The future challenges for "clean coal technologies": joining efficiency increase and pollutant emission control

Alessandro Franco, Ana R. Diaz*

Dipartimento d'Energetica "L. Poggi",
Università di Pisa
Via Diotisalvi 2, 56126 PISA – ITALY
phone: +39-050-2217154 fax: +39-050-2217150
e-mail: alessandro.franco@ing.unipi.it

ABSTRACT

Coal offers an abundant widely spread fossil energy resource. It is available at a quite stable price from many international suppliers and it will continue to play a significant role in new generating capacity, if security and diversity of supply remain fundamental. In this paper we point out the state of the art in the field of "Clean Coal Technologies" evidencing the perspectives of improvement and the critical elements. Both the emission control of NO_x, SO_x and Particle Matter and the advanced coal conversion pathways like USC, PFBC and IGCC are reviewed and analysed. At the end some elements concerning the perspectives of CO_2 emission control strategies are outlined.

Keywords: Coal, Energy production, Pollutant control, Advanced Technologies, IGCC.

* Corresponding author

Alessandro Franco
University of Pisa
Dipartimento di Energetica "L. Poggi"
Via Diotisalvi, 2 – 56126 PISA – ITALY
Phone +39-050-2217154 Fax: +39-050-2217150
e-mail: alessandro.franco@ing.unipi.it

Symbols, acronims and abbreviations

ASU	Air Separation Unit
CC	Carbon Content
CE	Combustion Efficiency
CR	Conversion Rate
CCT	Clean Coal Technologies
CFBC	Circulating Fluidized Bed Combustion
DFGD	Dry Flue Gas Desolforator
EF_C	Emission Factor of coal
EFCC	Externally Fired Combined Cycle
el	electrical
FBC	Fluidized Bed Combustion
FGD	Flue Gas Desolforator
GHG	Greenhouse Gas
HP	High Pressure
HV	Heating Value
IGCC	Integrated Gasification Combined Cycle
IP	Intermediate Pressure
LNB	Low NO_x Burners
LP	Low Pressure
NGCC	Natural Gas Combined Cycle
OFA	Overfire Air
PCC	Pulverized Coal Combustion
P-CFBC	Pressurized Circulating Fluidized Bed Combustion
PF	Pulverised Fuel
PFBC	Pressurized Fluidized Bed Combustion
PM	Particle Matter
SCPF	Super Critical Pulverized Fire
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
th	thermal
USC	Ultra Super Critical
η	efficiency

1. INTRODUCTION

Coal represents at the present about 70% of the world's proven fossil fuel resources. Moreover, coal is also the more delocalized resource and it has the lower cost among the different fossil fuels. Thus coal is likely to remain one of the main sources of primary energy for a long time, playing a strategic role in the medium- long- term energy production systems. [1-3].

Electric power from coal has been predominantly generated in pulverized coal-fired power plants. Due to thermodynamic (the use of water) and metallurgic constraints, the efficiency of such plants is rather low. Modern pulverized coal-fired power plants achieve efficiency of about 38- 40% (based on the Lower Heating Value of the fuel) operating at 250-300 bar and at maximum temperature of 550-570 °C. But they are characterized by quite high pollutant emissions especially carbon dioxide (about 800 g for each kWh of electric energy produced).

The growing energy demand of the developing countries together with the need of a significant reduction in greenhouse gases (GHG) emissions are the challenging tasks of future energy policies [4]. The perspectives of coal as energy source are based on the success into the energy market of "clean coal technologies" (CCT), where good thermodynamic performances of the power plant are joined with a control of pollutant emissions (mainly CO_2 emissions). The most promising are the Ultra Super Critical (USC), the Integrated Coal Gasification Combined Cycle (IGCC) and the Externally-Fired Combined Cycle (EFCC) power plants. [2-4]. The development of CCT is an objective not easy to be performed for different motivations. On the one hand coal is not a uniform source due to its extremely variable composition; this made difficult to reach a standardization of advanced technologies that can be very sensitive to the fuel used. On the other hand coal combustion produces structurally more pollutants that the other fossil fuel since it contains mainly carbon as reactive component (producing CO_2) and sulphur (SO_x is the resulting product) but very little hydrogen (turning into H_2O). From the aforesaid considerations, the aim of the work is to analyze the perspectives of the particular field of clean coal technologies starting from an analysis of the state of the art. The paper will focus on the emerging suite of technology options and on studies to evaluate their potential to contribute to the nation's energy mix. In addition the current research and development in the "clean coal field" is discussed.

2. THE EVOLUTION OF COAL TECHNOLOGY AND ITS PERSPECTIVES

Worldwide energy and mainly electricity consumption are projected to grow at an average annual rate of 2.4% between now and 2030 (Table 1) caused by increase of population (up to

7.5 billion) and increase of consumption (mainly of China and India). Coal offers an abundant widely spread fossil energy resource, available at a stable price from many international suppliers and it will continue to play a significant role in new generating capacity, if security and diversity of supply remains fundamental. In this paper we will point out the state of the art of coal technologies and discuss if coal is really an opportune pathway for 21st century.

