

# Overview of the Efficient Tehnologies for Power Generation Based on Coal

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**Abstract:** This paper gives an overview of effective technologies for coal-based electricity generation. The introductory chapter presents the development of efficient electricity production from the end of the nineteenth century to the present, and the emphasis is placed on the examination of modern efficient technologies for electricity production in the 21st century with a detailed comparison of hard coal combustion (PCC) and fluidised bed combustion (CFBC) technologies. Pollutants such as carbon monoxide (CO), sulfur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>) occur during the process of coal combustion. SO<sub>2</sub> and NO<sub>x</sub> cause the acid rain and CO<sub>2</sub> gas is the most responsible for the greenhouse effect. With using the new fire-resistant steels based on nickel, the TPP with advanced ultra-supercritical steam parameters (A-USC) with  $t = 700$  °C and working  $p = 350$  bar are expected, and also, this will increase the efficiency above 50%. In this paper, this and other emerging technologies have been presented as well as the comparison of their characteristics.

**Keywords:** characteristic comparison; coal; efficient technologies; environmental pollution; optimization; power plant lifecycle

## 1 INTRODUCTION - HISTORICAL EFFICIENCY DEVELOPMENT OF TECHNOLOGIES FOR ELECTRICITY PRODUCTION BASED ON COAL

A broad overview of historical parameters achieved in the consumption, emmission and efficiency in the electricity production, i.e. power generation is presented in Tab. 1.

**Table 1** Broad overview of historical consumption, emmission and efficiency parameters in power generation

Year	Consumption tce/1 kWh	Emission CO <sub>2</sub> /kWh	Efficiency $\eta$ / %
End of XIX century	0,01230	37 [1]	1
1900-1910	0,00670	2,5	5
1925 average	0,00080	2,1	15 [2]
1970	0,00028	0,76	43
1992	0,00031	0,85	38,90

Main remarks and historical achievements are presented as follows:

- Increasing the efficiency was achieved using a steam turbine.
- In 1926, the plant "Klingenberg" in Berlin commissioned a turbogenerator with power of 80 MW, (then the largest in the world, fuel coal), reached the highest efficiency 27%, consumption of 0,000045 tce/kWh and CO<sub>2</sub> emissions of 1,2 kg CO<sub>2</sub>/kWh.
- In 25 years, fuel consumption is reduced by more than two thirds [3].
- In the second half of the 90s, an efficiency of 47% was achieved in the TPP Nordjylland in Denmark with supercritical steam parameters and coal.
- Brown coal and lignite plants have lower efficiency due to the nature of coal in relation to mineral coal (moisture content).
- In Germany, new energy blocks on lignite achieved a net efficiency with DTV of 42,3% (Lippendorf, 2 × 920 MW, 260 bar / 554 °C / 583 °C) and 45,2% (Niederaussem K, 950 MW-net, 260 bar / 580 °C / 600 °C, in operation in 2002 year) [4].
- Net efficiency greater than 43% is expected in the power plant Neurath (Germany) powered on the Rhine lignite with power of 2 × 1120 MW (272 bar / 600 °C / 605 °C) [5].

- Similar energy efficiency results were achieved in new coal-fired power plants in Denmark, the US, Japan, China and South Korea [6].

Due to the environment, the question is whether the coal is compatible with sustainable development. Are the new measures taken to reduce consumption of fossil fuels and increasing the efficiency of energy transformation of coal into electricity appropriate? The new clean coal technologies are being developed without the growth of warming. As a large number of coal-fired power plants are at the end of their lifecycle, is it possible to achieve clean coal-based electricity production by replacing them with new clean coal technologies?

This paper aims to present the overview of the new efficient and clean technologies in order to try to answer these questions.

## 2 FUNDAMENTALS OF ENERGY EFFICIENCY

Specific energy consumption is expressed in the relationship of fuel heat consumed for production of 1 kWh of electricity and is the reciprocal value of the degree of power plant efficiency:

$$q_{TE} = \frac{1}{\eta_{TE}} = \frac{3600 \text{ kJ/kWh}}{\eta_{TE}} \cdot 100, \text{ kJ/kWh} \quad (1)$$

Specific energy consumption is expressed as a specific fuel consumption (kg) for producing 1 kWh of electricity (kg/kWh).  $\eta$  is expressed at lower heating fuel value. Total (gross) and annual net (operating)  $\eta$  differ. Overall  $\eta$  is the total production of electricity in the generator divided by the heat consumption of fuel in the boiler of thermal power plant (TPP), and for the net  $\eta$ , electricity at the doorstep of the power plant is calculated (total minus the local TPP consumption). Annual  $\eta$  is the annual production of electricity (gross or net) divided by the annual energy fuel consumption. The net  $\eta$  coal plants can be defined by the expression [7]:

$$\eta_{TE} = \eta_{RC} \cdot \eta_t \cdot \eta_g \cdot \eta_k \cdot \eta_{s.p.} \quad (2)$$

where labels and guiding values  $\eta$  for the steam temperature of 580 °C at the entrance of the modern turbine are:

