluorine F	HF emissions, corrosion
	Potassium K	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, aerosol formation, ash utilization (plant nutrient)
	Sodium Na	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, aerosol formation
	Magnesium Mg	Increase of ash-melting temperature, ash utilization (plant nutrient)
	Calcium Ca	Increase of ash-melting temperature, ash utilization (plant nutrient)
	Phosphorus P	Ash utilization(plant nutrient)
Heavy metals	Emissions, ash utilization, aerosol formation	

Table 4. Characteristic of selected fuels, adapted from [18]

Parameter	Fuel type			
	Pine sawdust <sup>8</sup>	Rice husk <sup>9</sup>	Bituminous coal <sup>10</sup>	Lignite <sup>10</sup>
Proximate analysis, wt% as received				
Fixed carbon	14.2	20.1	53.9	35.0
Volatile matter	70.4	55.6	28.2	44.5
Moisture	15.3	10.3	7.8	12.4
Ash	0.1	14.0	10.1	8.1
Ultimate analysis, wt% as received				
Hydrogen	5.0	4.5	3.9	4.1
Carbon	43.2	38.0	70.3	51.0
Oxygen	36.3	32.4	6.4	23.8
Nitrogen	0.08	0.69	1.07	0.4
Sulfur	-	0.06	0.41	0.16
Ash analysis, wt%				
SiO <sub>2</sub>	9.71	94.48	51.67	46.15
Al <sub>2</sub> O <sub>3</sub>	2.34	0.24	29.15	20.91
Fe <sub>2</sub> O <sub>3</sub>	0.10	0.22	10.73	6.77
CaO	46.88	0.97	3.72	12.54
SO <sub>3</sub>	2.22	0.92	1.47	8.00
MgO	13.8	0.19	1.41	2.35
K <sub>2</sub> O	14.38	2.29	0.29	1.49
TiO <sub>2</sub>	0.14	0.02	1.24	0.77
Na <sub>2</sub> O	0.35	0.16	0.31	0.73
P <sub>2</sub> O <sub>5</sub>	6.08	0.54	-	0.29
Heating value [kJ/kg]				
Higher heating value	17280	14980	28330	20070
Lower heating value	16180	13990	27340	19070

Table 4 compare basic characteristic of pine sawdust, rice husk, bituminous coal and lignite. The most of fixed carbon contains bituminous coal, it have also lowest level of volatile matter and moisture. On the other hand pine sawdust have littlest amount of ash. Comparing standard solid fuels (coal, lignite) with biomass – these second have much smaller content of sulphur. Ash analysis show that ash of pine sawdust is rich with alkaline oxides (CaO, K<sub>2</sub>O, MgO) whereas ash of rice husk is composed mainly from SiO<sub>2</sub>. Composition of bituminous coal and lignite ashes are similar, however lignite ash contain more alkaline oxides and bituminous coal more Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>.

8 Vassilev et al. (2010)  
9 Madhiyanon et al. (2009)  
10 Vassilev and Vassileva (2007)

## 2. BIOMASS CO-FIRING IN POWER PLANTS

In this chapter main information about biomass combustion are described. The process of biomass combustion depends significantly on fuel properties (moisture, particle size etc.) and the combustion technology (types of boiler, burners, process parameters). The overall process includes physical and chemical phenomenon of high complexity. The combustion process may be divided into several main steps: drying, pyrolysis, gasification and combustion [13].

### 2.1. TYPES OF TECHNOLOGY OF BIOMASS CO-FIRING WITH COAL

Co-firing or co-combustion, is the process in which two types of fuel are burned in the same boiler [19]. Despite that many types of fuel can be mixed, upper mentioned terms are mostly related to the burning of coal with solid biomass. The number of fuel types used together is not limited. The greatest advantage of co-firing is that already existing power plants can be used to co-combustion new mixture. In many cases new fuel is more environmental friendly and cheaper in the same time, for example agricultural residues. Often biomass is co-fired in already existing coal-fired power plants instead of building new blocks. Co-firing advantages:

- Considering that co-burning is realize in already existing coal-fired power plants, implementation can be achieved in short time and with low investment cost.
- Rural areas can gain economically benefits from the production of biomass.
- According to European Union Legislation biomass is CO<sub>2</sub> neutral, thus biomass co-combustion will not increase greenhouse effect and help reduce global CO<sub>2</sub> emission.
- Co-firing of biomass allows obtaining subsidies in countries where government offers them for replacing fossil fuels with clean technologies.
- Usually biomass fuels have fewer sulfur and nitrogen content than coal, hence emissions of SO<sub>x</sub> and NO<sub>x</sub> are reduced.
- Power plant still can operate only on coal in case of lack of biomass.
- Landfilled biomass residues are one of the main sources of greenhouse gases, methane which is released during rotting is 21 times more potent as carbon dioxide in terms of global warming impact [19].
- Co-combustion is one of the most efficient way to utilize biomass in power industry. Average efficiency of biomass power plant is in the 20 to 25% which is almost half lower for the considerable coal units. In the same time biomass co-firing at a 3-5% causes a decrease in boiler efficiency less than 1% [19].



Rational usage of renewable sources of energy is essential for sustainable country development. The level of their use is dependent from the reserves volume and available processing technology. The greatest interest of domestic energy producers in Poland are focused on co-firing of biomass in already existing power plants which are designed for coal burning. However, fact that power plants were built for coal as a fuel is not a barrier for co-firing of biomass. Adaptation for co-burning is possible and economical reasonable. Moreover, it can be shortest way to implement usage of biomass as a fuel in greater power production units. Presently there are three basic technologies for biomass co-burning:

- Direct co-firing
- Indirect co-firing
- Parallel co-firing

Co-firing process can be also used to boost combustion of fuels without high energy content. For instance landfill gas. Because of the origin, landfill gas contains high amount of carbon dioxide which is incombustible and unwanted. In case when landfill gas is burned without carbon dioxide extraction flow rates are increased and process is inefficient. However, when mixed with natural gas the heat content will rise and combustion process will be improved. In this example, biomass co-firing increase energy content of landfill gas which alone have too much quantity of carbon dioxide. Moreover co-burning may reduce emission of some pollutants. Carbon burned alone emits large amount of sulphur compounds, however when biomass is co-firing with coal sulphur emission will be reduced.

- **Direct co-firing**

Direct co-firing is the simplest idea of burning biomass with coal. The process takes place in one furnace. This option is cheapest and most commonly applied method. Many of the plants over the world chose this configuration. For example: tangentially-fired Greenidge Generation Station in Dresden, New York [20]; Gelderland Power Station in the Netherlands [13]. There are lot of types of biomass therefore fuel may be burned in the same or separate burners as coal. Presently for direct biomass co-burning in pulverized coal boilers there are four options:

- First method is most direct and cheapest. However, it may be only applied for low biomass amount (less than 5%) and only in regular (conventional) wall or corner-fired boilers [15]. Both fuels are blended in the fuel handling system and later this combination/blend is fed into the boiler. Moreover there are also limitation regarding biomass types. Co-firing of herbaceous biomass can lead to many complications while sizing and feeding. On the other hand sawdust, cocoa shells, olive or palm kernels do not cause any difficulties [15].
- Second option requires higher investment but co-firing may be achieved at higher ratio. The process include the separate granulating of biomass. Next step is injection milled biomass into the pulverized coal pipe which may work upstream of the burner or at the burners.