Even if coal does not represent a long term solution for the energetic problem it could be a strategic element in the mid term for the development of poor countries and for maintaining acceptable levels of welfare of others. Today the 23% of world primary energy comes from coal. About 36% of the world's electricity is produced using coal. Coal is the main fuel for electricity in USA, Germany, China, India, South Africa, Australia and much of central Europe [5-6]. Moreover 70% of the world's steel is produced by coal. The negative perception of coal is mostly related to the dirty and dangerous mines with poor working conditions, smog and suit, old technology and to the abundant pollutants (CO_2, SO_x, NO_x, and other). But in the last years a positive perception is emerging due to the abundant supply, the cheap nature of fuel, the growing interest of industrialized country and the efforts to R&D for the New Clean Technologies. All over the world there are today hundreds of Gigawatts (GW) of coal-fired generating capacity, mostly subcritical units with a capacity range of 100-300 MWe. The present policy is to close units of 100MWe and smaller, to modernize the 100-300 MWe units and to construct new larger units. Furthermore, environmental challenges can be addressed through technology improvements. Cleaner Fossil Fuels will remain the realistic option to provide Europe energy security, and commercial energy access. Coal-fired power plants are among the oldest power plants in operation in the world (at least on average). Although a lifetime of 30 years for a coal-fired power plant is not exceptional (more than 80 GW of plants installed in Europe are more than 30 years old). Thus in Europe, as in many countries there are both a desire and a necessity to utilize coal as an important energy resource to meet both rising electricity demand and plant retirements. Till to the beginning of the Sixties a great technological evolution of Pulverized Coal Combustion (PCC) based on thermodynamic optimization has been observed. At the end of the '50, the first supercritical cycles were developed in U.S.A. The majority of these PCC power plants had no emissions control equipments other than some particulate removal systems. Since the Sixties there has not been meaningful efficiency improvement, but growing attention to SO_x and NO_x emissions. Only in the Nineties a renewed interest in the Super Critical Pressurized Fuel (SCPF) technology was carried out reaching the actual standard level of 300 bar and 600 °C.

Table 2 contains data about some coal fired utility plants constructed worldwide during the second part of the 20^{th} century. The standard of today is represented by the parameters of Table 3 and the typical size of the plants is 700-1000 MW.

3. WHAT MAKES COAL "UNCLEAN" AND WHAT "CLEAN COAL" TECHNOLOGIES CLAIM

Coal is a complex chemical latticework of carbon, hydrogen, and dozens of trace elements. When combusted, some of these elements, such as sulfur, nitrogen and mercury, are converted to chemical forms that can create pollutants in the air and water. Carbon, the main constituent, combines with oxygen during combustion forms carbon dioxide (CO_2), which has been identified as a key contributor to Global Warming. Coal also contains sulphur that burns producing SO_2. Moreover coal-fired stations emit tonnes of ash through their chimneys, the 80% of which is particulates smaller than 10 micrometers (PM10), arsenic, hydrochloric acid, mercury, nickel and lead. Moreover combustion produces NO_x.

Public awareness and legislation have led to a policy of reduction of pollutant from coal-fired power generation, with the regulations partially driven by international initiatives such as the Kyoto protocol. The local acceptance of new plants is generally based on the choice of pollutant emission limits well below the existing legislation (e.g. in USA, Japan, Italy). The Italian environmental limits are represented today by 400/200/50 mg/nm^3 for SO_2, NO_x, and Particle Matter, while the European Directive 2001/80/CE that will be operative by the next years, reduces the limits at 200/200/30 mg/nm^3 for SO_2 NO_x and Particle Matter. "Clean coal technologies" are the basis for long-term acceptance of coal and is a flexible concept which can be used by all countries. Three different stages to achieve "clean coal" are available:

- I control and reduction of pollutants SO_2, NO_x, mercury and PM (excluding CO_2) without structural modification of the cycle
- II advanced technologies (the efficiency pathway)
- III long term vision of CO_2 capture and storage

3.1 Pollutant emission control

There are various technologies and processes that can be utilized throughout the coal fuel cycle to mitigate negative environmental impacts . The available technologies are:

1. Removal the source of pollution (sulphur, nitrogen) from the coal before it is burnt;

2. Avoiding the production of the pollutants during combustion (in-furnace measures);
3. Removing the pollutants from the flue gases by “end of pipe“ methods prior to be emitted.