- $\eta_{RC} = \eta_C \cdot \eta_{ex} = 0,65 \cdot 0,94 = 0,61$  ili 61% - Rankine efficiency at  $\eta_C = 65\%$  and content of exergy in steam at  $\approx 94\%$ ;
- $\eta_t = 93\%$  - efficiency of modern steam turbines;
- $\eta_g = 98\%$  - efficiency of modern electric generators;
- $\eta_k = 91\%$  - efficiency of modern boilers;
- $\eta_{s.p.} = 93\%$  - efficiency of auxiliary equipment of the TPP (own consumption approximately 7%).

Net efficiency of modern coal plants by improving conventional technologies would be 47% (61%\* 93%\* 98%\* 91%\* 93%). e.g. Danish power plants on coal dust "Nordjylland 3" of 400 MW, put into operation in 1998 with two of overheating and steam parameters: 290 bar / 580 °C / 580 °C / 580 °C [8] have such efficiency. Efficiency can further be increased by introducing new materials and improvement of thermal schemes by optimizing its components [9].

However, majority of existing coal power plants have lower efficiency (e.g. in Bosnia and Herzegovina brown coal or lignite are used, having a lower efficiency and technology from 1970s). Today's coal plants are in most cases 30-40 years old constructions, with subcritical steam parameters (530 °C to 540 °C and 140 bar to 180 bar), and degree of thermal efficiency of 36%- 39%.

Unfinished project "Lukovo" Šugarje in Croatia [10] predicted efficiency over 43%, while the last built German and Danish power plants on coal achieve a maximum efficiency of 47%. The most recently constructed coal plants with ultra-supercritical steam parameters (> 600 °C and > 300 bar) provide efficiency levels over 50% [11].

### 3 NEW EFFICIENT COAL COMBUSTION TECHNOLOGIES

Today, in the 21 century, special attention is devoted to the energy consumption in the developed countries. This is a first-rate issue in each country [12]. Relevant recommendations of the European Commission (document "Reference Document on Best Available Techniques for Large Combustion Plants", July 2006, Chapter 4, section 4.5.5. Thermal efficiency) are used to recommend the technologies and determine minimal efficiency of new coal power plant units. They are presented in Tab. 2.

**Table 2** Relevant recommendations of the EC on net thermal efficiency of the best available techniques for large coal combustion technologies

	Technology of coal combustion	Net efficiency new units, %
Lignite	PCC	42-45%
	FBC	> 40%
	CFBC	> 42%

Where: PCC - pulverised coal combustion, FBC - fluidized bed combustion and CFBC - circulating fluidized bed combustion.

Although the overview will focus on PCC, FBC and CFBC technologies, these are only a segment of advanced technologies for power generation from coal combustion and gasification where overall possible solutions are presented in Fig. 1.

Where abbreviations stands for:

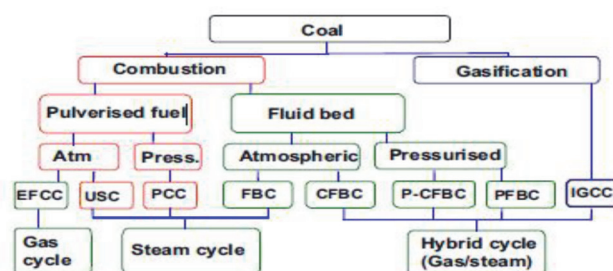
- EFCC external combustion in combined cycle

- USC Ultra-super critical plants
- PCC pulverized coal combustion
- FBC fluidized bed combustion
- PFBC fluidized bed combustion under pressure
- CFBC circulating fluidized bed combustions
- P-CFBC circulating fluidized bed combustions under pressure
- IGCC integrated gas combined cycle.

While FBC and CFBC take place at atmospheric pressure in steam generator, the PFBC and P-CFBC combustions take place at elevated pressure, which improves the characteristics and the overall efficiency.

Emerging IGCC (Integrated Gas Combined Cycle) is based on the PFBC which adds a carburator in which synthetic gas is generated. Heat from the gasification is used for steam production in steam turbine while the synthetic gas burns in a gas turbine. The plant has a very high degree of efficiency (57-59%) [14].

Also, at the global level, significant investment and research efforts are put to increase technological feasibility and economic viability of using coal to generate electricity, with most attention focused upon reducing CO<sub>2</sub> emissions. At present, the technology of separation and storage of CO<sub>2</sub> from the combustion of fossil fuels is expensive, costing from 40 USD/t CO<sub>2</sub> to 60 USD/t CO<sub>2</sub> [15]. This gives a gain of about 3,5 USc/kWh to 5,5 USc/kWh on electricity prices, with average efficiencies of coal plants of 35%.