- Third method also include isolated biomass milling, but has two independent delivering lines. Presented option is most expensive but allows to leave original coal injection system and directs biomass fuel into the special burners in the lower furnace. This option increases the number of biomass materials, which can be fed to the boiler.
- Last option requires isolated milling system with separate biomass-fired burners at the exit of the boiler. In this process  $\text{NO}_x$  emissions are controlled by re-burning of biomass.

Scheme of direct co-firing is presented on graphic below (Fig. 6):

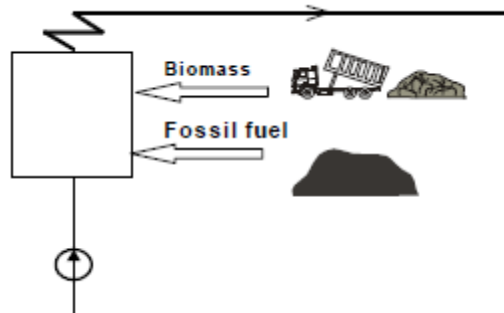


Figure 6. Simplified process of the direct co-firing, adapted from [5] with approval.

- **Indirect co-firing**

In this method of co-firing biomass is gasified or combusted. Combustion occurs in following processes. Firstly biogas or biomass is burned in pre-furnace and the heat of flue gases is used in the combustion chamber heating boiler surfaces. Other way is to transfer this enthalpy directly to the heat exchangers as a heat agent.

Second option is gasification. Gasification of the biomass is performed in biomass gasifiers from which produced gas is supplied to the combustion chamber, where is burned. This process does not allow coal and biomass ashes to mix with each other. Main disadvantage of indirect co-firing is high investment cost [21]. This technique allows produce coal and biomass ashes independently. Indirect co-firing by pre-gasification is currently operated in a number of demonstration plants in Austria (Zeltweg), Finland (Lahti) and the Netherlands (Geertruidenberg) [33]. The drawback of indirect co-firing option is relatively high unit investment costs [21]. Graphic representation of indirect co-firing is shown on next scheme (Fig. 7).

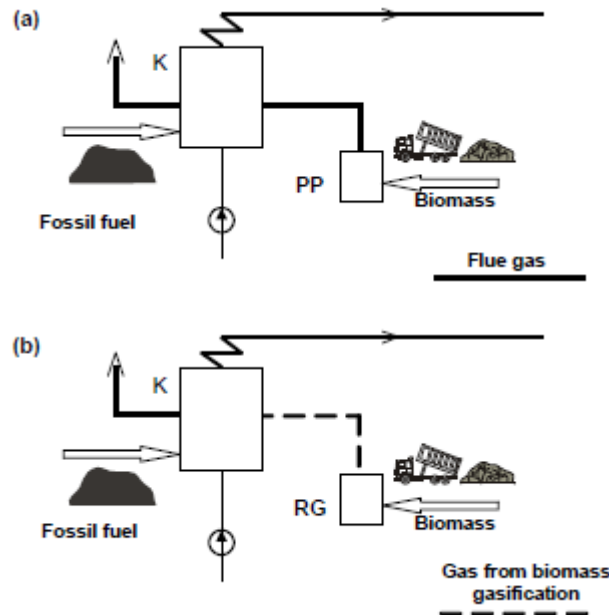


Figure 7. Simplified process of the indirect co-firing, adapted from [5] with approval.

- **Parallel co-firing**

Parallel co-firing is also called parallel co-combustion. In this technique coal and biomass are combusted separately. Biomass is used to produce steam which is directed to a common header. Steam generator is directly related with amount of burned biomass by his capacity. In that particular case it must be ensure that sufficient overcapacity of steam turbine is capable to accommodate the extra power from biomass combustion. However there is another option, simply decrease coal boiler capacity [5]. In parallel co-firing biomass and coal ashes are kept separately. Due to fact that both fuels are processed in different boilers, an optimal system for each can be used (e.g. CFB for biomass and PC for coal). The investment in parallel co-combustion technique is considerable higher than in the other options. Sample of existing unit is the Avedore Unit 2 project in Copenhagen, Denmark (International Energy Agency, 2009) On the other hand there are few really significant advantages for parallel co-firing:

- Prospect of optimization both combustion processes.
- Possibility of usage biomass with high chlorine and alkali contents.
- Receiving separated biomass and coal ashes [22].

Diagram of parallel co-firing is presented on the next page (Fig. 8).

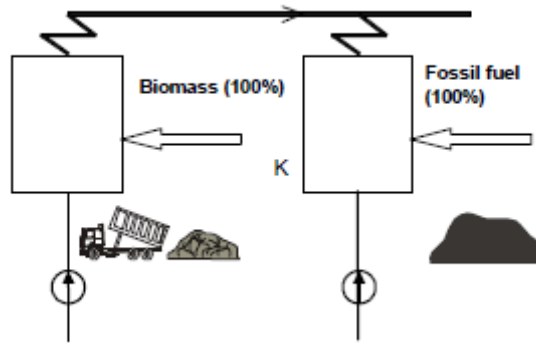


Figure 8. Simplified process of the parallel co-firing, adapted from (5) with approval.

## 2.2. ADVANTAGES AND DISADVANTAGES OF BIOMASS CO-FIRING

Co-firing of biomass can lead to many problems. The main technical risk areas are:

- Combustion related issue (burnout, flame stability) affecting plant operation and control.
- Feed stock preparation, transportation, processing and handling issues.
- Issues related with ash (slagging, fouling, corrosion).
- Emissions and environmental impacts (like deforestation)

A simplified overview of risk areas localization is presented on the figure below (Fig.9):

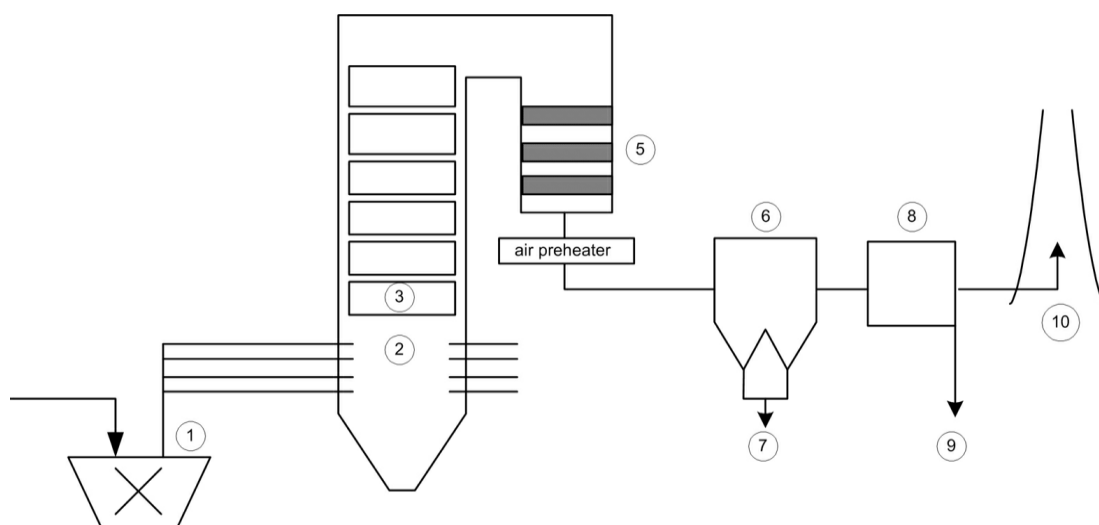


Figure 9. Effects of biomass co-firing at a coal-fired power station , adapted from [23], [13]

*Notes:* 1: grinding equipment: reduced capacity and lifetime, 2: combustion chamber: slagging, 3: superheater: high temperature corrosion, 4: heat exchanger: depositions and erosion, 5: de-NOx installation: capacity, poisoning, 6: electric precipitator: capacity, 7: ash: utilization, 8 de SOx installation: capacity, 9: utilization of residues from desulphurization, 10: flue gas: emissions.