3.1.1 NO_x control options

Depending on the fuel used, the combustion conditions, the air ratio and the flame type in the burner, a considerable mass of nitrogen oxide might be produced during the combustion process. Three primary sources of NO_x formation in combustion processes are documented:

- formation due to a high temperature combustion depending on the residence time of nitrogen at that temperature (Thermal NO_x);
- formation of fuel bound nitrogen to NO_x during combustion (Fuel NO_x);
- formation due to the reaction of atmospheric nitrogen, N_2, with radicals such as C, CH, and CH_2 fragments derived from fuel (Prompt NO_x).

One of the most common methods of post-treatment is the Selective Catalytic Reduction (SCR) generally used when higher NO_x reduction is required. The SCR achieves reductions of about 90% when is applied by temperature from 300 to 400ºC. Many other technologies are available; Table 4 summarizes the various options with their limits level. [7]. The paper [8] reviews the history of NO, control implementation, with an emphasis on the role that research has played on NO, control technology, development and implementation.

3.1.2 SO_x reduction

Coal contains significant amounts of sulfur. When burned, about 95% or even more of the sulfur is converted to sulfur dioxide (SO_2). SO_2 can be removed from flue gases by a variety of methods (Table 5). SO_2 is an acid gas and thus the typical sorbent used to remove the SO_2 from the flue gases are alkaline. Post-combustion removal, including Wet and Dry Flue Gas Desulphurization (FGD and DFGD) or spray dry-scrubbing. FGD is the current state-of-the art technology used for removing SO_2 from the exhaust gases in power plants. Many “conventional” PF stations (with Low NO_x burners) have FGD fitted. For a typical coal-fired power station, FGD will remove 95% or more of the SO_2 in the flue gases. Wet Flue Gas Desulphurization (FGD) utilizes a variety of slurry of sorbent materials to scrub the gases in order to accomplish SO_2 removal efficiencies approaching 99% (reduction in the treated flue gas). These reagents include limestone ($CaCO_3$), lime (CaO), caustic soda (NaOH) and related variants to absorb and neutralize the SO_2 in the flue gas. Table 5 provides the main control technologies with their potential reduction [7]. A book, [9] provides a collection of papers concerning emissions reduction of SO_x and NO_x.

3.1.3 PM controls (Mainly post-combustion methods)

PM composition and emission levels are a complex function of coal properties, boiler firing configuration, operation and pollution control equipments. In the combustion of solid fuel dust and ashes, that are included in the exhaust gases as small particulate, are produced. PM control is mainly possible with post-combustion methods, like electrofilters, cyclones and ceramic filter with quite good results (Table 6). The problem of PM emission of coal plants is discussed in several scientific papers like [10] and [11].

3.1.4. Mercury control

Mercury control R&D includes sorbents and oxidizing agents that can change gaseous mercury into solids, which can be captured. The oxidizing agents work inside wet flue gas scrubbers to capture mercury in the sulfate by-product. Hg capture with existing controls depends on coal and technology type, being more difficult to control Hg from low rank coal-fired boilers. Sorbent injection is an emerging Hg control technology. The paper [12] presents an overview of research related to mercury control technology for coal-fired power plants and identifies areas requiring additional research and development.

3.1.5. The new concept of coal plant

Each component in the flue gas cleaning section is designed to remove a specific pollutant but, besides this, can also have a beneficial effect on other macro and micro pollutants, substantially increasing the global abatement performance. According to literature, good results can be obtained using the various pollutant control technology [13]. But a different vision of coal plant as energy system is emerging. Coal-fired power plants as the one described in Fig. 1 generate significant quantities of solid byproducts such as fly ash or gypsum. The call for more stringent emission reductions through multi-pollutant regulations has the potential to alter the future use of coal by-products and may make certain auxiliary product (limestone) or by-products (gypsum) a problem that need to be considered.

3.2. Advanced technological options for coal conversion

Energetic performances and pollutant emissions from electric power generating plant can be further reduced by the improvement of the thermodynamic cycle of power generation. New requirements to limit environmental emissions impose a shift from the steam cycle to the gas cycle based plant. Technologies of interest with the possible variant are summarized in Fig. 2. Those are mainly

- Advanced Ultra Supercritical Pressurized fuel combustion plants (USC)
- Fluidized Bed Combustion (FBC) incorporating also advanced supercritical steam cycle
- Integrated Gasifier Combined Cycle (IGCC)
- Externally Fired Combustion Combined Cycle (EFCC)

3.2.1 Ultra Super Critical Plants (USC)

The use of Ultra Super Critical (USC) parameters for steam represents on of the sure evolution of pulverized coal fired power plants. [14]. In addition to the advance in the steam conditions, it incorporates several clean air technologies: new design of burners, new scheme of combustion in the boiler furnace, new design of steam super heaters and gas cleaning systems. USC technology is well known; according to [15] over 550 super critical PCC are available all over the world for an amount of 300 GW (about 150 in USA, over 100 in Japan and Russia, more than 30 in Germany). With the term "ultra-super-critical" the overcoming of the limit conditions for the steam at the level of 300 bar/600 °C/600 °C, to reach more advanced operating parameters towards to the increase of pressure and turbine inlet temperature is evidenced. The currently available power plants based on supercritical steam boiler at 600 °C permit to reach efficiencies of 45-47%. The limits of this technology are today under discussion. The analysis carried out by some researchers and producers indicated an agreement about the long-term objective of reaching a steam pressure level of 350 bar and maximum steam temperature of 700 °C with the use of advanced material (AD700 USC plants). The perspective is to achieve net efficiencies of 50% and more.