**Figure 1** Advanced technologies for the coal combustion [13]

#### 3.1 The Pulverised Coal Combustion Technology - PCC

The pulverised solid fuel (coal) combustion technology (PCC) is used by approximately 90% of all coal-fired boilers. Grinding and drying of coal in order to increase efficiency is becoming more common. The level of efficiency in the process of exploitation is significantly influenced by soiling, coal quality, steam pressure and steam temperature. Efficiency is increased with raising rated (installed) power of the block and with greater availability, in case of optimal load. Additional measures to increase the efficiency are coal drying and use of waste heat from flue gases.

Supercritical parameters to achieve efficiency increase are used for blocks with a capacity greater than 400 MW. Power plants on coal with supercritical parameters can reach the energy efficiency over 42% depending on the quality of coal and the block size. For block-based combustion technology of pulverized coal (PC) it is hard to reach the net efficiency over 42%, which can only be realized by using so-called ultra critical (USC) steam parameters (pressure 250-275 bar, fresh steam temperature > 585 °C). These steam parameters require technical

minimum of more than 370 MW. With the current state of technology for conventional PCC coal plants, the maximum achievable performance is about 46%. This performance is achieved in subcritical and supercritical conditions (steam temperature of about 610 °C instead of the current 540 °C).

**Table 3** High-efficiency PCC power plants

Power plant	Rated power	Efficiency	Type
Neurath (D)	2 × 1100 MW	43	PCC
Walsum (D)	750 MW	43	PCC
Šoštanj (SLO)	600 MW	43	PCC
Ledvice (CZE)	660 MW	42,5	PCC
Civitavecchia (ITA)	3 × 660 MW	45	PCC
Tušmice (CZE)	4 × 200 MW	37,82%	PCC

Development of PCC technology is focused on:

- increasing the thermal  $\eta$  - by increasing steam
- parameter from the boiler/ on the entrance of the steam turbine,
- flexibility of the boiler operation at lower loads and,
- meeting the environmental demands (flue gas emissions).

**Table 4** Reference list of blocks 200-660 MWe[16]

Boiler supplier	Foster Wheeler	Babcock & Wilcox	Alstom	Rafako
Client	Kiewit/Black & Veatch, Bechtel, Power Corp.	WPS, PT PLN	Elektrownia Patnow II	Polska Grupa Energetyczna
Construct. start	2009,2006	2008, 2006	2004	2009
Object	Dallman #4, Springerville #3	Weston 4, TanjugJati B	Patnow blok 1	Belchatow
Country	USA,USA	USA, ndonezija	Polska	Polska
Rated power/steam production	200 Mwe, 400 Mwe	590Mwe, 2x660MWe	460 MWe	2004 t/h
Primary fuel	Coal,Coal	Coal,Coal	lignite	lignite

Boiler supplier	Alstom	Alstom	Alstom	Siemens
Client	ŠKODA Praha Invest	Holding HSE	ČEZ	
Construct. start	2016	2014	2016	2013
Object	Ledvice	Šoštanj	Ledvice	Lünen
Country	Czech	Slovenia	Czech	Germany
Rated power/steam production	660 MWe	600MW	660 MW	750MW
Primary fuel	lignite	lignite	lignite	hard coal

PCC process is extremely complex and depends on several factors, because getting the boiler surfaces on the gas side dirty is not recommended for coal with high ash content or for problematic coal from the combustion point. PCC technology includes preliminary preparation of coal, grinding and drying the logs in dust outside the boiler in an installation in which a process of coal grinding and drying is conducted. Depending on the type of coal, the combustion takes place at temperatures between 1100 °C and 1700 °C. The process of making is the combination of two opposite processes: agglomeration i.e. deposition of

un-burnt smaller airborne particles and abrasion i.e. wear layers deposited with large particles.

The main suppliers of PCC boilers are: Alstom, Babcock Power (BP), Babcock and Wilcox (B & W), Babcock-Hitachi (BH), Foster Wheeler (FW), Hitachi Corp., Mitsui Babcock (MB ), Ishikawajima Harima Heavy Industries (IHI), Rafako, SAS, etc. The size and classification of the existing steam blocks suppliers, reference list of blocks built after 2004 is presented in Tab. 4.

Today, the rated power of a steam turbine with PCC technology is in the range of 50 MWe to 1300 MWe. From the point of utilization of economies of scale, most of the new blocks have capacity of more than 300 MWe, and less than 700 MWe, because of the significant influence of such large blocks on power system in the case of failure or other unplanned downtime.

### 3.2 The Fluized Bed Coal Combustion Technology - FBC

Research and implementation of fluized bed solid fuel (coal) combustion (FBC) emerged as an alternative to boilers with combustion of pulverized coal (dust) in the chamber, looking for cheaper and more efficient solution for reducing sulphur-oxides ( $SO_x$ ) from flue gases. The development of FBC started with Winkler patent for the gasification of lignite (1922)[17], used for different purposes since then. Over time the main FBC goal has evolved into a "clean energy for the future" [18].