### **2.3. FUEL PREPARATION, PROCESSING AND HANDLING ISSUES**

In this chapter issues of the material preparation are described. Moreover processing and handling of biomass or biomass with coal are listed. The most important processes for solid fuels preparation are:

- Bulk handling, transportation and storage;
- Initial particle size reduction;
- Final size reduction (milling, comminution)
- Washing or cleaning (to remove tramp material or reduce ash content);
- Preliminary drying (depends on the feedstock)

Nevertheless, biomass parameters are dependent on the fuel source. There is various origin of biomass and each group will have different characteristic, physical form and moisture content.

### **2.4. SLAGGING AND FOULING ISSUES IN BIOMASS CO-FIRING UNITS**

Biomass and coal as the solid type fuels generally contains significant amount of ash forming components. This feature distinguish all solids fuels from gaseous and liquid fossil fuels. Fly ashes and bottom ashes are mainly formed during combustion. Ash fractions are dangerous for environment and may cause internal and emission problems. The fly ash can be divided into aerosols and fly ashes. Aerosols are particles with a diameter less than 1 ( $\mu\text{m}$ ) [4].

To meet current European dust emission standards [25], proper dust separation device must be installed. For that reason large and medium scale industrial plants may apply electrostatic precipitators and baghouse filters, which are highly efficient filter system. However, smaller biomass combustion systems cannot install these installation due to economic reasons, which has led to significant research and development efforts in this field. This is very important since many regions in Europe are presently fighting with air quality problems related with fine particulate matter (PM10, PM2.5) [26], and small biomass combustion systems have been identified as a main emission source together with traffic and industry.

Focusing on power plants, main problems caused by ashes are slagging, deposit formation and corrosion. Fouling on boiler heated surfaces reduces the heat transfer and as a result decrease efficiency of combustion units. Slagging on the boiler grate can disrupt the combustion process and damage the grate. Serious deposit formation may lead to the clogging of heat exchanger sections, forcing plant shutdowns for boiler cleaning and deposit removal. Moreover, fouling can be corrosive and may reduce installations lifetime. Significant research and development efforts are being made to find solutions for these issues. Principally for large-scale biomass combustion units fueled by herbaceous biomass or waste wood [4].

Contracting with main organic components (C, H, O, N), biomass fuels contains appreciable amounts of ash forming elements. Elements with major importance are: K, Na, Ca, Mg, Si, S, Cl as well as heavy metals such as Pb and Zn. From practical point of view problems with ash deposition in biomass co-firing and biomass combustion generally are related with:

- Slag deposition and formation of fused ash agglomerates at high temperatures;
- Bonded ash deposit formation on the heat exchangers at lower gas temperatures;
- The increased metal wastage of boiler components related to erosion and corrosion;
- Sub-micron aerosols and fumes formation and emission;
- Problem related to utilization and handling of ash residues from biomass combustion, also of mixed ash residues from co-burning of biomass with coal.

Typically, the nature of the problem is influenced by biomass properties i.e. ash chemistry, ash content, and on the process design and parameters. There are different ash deposition rates from coal and from biomass. Furthermore, ash deposition depends largely on the type of burned biomass. Properties of ash deposition of some herbaceous materials will exceed coal by significant number, however those for low ash wood materials tend to be lower [13].

From observation following conclusion were drawn:

- When co-firing wood or similar (low ash, low alkali, low chlorine) fuels ash deposition rates should not be influenced significantly.
- When co-burning agricultural residues or herbaceous biomass (with high as, high chlorine, high alkali content) ash deposition rates should dramatically increase.
- Both fuel properties and relations between them affect ash deposition rate significant.

### **Source of inorganic matter in biomass**

There are mainly two sources for inorganic ash creating matter in biomass. Ash forming elements exist in the plant itself, as a structure of the fibers (Si, Ca) or are macro and micro plant nutrients (K, P, S, Zn). Differently, biomass can be also contaminated with stones, soil or sand. Paints, coatings, metal and glass pieces are major sources of pollutions in waste wood.

## 2.5. LITERATURE REVIEW OF CO-FIRING UNITS

Concept of biomass co-firing is not new. There are already existing plants using technology of co-firing. Examples of power plants that co-burning biomass [13] [21]:

- Parallel co-firing of biomass and fossil fuels, Avedøre Power Plant, Denmark
- Indirect co-firing of biomass fuel gas with coal, Amer Powe Plant, The Netherlands
- Indirect co-firing of biomass fuel gas with coal, Zeltweg Powe Plant, Austria
- Direct co-firing of wood fuels on a grate located directly under the furnace of a PC boiler, St Andra, Austria
- Direct co-firing of straw with coal, Strudstrup, Denmark
- Direct c-firing of sawdust and woodchips with coal at Wallerwang Power Station, NSW, Australia
- Direct co-firing of demolition wood waste with coal, Gelderland Power Station, Nijmegen, The Netherlands

In this work Avedøre Power Plant is described since this power plant is relatively new and innovative. This project is one of the more advanced biomass co-utilization facility. Avedøre Unit 2 is located in Denmark, near Copenhagen [10]. The main unit is a large ultra-supercritical power plant which fires natural gas. However, was designed for coal, gas and oil firing. Power plant is equipped with supercritical boiler, rated at 430 (MW), with a steam turbine, electricity generator and a flue gas clean-up plant. The plant has also two aero-derivative gas turbines, rated at 51 (MW) each, which provide electricity at peak load. Moreover, they are used to pre-heat feed-water to the USC boiler, via exhaust heat recovery units. Additionally, a biomass boiler provides steam to the system, it is feed by straw , and rated at 105 (MW). The biomass boiler generates up to 40 (kg/s) of steam at 583 (°C) and at pressure up to 310 (bar) – for that reason it consumes 150.000 tons of straw per annum [13].

All of the key components of the Avedøre Unit 2 power plant has special and unique operational capabilities. The reason for that is because the biomass boiler, USC boiler, the steam turbine and the two gas turbines with their heat recovery units, are integrated into one process. Company which built plant was l/s Avedøre 2 – joint venture between Vattenfall and Energy E2 (the main power company in Eastern Denmark). It start commercial operation by the end of 2001 and is working till nowadays according to expectations. A diagram of the general multi-fuel concept is showed below (Fig. 10) [13].

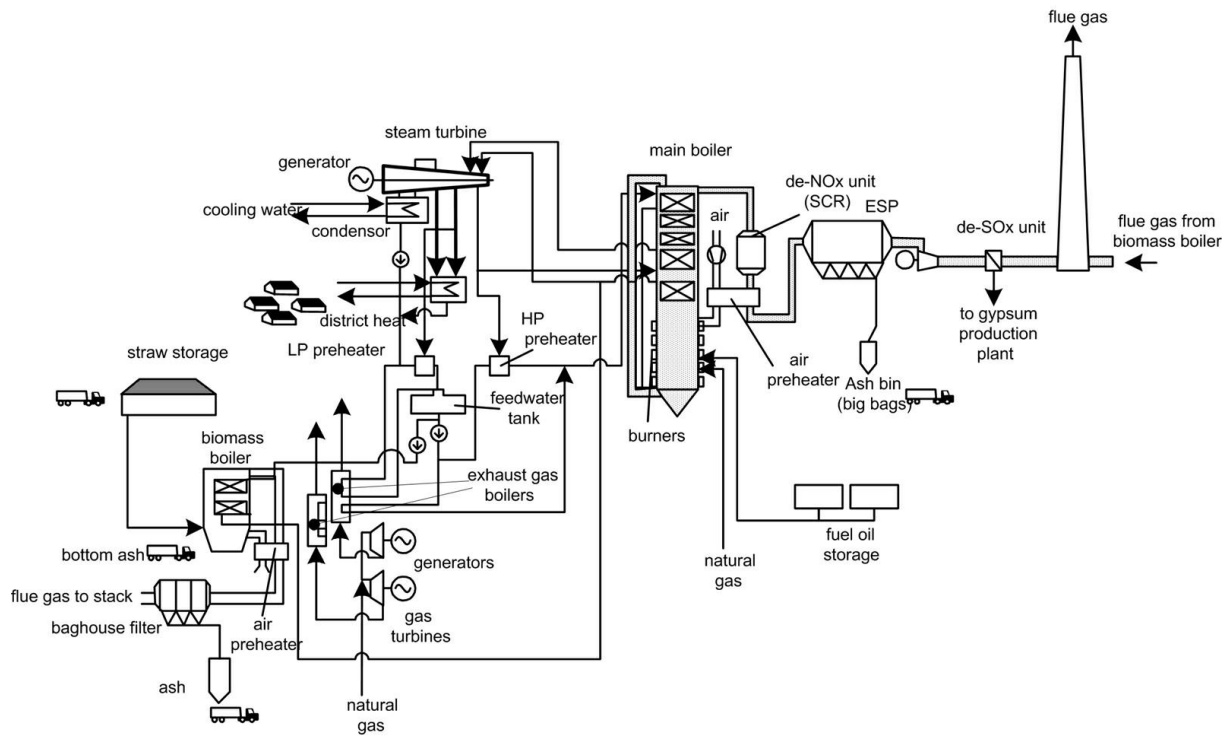


Figure 10. Scheme of Avedøre 2 multifuel system, adapted from [13]

### Summary of gathered experience of co-firing of biomass

Over the last 15-20 years there has been rapid increase in the development of the co-firing of biomass in coal fired power plants. In Europe main factor was law regulation, which encourage energy companies to include biomass as a partial feedstock. Moreover, in North America and Australia biomass usage have been supported through different funding schemes. The European research, development and demonstration, have been stimulated by the EC Thermie Programme funds, and furthermore by particular subsidy schemes for generation energy from renewable sources.



### 3. CO-FIRING TECHNOLOGY USED IN PGE POWER PLANT IN KRAKÓW

#### 3.1. CHARACTERISTIC OF BOILER OP-380 FROM PGE POWER PLANT IN KRAKÓW

Table 5. Boiler OP-380 parameters, adapted from [24]

Parameter	Value
Circulation	Natural
Furnace type	Tangent
Maximum efficiency	105.6 (kg/s)
Temperature of fresh steam (outlet)	540 (°C)
Pressure of fresh steam (outlet)	13.9 (MPa)
Temperature of secondary steam (outlet)	540 (°C)
Pressure of secondary steam (outlet)	2.65 (MPa)
Temperature of feed water	227 (°C)
Boiler efficiency	91%
Fuel type	Hard coal
Fuel Heating value	21 (MJ/kg)

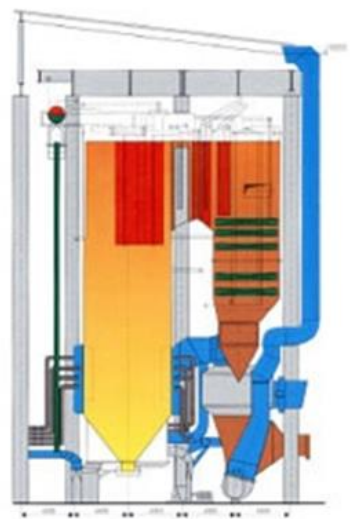


Table 5 show general parameters of boiler OP-380. Boiler OP-380 was produced by RAFAKO S.A. (PBG Group), and moreover this type of boiler is installed in following power plants:

- Poland: Łagisza (5), Łaziska (2), Kraków (2), Siekierki (1), Siersza (4);
- China: Huainan (2).

Together there are 16 operating boilers OP-380 in the world [24].

Data was collected from coal fired boiler OP-380 with steam output of 105 (kg/s) which is equal to 380 (t/h). Boiler has two-courses shape with tight packed membrane walls. Circulation of working medium occurs in natural way. Feedstock is coal which is introduced by four mill sets. In next chapter I present scheme of boiler OP-380.

### 3.2. BOILER OP-380 TECHNOLOGY SCHEME

Diagram below represent technology scheme of boiler OP-380 (Figure 11).