The test plant with the bubble (stationary) fluidised bed started in US in 1965 with the aim of controlling  $SO_2$  emissions. To date, four generations of FBC have been developed and they belong to the clean coal technologies (CCT). FBC is known for its ability to burn substandard fuels with low calorific value, fuels with high ash content and high humidity. Other benefits are reduced emissions, re-use of non-hazardous by-products from the desulfurization (eg. Gypsum) and the possibility of applying this technology in already built facilities.

The fuel that makes 1-3% of the material layer mass, burns in a hot bed of inert material (quartz sand, ash, limestone/sorbent) due to flow-through of air from the bottom of the combustion chamber in a state of levitation and shows properties similar to liquid (state of fluidization) [19]. Fluidization occurs when the fluid flows around particles of solid material in the opposite direction of gravity, and apparently reduces their weight. At the time of transition from hibernation to the fluidized state, the resistance force of gas passing through layer of particles is equal to the weight of particles in the layer. Since the fluid has mutually separated particles of layer, it can no longer hold shear force and begins to behave like a liquid. A layer of fine-grained solid material which has these characteristics is called a fluidized bed. High speed dispersion of fuel inserted in a large mass of inert material, intensive mixing of fuel, a large surface area for the exchange and transfer of heat through contact with the particle layers allow combustion of the fuel at a lower temperature (760-900 °C) as compared to boilers with air cobustion. Lower teperature is resulting in a significant reduction in forming thermal  $NO_x$ , while the effective retaining of the sulfur and halogen in the combustion chamber is achieved by introducing limestone or dolomite

in layer. Combustion of solid fuel in a fluidized bed is a transition process between the combustion in the combustion layer and in the air. These are the newer technologies, flexible in terms of fuel use of different quality. A stable activity on the low power and significant reduction of pollutant emissions ( $\text{SO}_2$  and  $\text{NO}_x$ ) are positive sides of this technology.

Depending on the regime of fluidization i.e. speed of flow-through gas through the layer, we differ [20]: stationary or bubbly fluidized bed (BFB) and circulating fluidized bed (CFB). Tab. 5 shows the comparative analysis of these two types of boilers.

**Table 5** Comparative characteristics of boilers with stationary (bubble) (BFB) and circulating fluidized bed (CFB):

Parameter	BFB	CFB
Combustion temperature / °C	760-870	800-900
Fluidizing velocity / m/s	1-3	3-10
Middle steam parameters		
Steam flow / kg/s	13-139	12-360
Steam temperature / °C	150-543	180-580
Steam pressure / bar	10-160	10-275

Boilers with CFB have an advantage in the field of higher power (over 100 MW) in burning low-active coals and in the terms of the sharp emission regulations. They are almost exclusively steamy, industrial, and they have been recently integrated in the electric power systems. The initiators of the development and expansion of the CFB technology are regulated market, regulations for the environmental protection, specificity of region and it is bound to the available fuel (its quantity and quality). Some constructed FB boilers:

- BFB boiler Metso Power ACZ [21] for burning waste;
- CFB boiler Alstom Sulcis, Italy (340 MWe steam parameters: 197 bar, 565/580 °C, 1026 t/h), 2006;
- CFB boiler Metso Power CZMIC, Manitowoc Public Utilities, Wisconsin, United States (160 MWth, 60 kg/s, 103 bar, 541 °C), burns petroleum coke, brown coal, 2005;
- Foster Wheeler Energy CFB boiler in Turow'u Poland ( $3 \times 557$  MWth, 195/181 kg/s, 170/39 bar, 568/568 °C) fuel-lignite, 2003 to 2004;
- Foster Wheeler supercritical [22] CFB boiler, Lagisza, Bedzin, Poland (996 MWth, 361/306 kg/s, 275/50 bar, 560/580 °C), 2009.

Today, boiler units for FBC have developed the rated power of typical PCC boiler. The FBC technology is based on the introduction of coal particles about 3 mm into the hot turbulent layer in which, from the bottom of the boiler, the air needed for combustion is developed. The amount of fuel in the layer is approximately 1% to 3% of the base material, and the remaining is ash, sand and sorbents, required to start the process. Due to the initiation of air the whole mixture becomes fluidized and abrasive bits of coal are added into the layer. Because of high combustion temperatures (750 °C-950 °C) and a long period of stay in combustion zone, the particles of coal burn quickly, which gives a lower value of emissions of combustion products.

For combustion in the CFB boiler mixture of fuel, sand, ash, sorbate and air, which is initiated from the bottom of the firebox, the boiler achieves high speed, the particles are whole time in the flue gases.