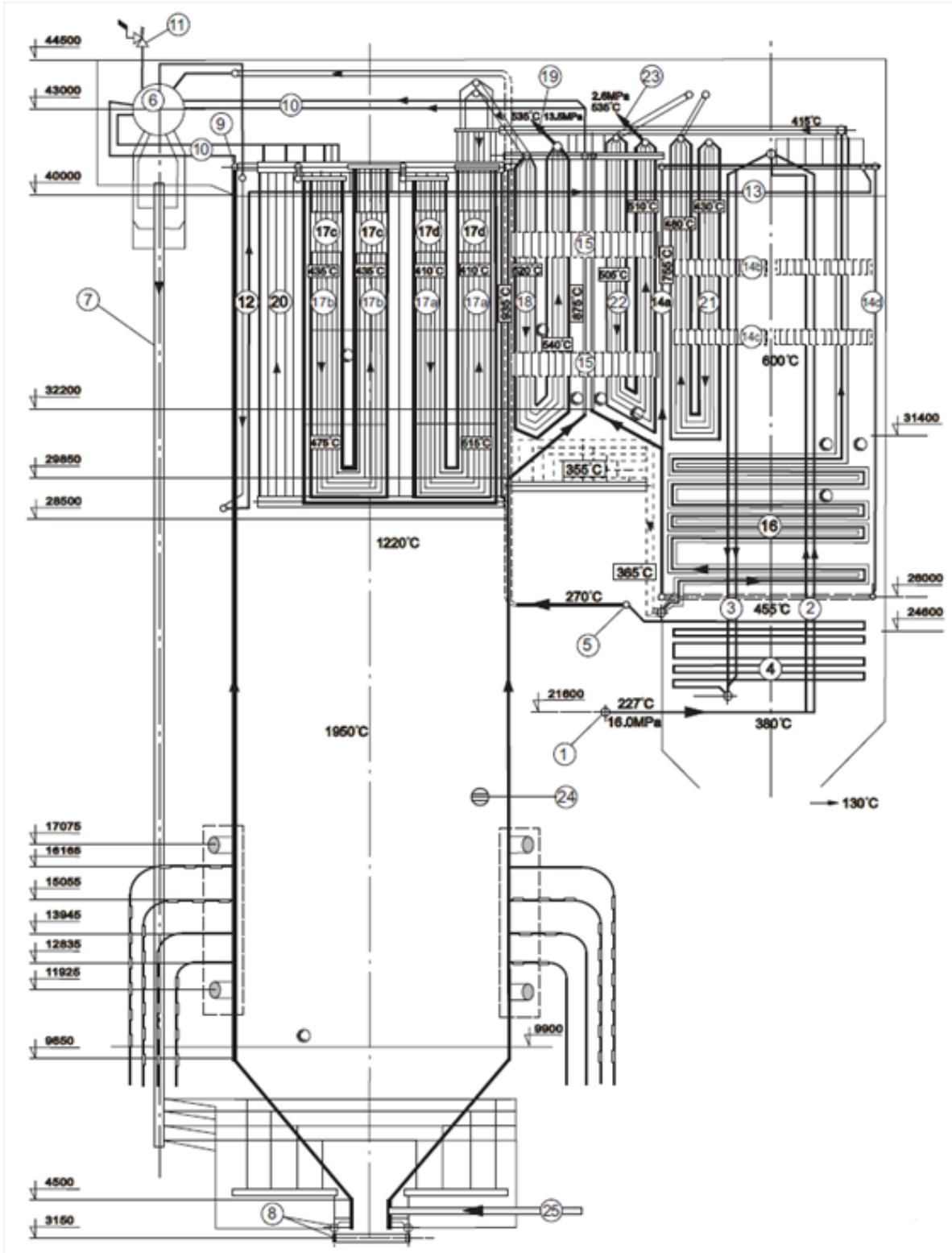


Figure 11. Scheme of boiler OP-380, adapted from [25]

Elements description	
1. Feed water inlet	a. Front wall of II <sup>nd</sup> course
2. Rising rack pipes	b. Side walls of II <sup>nd</sup> course
3. Down falling rack pipes	c. Side walls of II <sup>nd</sup> course
4. Heating coil pipe	d. Back wall of II <sup>nd</sup> course
5. Outlet chamber of water heater	15. Side superheaters of middle course
6. Steam drum	16. Convection superheater
7. Down falling pipes	17. Fence II <sup>nd</sup> superheater
8. Lower screen chambers	18. End III <sup>rd</sup> superheater
9. Upper screen chambers	19. Outlet of fresh steam to the turbine
10. Connecting pipes	20. Secondary steam wall superheater
11. Steam drum safety valve	21. Secondary steam middle superheater
12. Fresh steam wall superheater	22. Secondary steam end superheater
13. Ceiling superheater	23. Outlet of secondary steam
14. Fresh steam I <sup>st</sup> superheater	24. Air inlet (OFA nozzle)
	25. Exhaust gases recirculation inlet

#### Process description:

Firstly, water is directed to feed-water heater which is located in lower part of the second boiler course (4). Secondly, water goes right into steam drum (6) and by flow pipes (7) straight into lower screen collectors, and then to raising pipes and to the upper collectors. Downfall pipes and rising pipes creates boiler evaporator.

Water and steam mixture which was created in evaporator turn back into steam drum where vapor is separated from water. Isolated steam is directed into the first level superheater of primary steam, whereas water back into the evaporator. I<sup>st</sup> level primary steam superheater is consist of four parts: mural superheater (12), ceiling superheater (13), superheater screens (14a, 14b, 14c, 14d, 15) and convectional superheater (16).

Superheated steam flow into the II<sup>nd</sup> level primary steam superheater, which is called fenced superheater (17a, 17b, 17c, 17d) and located in upper section of furnace chamber. Further, superheated steam is directed to the III<sup>rd</sup> level primary steam superheater (18) placed at the front of the canal in intercourses boiler and later by pipes right into turbine. From turbine steam is transported to superheater of secondary steam which is consist of three steps.

I<sup>st</sup> step is mural superheater (20) hanged to the furnace chamber side wall. From this place, turbine stream goes into the intermediate preheater (21) located in the front part of II<sup>nd</sup> course and further is transported to the final preheater (22) located in the rear part of intercourses boiler, and finally flows back to the turbine.

### 3.3. FEEDSTOCK FOR BOILER OP-380

### 3.4. SOOT BLOWERS

A soot blower is a device which remove the soot from furnace tubes of boiler during combustion. Medium used in soot blowers can be steam or air. Mostly power plants use steam as a medium for blowing away the fly ash. Cost of compressors, motors and control of air system is more expensive that usage of already generated steam. Types of soot blowers:

- Air heater blower
- Wall blowers (IRs – Insertable Rotating)
- Long Retractable Soot Blower (LRSB or IK – Insertable Kinetic)

Soot deposit can lead to soot fired and cause local hotspot. The result is that boiler material can be local overheated and weaken. In PGE Power Plant in Kraków there are 28 soot blowers working in boiler OP-380. All blowers are provided by Clyde Bergemann Company, the types are following:

- Blowers from 1 to 12 are type V92E;
- Blowers 13-22 are type PS-SL;
- Blowers 23-24 are type PS-SB;
- Blowers 25-28 are type PS-AL.

Description of soot blowers:

- Type V92E (Fig. 14)

Short blowers mounted on the wall for cleaning furnace parts. They are mounted on the outside of the boiler. When blowing process start, head jet is going into boiler interior by rotation movement. V92E blower is equipment with two jets and is steam powered. Blowing angle can be set between  $-30^{\circ} \div 360^{\circ}$  and should be directed to the screening pipes.

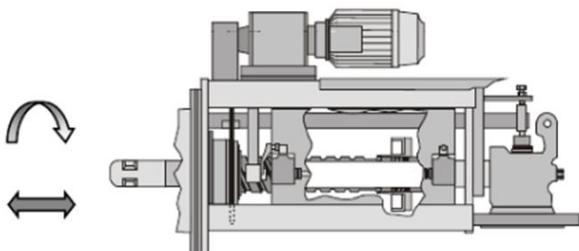


Figure 12. Blower V92E, Clyde Bergemann, adapted from [26]



Figure 13. Commercial photo of the wall soot blower by Clyde Bergemann, adapted from [26]

- Type PS-SL (Fig. 16)

Long, exerted blowers dedicated for cleaning upper parts of first and second course in boiler. In boiler OP-380 in PGE Power Plant in Kraków blowers PS-SL clean wall superheaters of fresh and secondary steam, fence superheater and end superheater of fresh steam. They are mounted on the outside of the boiler. Rest parameters are similar to blower type V92E.