The fluidized bed was maintained so that the flue gases from the combustion chamber are introduced into the cyclone (separator), where the larger unconsumed particles of layer (sand and ash) and fuel are separated from the flue gases, and then they are reintroduced i.e. recirculate fluidized bed. Because of the recirculation of materials the name of the technology is circulating fluidized bed. Depending on the size and speed of combustion, some fuel particles can be recirculated 10 to 50 times, and their time of stay in the boiler is a tenth of a second. For combustion technologies in the circulating fluidized bed (FBC), a net efficiency over 40% is required, which (along with the specified parameters of steam) is achievable in practice and proven on reference plants. The projected level of net efficiency with FBC technology is 40,82%.

Fuel combustion in the CFB boiler gives lower emissions of  $\text{NO}_x$  compared to PCC technology, and higher emission levels of  $\text{N}_2\text{O}$ .  $\text{SO}_2$  emissions can be effectively and economically reduced directly by injection of sorbent (limestone) in the layer which upon reaction with sulfur from the flue gases drains away from the process together with the ash. Therefore, construction of chamber for desulphurisation of flue gases is not needed. The technology is suitable for low-calorie coal with a large amount of ash, which is difficult to translate in the pulverized coal and coals whose characteristics are subject to change. The technology is also suitable for the combustion of coal as the main fuel to whom the fuel of inferior quality is added, (eg. Scrap). Designers Supplier of equipment is Foster Wheeler and Alstom for Turow, and the power plant owner is PGE- Polska Group Energetyczna.

The main suppliers of CFBC boilers are: Alstom, Austrian Energy & Environment, Babcock and Wilcox, Foster Wheeler, Metso. Overview of the blocks with atmospheric FB (BFB aor CFB) boiler of unit capacity above 150 MWe is presented in Tab. 6.

Benefits of technologies with wet limestone process are that it is cheap and available in nature, a by-product (gypsum) has a market value, low consumption of ground limestone and a high degree of separation of  $\text{SO}_x$ . Lack of technology is the low temperature of unsaturated wet flue gases (conditional use of materials flue-resistant acid), producing waste water, the higher the investment value - complex equipment plants and use of materials resistant to acid, additional  $\text{CO}_2$  emissions because of the reaction of limestone and of  $\text{SO}_2$ , greater surface area.

Emissions of carbon monoxide (CO) are for the PCC technology slightly lower. For PCC technology, building a plant for desulfuration by wet process is essential, which requires larger investments, more maintenance costs, larger required area for the plant construction.

Abrasive slurry and corrosive flue gases are the main reason for the application of special anti-corrosion protection and use of pumps resistant to abrasion and corrosion. For the block with CFBC boiler, it is possible to desulfurate in the boiler, upgrading the plant for desulfuration by wet process and so reduce the consumption of limestone. If the removal of the powder particles from the flue gases uses the electrofilter or bag filters, the emission values are around 30 mg/Nm<sup>3</sup> for both technologies.

**Table 6** Overview of the blocks with (atmospheric) BFB and CFB boilers of rated power over 150 MWe

Company/ Power plant	Location	Supplier	Type	Rated power MWe	Cogen-eration / kg/h of steam	Start	Fuel
Tennessee Valley Authority	Paducah, KY	CE (1)	BFB	160			Brown coal 3,5% sulphur
Texas New Mexico Power Company	Bremond, Texas	ABB-CE (1) CFB 2*160	CFB	2 × 160		1990	Designed for lignite, burns even petroleum coke
Nova Scotia Power Corporation	Point Aconi, Nova Scotia	Pyropower (2)	CFB	180		1993	Brown coal 20% of ash, 0,3% chlore, petroleum coke, coal from import
Electric Power Development Corp	Takehara, Japan	Hitachi (BFB)	BFB BFB	340		1995	Brown coal from import
Electricité de France, Gardanne	Provence, France	GEC-Alsthom-Stein (1)	CFB	250		1996	Brown coal with 30 % ash, 4 % sulphur
KEPCO	Tonghae, S. Korea	KHI/ABB-CE	CFB	230		1998	Korean anthracite
National Power Supply	Thatoom, Thailand	Pyropower (2)	CFB	2 × 150		1998	anthracite, brown coal and biomass
Turow Power Station	Silesia, Poland	Pyropower (2)	CFB	3 × 230		1998-2000	Brown coal 23% ash, 44% humidity
AES, Warrior Run	Cumberland, MD	ABB-CE (1)	CFB	180	82	2000	Brown coal
First Energy, Bay Shore	Toledo, Ohio	Foster Wheeler	CFB	155	155 t/h psig of steam	2001	Petroleum coke
Alholmens Kraft Oy	Finland	Kvaerner	CFB	240		2001	Wood, peat and lignite
Poland's Electric Power Industry	Zeran, Poland	Rafako	CFB	2 × 450 t/h		1995 2001	Coal
JEA	Jacksonville, FL	Foster Wheeler	CFB	2 × 300		2002	Brown coal, petroleum coke
Tractabel Power, Red Hills	Chester, Mississippi	ABB-CE (1)	CFB	2 × 220		2002	Lignite
AES	Guayama, Puerto Rico	ALSTOM Power	CFB	2 × 250	181	2002	Brown coal from import
Turow Power Station	Silesia, Poland	Foster Wheeler	CFB	3 × 260		2002 2004	Brown coal 23% ash, 44% humidity
Donbas Energo	Ukraine	Lurgi	CFB	200		2003	Anthracite, low-energy coal and mud
Reliant Energy	Seward, PA	ALSTOM Power	CFB	2 × 260		2004	Low-energy coal
East Kentucky Power Coop	Maysville, Kentucky	ALSTOM Power	CFB	268		2004	Unwashed, Brown coal with a lot of sulphit
ENEL Sulcis	Sardinia	ALSTOM Power	CFB	220	858	2004	Various coals
Taiheyo Cement	Shikoku, Japan	Foster Wheeler	CFB	168		2005	Brown coal
Baima	Sichuan, PRC	ALSTOM Power	CFB	300		2006	Anthracite 35% ash and 3,5% sulphit
Kaiyun Power, Units 1 & 2	Yunnan, PRC	ALSTOM Power	CFB	2 × 300		2007	Lignite
Dong Fang Boiler Group	Baima, Sichuan Province	ALSTOM Power	CFB	2 × 300		2008	Brown coal
Shanghai Boiler Works	Yunnan, PRC	ALSTOM Power	CFB	2 × 300		2008	Lignite
PEK	Lagisza, Poland	Foster Wheeler, Energia Oy	CFB	460 (3)		2008	Brown coal 12% humidity and 23% ash
CLECO, Rodemacher #3	Boyce, Louisiana	Foster Wheeler	CFB	2 × 300		2009	Petroleum coke and biomass if needed
East Kentucky Power Coop, Spurlock #	Maysville, Kentucky	ALSTOM Power	CFB	278		2009	Unwashed, Brown coal with a lot of sulphit
TXU, Sandow #5	Milam Co., Texas	Foster Wheeler	CFB	2 × 300		2010	Lignite
Easti Kentucky Power Coop, Smith#	Winchester, Kentucky	ALSTOM Power	CFB	278			Unwashed, Brown coal with a lot of sulphit

(1) Now ALSTOM Power (2) Now Foster Wheeler (3) Cycle with supercritical parameters

### 3.3 Research Projects

Various energy technologies that will enable greater utilization of coal energy are being developed. Available technologies based on coal, today have reached 43-45% efficiency compared to the world average of 28-30%, the specific CO<sub>2</sub> emission of 730-930 g CO<sub>2</sub>/kWh, as compared to the world average from 1.100g CO<sub>2</sub>/kWh to 1400 g CO<sub>2</sub>/kWh with an appropriate reduction in specific fuel consumption. Reached steam temperatures and optimization of plant components, have enabled efficiency of TPP on stone coal to 47% and TPP on lignite to 45%.

A further increase in the efficiency of "classic" coal fired thermal power plants is only possible by increasing the temperature of steam up to 700 °C (Europe) or up to

760 °C (The USA). It is possible only by the development of new fire-resistant steel with large enough creep strength at such high temperatures. That is why the development programs are realized in the United States, Japan and the EU [23].

By the development of new fire-resistant steels based on nickel, thermal power plants with these advanced ultra-supercritical steam parameters (USC) with operating temperature of 700 °C and pressure over 350 bar will have increased efficiency above 50%.

According to the European project AD700 (Advanced 700 °C Pulverized Coal-fired Power Plant), usage of alloyed steels (Super Alloy) on the basis of nickel is needed, which would use fresh steam pressure of approximately 375 bar and the temperatures of 700 °C to

720 °C but it needs to have adequate tensile strength and the yield strength during the ongoing 100.000 operating hours of work. Super alloy should have a yield strength of about 100 N/mm<sup>2</sup> at 750 °C. The material, a candidate for the aforementioned conditions of steam temperature between 620 °C and 720 °C is the alloy Inconel 617 (NiCr23Co12Mo).

Achieving such a high initial steam parameters would enable thermal efficiency of 52 to 54,5%, depending on the application of one or two overheating secondary steam.

Large companies on EU electricity market realize the European program COMETES 700, and it is implemented in more power plants in the EU. On the specific elements of the boiler (superheaters and intermediate superheaters steam collectors, pipelines), parts are made of materials that will be evaluated for their durability bed (creeping) and high temperature corrosion in the real conditions of the atmosphere gas in the boiler. Primarily, this applies to the austenitic steel and materials based on nickel. The pre-drying lignite with deducted steam turbine with a low-pressure (low temperature heat) is proposed.

There are two procedures for external dry lignite which are in the development: mechanical dewatering and thermal drying in a stationary fluidized bed with steam.

The heat of condensation (evaporation), the heating steam and Brid's steam coal are used. By combination of such advantageous conditions, it is possible to increase efficiency for extra 5% when using the coal with moisture content of 50%.