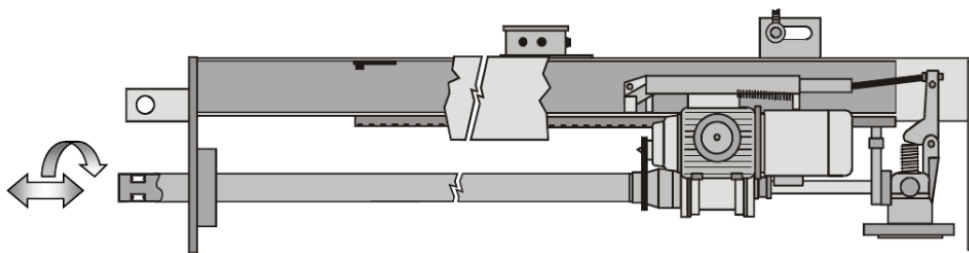


Figure 14. Blower PS-SL, Clyde Bergemann, adapted from [26]

- Type PS-SB (Fig. 17)

Long blowers designed for cleaning upper part of first coarse, middle course and second boiler coarse. In boiler OP-380 they are cleaning convectional superheater. They are mounted on the boiler exterior, however pipe with jets is constantly installed inside of the boiler, even if blower is off. Steam jets are mounted on the whole length of the blower pipe.

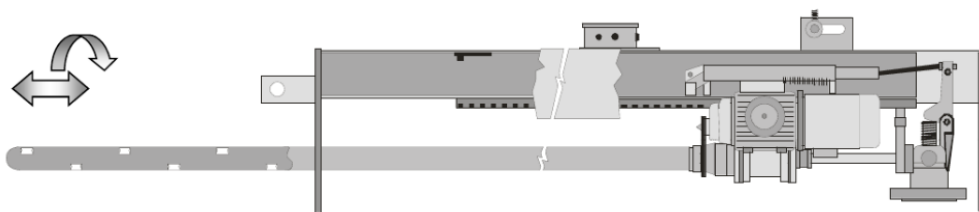


Figure 15. Blower PS-Sb, Clyde Bergemann, adapted from [26]

- Type PS-AL (Fig. 18)

Long soot blowers designed for cleaning upper part of first coarse, middle course and second coarse of the boiler. In boiler OP-380 in PGE Power Plant in Kraków blowers PS-AL clean rotating air heaters. They are mounted outside of the boiler and pipe went inside by a rotating movement. Head of the blower is equipment with two steam jets located parallel.

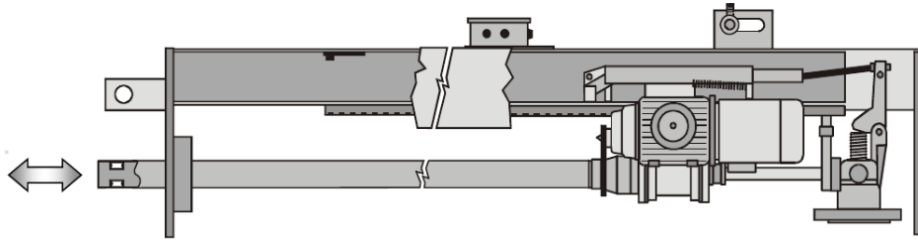


Figure 16. Blower PS-Sb, Clyde Bergemann, adapted from [26]

Soot blowers operation sequence is similar for every blower type:

- Start blowing sequence.
- Blowers head with pipe goes into boiler by a rotating movement.
- Boiler parts are cleaned from soot. Blower head get on the finish position and heading back to the start-up position also by a rotating movement.
- Finish of the blowing sequence.

Work sequence for each type of soot blower is presented graphically on graphs below (Fig. 18):

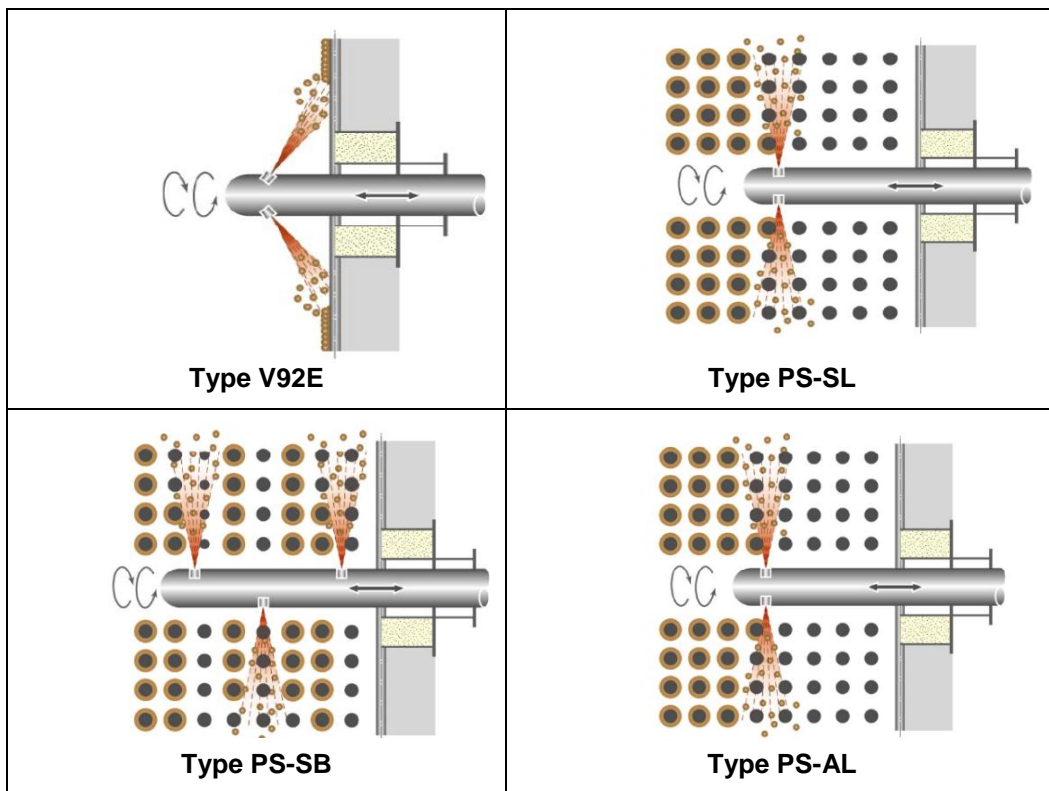


Figure 17. Graphical representation of work cycle each soot blower type, adapted from [26]

### Soot blowers operation

Boiler OP-380 no. 2 is equipped with short and long soot blowers. Short (V92E) are located in furnace part of boiler, whereas long (PS-SL, PS-SB, PS-AL) in upper part of first course, middle course, second course and in rotating air heaters. Depending on soot blowers type, the electricity consumption is as follow:

- Short soot blower:  $I \leq 0.7$  (A)
- Long soot blower:  $I > 0.7$  (A)

In the interest of the limited size of the work I will not attach graphs from work of each soot blower, instead I will present results and conclusion of soot blowers work in the summary chapter.

## 4. METHODOLOGY AND RESULTS

### Method of determination ratio of heat transfer and theoretical value of heat transfer

To define slagging and fouling of given heat surface element, necessary is to find value of theoretical thermal load for this element. Comparing obtained value with real thermal load it is possible to determine level of slagging and fouling given part. Theoretical value is determined by using temperature flue gases coefficient, whereas to compare both values of thermal load the coefficient of heat transfer is used.