Another way of reducing specific CO<sub>2</sub> emissions at TPP on coal dust is a combined combustion of coal and biomass (Effects of co-firing), by adding the biomass carbon in the amount of 10% to 20%. Calculations and experiences show: with net efficiency of 40% for each addition of biomass of 10%, reduction of the specific CO<sub>2</sub> emissions is 56 g/kWh [24].

PFBC plant efficiency is above 42% (HHV). The results show that the second generation of PFBC thermal units has as high efficiency as 46% (HHV). PFBC plant development aims achieving the efficiency of approximately 54%, and up to 70% reduction in NO<sub>x</sub> and SO<sub>x</sub>, and reduction of CO<sub>2</sub> emission.

Lack of CFBC technology is higher consumption of limestone, a critical place is the exit of flue gases from the combustion chamber where flue gases are changing direction. The pipes in this part of the boiler are protected by the masonry walls, protected by cyclone and by the drain of hard particles back into the combustion chamber.

Table 7 Comparison of characteristics of combustion technology PCC and CFBC

	Characteristics	PCC	CFBC
FUEL CHARACTERISTICS	a) the sensitivity of the quality of coal	- larger	+ smaller
	b) the possibility of combustion problematic coals	- no	+ yes
	c) requirements by granulation of fuel for distribution in boiler	extremely accurately specified	+ accurately specified
	d) mixing		+ the best
TECHNICAL CHARACTERISTICS	a) technical minimum		+ low
	b) range of block rated power	+ wide (300÷800 MWe)	- narrow (to 460 MWe)
	c) gradient of load changes	+ high	- lower
	d) Availability	> 90%	> 90%
	e) time for cold start	+ shorter	- longer
	f) additional power	- larger (BFBC)	- larger (fan blower)
	g) the complexity of the plant	- larger (mills, burners, FGD, ...)	+ smaller
	h) floor area of building blocks	- larger	+ smaller
ENVIRONMENTAL CHARACTERISTICS	a) emission values of NO <sub>x</sub> -	higher values of NO <sub>x</sub>	+ lower
	b) emission values of CO	0	lower
	c) injection process NH <sub>3</sub> for SNCR	0	+ optimization of temperature
	d) desulphurization in the combustion chamber	no	yes
	e) temperature control in the combustion chamber	0	the best
	f) quantity of products desulphurisation	smaller	arger
	g) use of products	application / use	conditional use
	h) waste water from FGD	- requiring treatment	0
	i) solid waste and waste water	+ smaller - water must be treated	- larger + none
	j) use of flying ash and desulphuration products	+larger	- smaller
ECONOMICAL ASPECTS	a) investment costs	- higher*	+ lower
	b) operational costs	- might be high (mills, installations, ...)	- might be high (erosion, material fatigue, ...)
	c) electricity prices	- less competitive	+ competitive

\*) Include cost of catalyst for the separation of NO<sub>x</sub> from flue gases.

### 3.4 Comparison of Combustion Technologies

Finally, an overview comparison of different characteristics of PCC and CFBC combustion technologies has been made and presented in Tab. 7.

The advantages of using CFBC technology include:

- investment, operating costs and electricity prices,
- a wide range of fuel flexibility and the fuel consumption,
- stable efficiency on partial loads,
- effective cleaning of flue gases is only in the boiler,
- waste water does not have the facility for desulphurization,
- technical minimum (without reserve fuel),
- flexibility of action depending on the load.

From the standpoint of the degree of development, a great progress has been made with CFBC, as a stand-alone technology. Fuel for these types of boilers is coal, lignite, biomass and a mixture of coal and biomass. In CFB combustion plants, a higher degree of combustion efficiency is achieved in the combustion chamber than in BFB, more than 99%. In terms of low-temperature combustion, effective binding reaction is conducted with  $\text{SO}_x$  particles limestone- $\text{CaCO}_3$ , lime ( $\text{CaO}$ ), and produced  $\text{CaSO}_4$ , which is guided by the ashes from the boiler.

At relatively low temperature, in the combustion chamber, a smaller quantity of nitrogen oxides ( $\text{NO}_x$ ) is formed, which is important for the environment. Efficiency of thermal power plants with FCB combustion of coal is similar to conventional PCC ones. The experience of the previous two thermal power plants with the CFB-boilers and supercritical parameters, Foster Wheeler will use as the basis for developing a set of such blocks with the supercritical steam parameters of 800 Mwe [25].

Operating expenses of CFBC technology are lower than in the PCC. Fuel supply in the combustion chamber is simple, fuel is only crushed, flue gas cleaning does not require additional installations (desulfuration is in the boiler). Maintenance costs for PCC boilers are higher for plant and for cleaning flue gases but for CFBC boilers these costs may be higher due to erosion and fatigue. The investment value of blocks with PCC boilers is higher than for CFBC boilers, because of the additional facilities for cleaning flue gases. Due to lower construction costs and operating costs, CFBC boiler technology is more competitive than PCC technology. Various studies compare these two technologies and state a difference of approx. 7%. Technology with CFBC boilers with sub-critical parameters has certain economic advantages over the technology of PCC boilers.