### Temperature flue gases coefficient and theoretical thermal load

Temperature flue gases is ratio between real flue gases temperature on intermediate superheater or before convectional superheater (depends on analyzed element) and nominal temperature based on mass flow of agent flowed by given heated surface. It is correction coefficient for nominal thermal load, which is dependent only on mass flow of agent. If flue gases temperature increase on intermediate superheater and before convectional superheater, that indicate about decreased heat transfer by working substance, which is caused by slagging and fouling of boiler. From that reason temperature flue gases coefficient is implemented, by given formula:

$$\varphi_{fg,i} = \frac{T_{r,i}}{T_{n,i}} \quad (-)$$

$\varphi_{fg,i}$  – flue gases temperature coefficient  $i$ , (-),

$T_{r,i}$  – real temperature of flue gases, (K),

$T_{n,i}$  – nominal temperature of flue gases, (K).

Theoretical thermal load of heated surface include impact of changing mass flow agent as well as influence of changing flue gases temperature in the middle course for thermal load of given element. This value is equal to thermal load, with which device should work in given conditions and furthermore it is template used to calculate heat transfer coefficient. Equation:

$$Q_{t,i} = \varphi_{fg,i} \cdot Q_{n,i} \quad (kW)$$

$Q_{t,i}$  – theoretical thermal load of element  $i$ , (kW),

$\varphi_{fg,i}$  – flue gases temperature coefficient  $i$ , (-),

$Q_{n,i}$  – nominal thermal load of element  $i$ , (kW).



### Heat transfer coefficient:

Heat transfer coefficient is percentage ratio of real thermal load of this element to theoretical value of temperature load calculated by taking into account mass flow agent amount and temperature coefficient. He allows to determine percentage difference of thermal load between real value occur in real time and theoretical value which should occur in given conditions (agent mass flow and flue gases temperature). Coefficient of heat transfer is defined by formula:

$$\xi_i = \frac{Q_{r,i}}{Q_{t,i}} \cdot 100\% \quad (\%)$$

$\xi_i$  – heat transfer coefficient of element  $i$ , (%),

$Q_{r,i}$  – real thermal load of element  $i$ , (kW),

$Q_{t,i}$  – theoretical thermal load of element  $i$ , (kW).

## 4.1. ANALYSIS OF HEATING SURFACES AT EARLY PHASE OF SLAGGING AND FOULING

### Early phase (Fig. 20-27)

Examination of early phase of slagging and fouling heated surfaces of boiler OP-380 was conducted for days 05.12.2014, when it was observed beginning of changes: pressure and flue gases temperature. In the further part of this chapter there will be presented graphs with curves of theoretical and actual thermal load of each elements and moreover curve of mass stream which is flowing by it.

## 4.2. ANALYSIS OF HEATING SURFACES AT FINAL PHASE OF SLAGGING AND FOULING

### Final phase (Fig. 29-36)

Examination of early phase of slagging and fouling heated surfaces of boiler OP-380 was conducted for days 06.01.2015, when pressure and flue gases temperature parameters were drastically different from standards. Below there are shown graphs with curves of theoretical and actual thermal load of each elements and moreover curve of mass stream which is flowing by it.

### 4.3. CORROSION DAMAGES OF SUPERHEATERS IN BOILER OP-380

**Example 1 – Oxidation in high temperature (overheat) [27] [28]**

**Example 2 – Oxidation in high temperature (overheat) [27], [28]**

**Example 3 – Oxidation in high temperature (overheat) [27], [28]**

**Example 4. Aggressive corrosion by flue gases component [27], [28]**

Influence of biomass co-firing on superheaters damages can be divided to direct and indirect impact:

- **Indirect impact** lead to increase temperature of flue gases in region superheaters as the effect of lower milling level in coal mills. However it is hard to say which parameter have bigger impact on temperature rise - biomass or low emission technology of burning.
- **Direct impact** is caused by chemical composition of burned biomass which consist aggressive for superheaters material chemical compounds.

To prevent from preheaters corrosion firstly cause must be determined precisely. For each other, increased temperature and chemical compounds in flue gases counter-measures will be different.

## 5. SUMMARY AND CONCLUSIONS

### 5.1. SUMMARY

In the first part of thesis European Union policy about renewable energy was discussed. Then the brief studies of characteristic of biomass and coal were presented which shows that biomass is a good source of renewable energy. Further a introduction of co-firing technology and all issues related with it. After that specification and scheme of boiler OP-380 in PGE Power Plant in Kraków were presented with description of the whole process. In the last part of thesis methodology of examination of slagging and fouling was discussed and results were shown. Moreover, at the ending chapter photographs of damages caused by (indirect) slagging and fouling were presented.

Co-firing of biomass is competitive and stable source of renewable energy. Advantages of co-combustion beside solar and wind energy are availability of energy source in majority of environments, low cost investments, possibility of usage already existing power plants and stability of electricity generation without fluctuations.

During the exploitation of boiler Op-380 No. 2 in PGE Power Plant Kraków problem of heat transfer between different levels of superheaters was detected. Symptoms of incorrect behavior which were found are as follow:

- Increased temperature of steam.
- Increased temperature of pipes material in boiler 1<sup>st</sup> level course neighborhood.
- Too low heat transfer caused by intense process of superheaters fouling in convection course.

Data was collected for exact purpose. R&D Department in PGE Power Plant in Kraków gathered information and introduced diagnosis system which allowed to continuous control of fouling level on heated surfaces in boiler.

Subsection 4.3 contain photographs of damages pipes. There are two types of corrosions: first caused by oxidation in high temperature and second caused by content of aggressive compounds in flue gases.

## **5.1. RECOMMENDATIONS FOR ELIMINATIONS OF FOULING FROM HEATING SURFACES**

Biomass co-firing is a technology used worldwide. Mostly it is applied in power plants designed for coal burning, not for biomass co-combustion. Slagging and fouling process is common and exist in industry. To prevent from damages of superheaters parts caused by overheating, there must be designed system which warn power plants operators long before critical temperatures. That may be obtain by set of following states of heat transfer coefficient: acceptable, alert and critical; for each boiler part. With mentioned system overheats could be easily reduced by implementation of response of soot blowers in alert states. Optimization of soot blowers work is very important since economic reasons. However, there are limitation of that solution. After continuously biomass co-firing, at some stage, slagging and fouling process is so expanded that soot blowers cannot deal with contaminations. Then unit must be stopped and cleaned mechanically. For the boiler OP-380 the service break occurred after 7 months.

## 5.2. CONCLUSIONS

The effect of biomass co-firing on slagging and fouling of heated surfaces in boiler OP-380 installed in PGE Energia Ciepła S.A. Power Plant in Kraków have been presented in this work. Main parameter which was analyzed was heat load. Correlation between slagging process and decreased parameter of heat load has been described. The following elements of the boiler were taken into account: feed-water heater, evaporator, primary steam I<sup>st</sup> level superheater, primary steam II<sup>nd</sup> level superheater, primary steam III<sup>rd</sup> steam superheater, secondary steam I<sup>st</sup> level superheater, secondary steam II<sup>nd</sup> level superheater, secondary steam III<sup>rd</sup> level superheater.

To verify used methodology and determine changes of amount of exchanged heat three examination periods were set: reference period, early phase of slagging and fouling and final phase of slagging and fouling. Quantity of exchanged heat was dependent on boiler exploitation time and boiler technical condition. Graphs from obtained results are presented in chapters 4.1 and 4.2.

## BIBLIOGRAPHY

1. **IEA.** *Power generation from coal - ongoing developments and outlooks.* s.l. : IEA, 2016.
2. **James Katzer, MIT.** *The Future of Coal.* s.l. : Massachusetts Institute of Technology. ISBN 978-0-615-14092-6.
3. **P. Teixeira, H. Lopes, I. Gulyurtlu, N. Lapa, P. Abelha.** Evaluation of slagging and fouling tendency during biomass co-firing with coal in a fluidized bed. *Biomass and bioenergy.* 2012, 39, pp. 192-203.
4. **Obernberger, Ingwald.** *Ash related problems in biomass combustion plants.* Eindhoven : Technische Unibersiteit Eindhoven, May 2005. ISBN: 90-386-1443-8.
5. **M.Ściążko, J. Zuwała, M. Pronobis.** *Współspalanie biomasy i paliw alternatywnych w energetyce.* Zabrze : IChPW, Politechnika Śląska, 2007. ISBN 978-83-913434-3-2.
6. **Bourguignon, Didier.** *Biomass for electricity and heating.* s.l. : EPRS, 2015. PE 568.329.
7. [www.weforum.org.](https://www.weforum.org/agenda/2016/05/can-the-circular-economy-transform-the-world-s-number-one-consumer-of-raw-materials/) [Online] <https://www.weforum.org/agenda/2016/05/can-the-circular-economy-transform-the-world-s-number-one-consumer-of-raw-materials/>.
8. [www.ec.europa.eu.](http://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources/natural-resources/energy-resources/energy-from-biomass) *EUROSTAT.* [Online] <http://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources/natural-resources/energy-resources/energy-from-biomass>.
9. [http://ec.europa.eu/eurostat/data/database.](http://ec.europa.eu/eurostat/data/database) [Online] 11 26, 2017.
10. Frontline BioEnergy Inc. *What is biomass.* [Online] [Cited: 12 03, 2017.] <http://www.frontlinebioenergy.com/en/advantages/biomass/>.
11. **W.R., Livingstone.** *A review of the recent experience in Britain with the co-firing of biomass with coal in large pulverised coal-fired boilers.* Renfrew, Scotland : Mitsui Babcock, 2005. Presented at IEA Exco Workshop on Biomass Co-firing, Copenhagen.
12. **VIEWLS.** *Biofuel and Bio-energy Implementation Scenarios, Final report of VIEWLS WP5, modeling studies.* 2005.
13. **Loo van S., Koppejan J.** *The Handbook of Biomass Combustion and Co-Firing.* s.l. : Twente University Press, 2008.
14. **A. Maciejewska, H. Veringa, J. Sanders, S.D. Peteves.** *Co-firing of biomass with coal: Constraints and role of biomass pre-treatment.* Netherlands : © European Communities,, 2006. EUR 22461 EN.
15. **EUBION (European Bioenergy Networks), K. Veijonen, P. Vainikka, T. Jarvinen.** *Biomass co-firing - an efficient way to reduce greenhouse gas emissions.* Finland : ALTENER, 2003.
16. **Laboratory, AAD Document Control U.S. Deparment of Energy National Energy Technology.** *Impacts of cofiring biomass with fossil fuels, Final Report (for the period April 1, 2001.* 2001-EERC-08-03.

17. **Hartmann, H.** *Influence on the quality of solid biofuels - Causes for variations and measures for improvement.* Rimpfing, Germany : CARMEN, June 1998.
18. **Dahlquist, E.** *Technologies for Converting Biomass to Useful Energy.* London, UK : Taylor & Francis Group, 2013. ISBN: 978-0-415-62088-8.
19. **Marc A. Rosen, Bale V. Reddy, Shoaib Mehmood.** *Energy and exergy analyses of power generation systems using biomass and coal co-firing.* London : Taylor & Francis Group, 2013. ISBN 978-0-415-62088-8.
20. **Agency, International Energy.** 2009.
21. **J. Zuwała, M. Ściążko.** *Co-firing based energy systems - modelling and case studies, Paper presented at the 14th European Biomass Conference & Exhibition Biomass for Energy, Industry and Climate Protection.* Paris : s.n., 17-21 October 2005.
22. **P. A. Jensen, B. Sander, K. Dam-Johansen.** *Pretreatment of straw for power production by pyrolysis and char wash, Biomass & Bioenergy.* 20, 431-446 : s.n., 2001.
23. **H. Spiliethoff, V. Siegle, K. Hein.** *Zufeuerung von Biomasse in Kohlekraftwerken' Auswirkungen auf Betrieb, Emissionen und Ruckstande, Technik und Kosten.* s.l. : ENET, Bundesamt fur Energie, 1996.
24. **RAFAKO, PBG Group.** <https://www.rafako.com.pl/produkty/kotly/sylwetki/kotly-pylowe-walczakowe>.
25. **PGE, U. Orzełowska.** *Analiza procesu zanieczyszczania powierzchni ogrzewalnych kotła OP-380.* Kraków : EDF Polska S.A., 2015. DBAA/12-903/3301.
26. **Bergemann, Clyde.** <https://www.cbpg.com/pl/produkty-i-rozwiazania/sprawnosci-kotla/systemy-czyszczenia-kotlow-na-ruchu/furnace/zdmuchiwacz>. 10.02.2018.
27. **F. Klepacki (Pro Novum), K. Panaś (PGE), E. Wojtkiewicz (PGE).** *Korozja przegrzewaczy kotłów współpalających biomasę.* Kraków : s.n., 2011.
28. **Novum, Pro.** *Pro Novum Report* . not published : s.n., 2006. nr 9.1816/2006.
29. **Belgiorno V., Feo de G., Della Roca C., Napoli R.M.A.** *Energy from gasification of solid wastes. Waste management.* 23, 2003, 1-15.
30. **Bourguignon, Didier.** *EU biofuels policy, Dealing with indirect land use change.* s.l. : EPRS European Parliamentary Research Service, February 2015. PE 548.993.
31. **CHRISTENSEN, K. A.,.** *The formation of submicron particles from the combustion of straw PhD thesis.* Denmark : Department of Chemical Engineering, Technical University of Denmark, 1995.
32. **S. Black, J. Szuhanski, A. Pranzitelli.** *Effects of firing coal and biomass under oxy-fuel conditions in a power plant boiler using CFD modelling.* Leeds : Fuel, 2013, Vol. 113.

33. **I. Obernberger, J. Dahl, T. Brunne.** *Formation, composition and particle size distribution of fly ashes from biomass combustion plants.* Oakland : Elsevier Science Ltd., Oxford, UK, September 1999. pp 1377-1385.

34. [www.ec.europa.eu](http://ec.europa.eu). [Online] [http://ec.europa.eu/environment/green-growth/index\\_en.htm](http://ec.europa.eu/environment/green-growth/index_en.htm).