The cost of technology with CFBC boilers and PCC is conditioned by current scale on the market, and the difference is relatively small. The difference is greater in the example of coal with the high sulfur content. Block boiler of PCC requires more space to build.

**Table 8** The cost comparison for PCC over CFBC technology

TEHNOLOGY	PCC	CFBC
Fuel / %	100	102
Efficiency block to TPP*	Might be larger to 0,5%	
Construction work / %	100	90
Investments / %	100	90
Operational and maintenance costs / %	100	90
The price of electricity / %	100	95

\* - Refers to the lower calorific value

A comparison of costs for PPC over CFBC is presented in Tab. 8.

## 4 CONCLUSION

The consumers will certainly reduce energy consumption which will result in reduction of the environmental pollution [26]. Although the world is committed to reducing  $\text{CO}_2$  emissions in the next fifty years, its emissions will still be significant [27].

Since its introduction and use started in the early twentieth century, PCC technology has maintained a dominant role in the production of electricity from coal, and currently represents more than 90% of installed capacities in the world. Grinding and drying of coal in order to increase the efficiency is becoming more common. At the level of efficiency in the process of exploitation, it significantly influences soiling, coal quality, pressure and temperature of steam. Efficiency and availability are increasing with economies of scale, or as units with higher power, in case of the optimal load [28].

In addition to increasing the efficiency of coal drying and utilization of waste heat from flue gases, supercritical parameters for increase in efficiency are used for blocks capacity greater than 400 MW, depending on the quality of coal and the block size.

CFBC is the simplest technology for coal combustion, due to the construction of devices for the introduction of fuel as a combustion chamber; a flue gas cleaning process begins in the combustion chamber, represents the best compromise of efficiency and ease of installation, environmental requirements and economic indicators. The biggest advantage of this technology is flue gas desulphurization in the boiler combustion chamber; it is possible to achieve the required emission of  $\text{SO}_2$  in flue gas of  $150 \text{ mg/Nm}^3$ . With supercritical parameters and a steam turbine it is possible to increase the degree of efficiency of the block to 0,4%, additional refrigerator of flue gases from new power plants is often built and increases energy efficiency by 0,6% and enables the use of a cooling tower for flue gas.

The technology of production of electricity from fossil fuels with zero emission of  $\text{CO}_2$  in atmosphere has not been developed yet to the level of commercial viability, but its realization can be expected in the next decade. Advances in the development of clean coal technologies should be taken into account in strategic planning capacity expansion in the power system, because relying on various primary energy sources, partly on coal, can ensure long-term reliability of electricity supply.

Newer CFB boilers are able to burn up to 20% biomass with little change in the boiler design. Addition of limestone in CFB boiler has the unwanted side effect of applying for the production of a much larger quantity of solid waste unsuitable for use as a replacement for cement. This is in contrast to the steady sales of fly ash and gypsum, produced by PCC boiler with wet FGD.

Fluidized bed combustion is gaining more than ever a ground among traditional ways of combustion due to high fuel flexibility. To conclude, a CFBC technology compared to PCC has:

- CFBC has higher boiler efficiency due to the lower temperature exhaust flue gases and lower energy content paramount;
- CFBC boiler is more expensive (more complicated additional equipment: cyclones, fans of high pressure, fluidized bed, container limestone, preparation and transport of dry ash system by cooling water);
- CFBC has greater risk of erosion of hard bits of ash than PCC;
- CFBC has higher net electricity consumption (greater consumption of air fan and induced draft fan, especially in partial load);
- CFBC is less flexible to load changes (due to the heat accumulated in the circulation mass that is high; this causes worse conditions for the provision of primary and secondary control of frequency).
- CFBC requires better trained staff (due to different types of boilers and different technology than PCC).
- CFBC has greater flexibility in terms of different characteristics of energy (coal fluctuation of pits and mines, etc.).
- CFBC has greater sensitivity to maintenance (internal components of the boiler exposed to extreme erosion)
- CFBC has less flexibility in terms of the diagram start (cold start for a long time: 7-8 h)
- CFBC power plants have lower availability due to complex maintenance.

The advantage of CFBC (to avoid flue gas desulphurization) is lost in case of a larger sulfur content in coal; then it is necessary to incorporate an additional plant for desulphurisation (NID system is semi-dry method - cheaper than wet); slag and waste as combustion products cannot be used in construction or other purposes (contaminated with ash and ammonia). The risk is in non-permissible limit values for emissions with CFB technology (need additional installation of plants for flue gas desulphurization (FGD) and denitrification DeNO<sub>x</sub>). Both technologies can guarantee more than adequate reliability and availability.

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