3.2.2. Pressurized Fluidized Bed (PFBC)

Fluidized bed combustion represents a straightforward evolution of the circulating fluidised bed combustion, which has gained great attention from the Seventies [16]. Fluidization means that the solid coal particles are supported and mixed with air which is injected into the system. Burning occurs at 760-930°C, well below the 1370°C needed to generate nitrogen oxide pollutants. It permits basically the possibility of a strong reduction of SO_2 and NO_x emissions with respect to pulverized coal power plants. SO_2 is captured by limestone injection, CO_2 is controlled by sorbents. The resulting flue gas can be used in turbine.

Fluidised bed combustion technologies are of various types. They include atmospheric pressure Fluidised Bed Combustion (FBC), Circulating (CFBC) or Pressurized Fluidised Bed Combustion (PFBC) and Pressurised Circulating Fluidised Bed Combustion (P-CFBC).
From the thermodynamic point of view, the main benefit obtained from pressurized fluidised bed consists on the possibility of increasing the plant efficiency, coupling a Rankine cycle with a gas turbine. The controlled combustion permits a flexibility in the use of fuel (i.e. the use of a low quality coal). The resulting process is a hybrid cycle, but the steam turbine generates the high percentage of the power (until the 80%). The currently available efficiency is lower than 40% and many problems during operation have been evidenced in the various experimental facilities.

3.2.3 Integrated Gasifier Combined Cycle (IGCC)

Since twenty years ago Integrated Gasifier Combined Cycles (IGCC) are considered the future of coal combustion. IGCC first turns the coal into gas (mostly CO and H_2), then sulphur, ash, mercury and other pollutants are removed and finally the clean gas is fed to the Central Power (Fig. 3). IGCC allows coal to benefit from gas turbine advances [17] and permits simpler CO_2 control if required [18]. Multiple Gasification process technologies are available, like as [19]:

–Entrained flow (Shell, GE (Texaco), Conoco-Phillips (Dow/Destec))
–Fixed bed (BGL, Lurgi, EPIC)
–Fluidized bed (Southern Co- Staunton, KRW)

These processes allow a large variety of plant configurations [20]. Plants are operating successfully in Spain, the Netherlands and USA. Among them a 253 MWe IGCC power plant of Buggenum (the Netherlands), a 252 MWe IGCC of Wabash River (Indiana-USA), a 250 MWe IGCC of Polk County (Florida-USA) and a 318 MWe IGCC of Puertollano (Spain) are of particular interest because based on coal as primary fuel. Efficiency is in the range between 35 and 42%. The specific cost of commercial version of similar plants is estimated to be about the 40-60% higher than a conventional PCC plant. IGCC is basically the cleanest coal technology with inherently lower SO_x, NO_x, and PM, lowest collateral solid wastes and wastewater, potential for lowest cost removal of mercury and cheapest route to CO_2 separation. Notwithstanding some successful experiments, the low number of operating plants showed a lot of problems, mostly concerning the availability. In the meantime the renewed interest in the conventional PCC power plants made quite less attractive investments on IGCC. But IGCC becomes a solution of interest for petrolchemical industry (Tab. 7). More than 120 plants were in operation in 2004. The facilities produce mostly chemicals (37%), gas (36%) or power (19%). In terms of feedstock, some of them are solid feedstock based (coal and petroleum coke), others are refinery high sulfur heavy oil based. Only a small number of them is based on coal.

For this reason IGCC technology holds great promise for the future due to the flexible feedstock, process options and products and opens new markets for coal (syn-fuels, chemicals, fertilizers). It also provides the only feasible bridge from coal to hydrogen (directly converts coal to hydrogen). But in the meantime new barriers are growing to deployment of IGCC. The first is the power industry culture. While a conventional coal plant places a chemical plant at the *back end*, attempting to capture pollutants after combustion with much dilution, IGCC places the chemical plant in the *front end* of the power plant (Fig. 3) and it is basically a chemical plant. Power companies do not like chemical units, moreover there are a lot of technical and financial risks and finally companies don't understand why they should build IGCC when it is possible to get a permit for a conventional coal plant.

4. THE FUTURE CHALLANGES OF CLEAN COAL TECHNOLOGIES

CO_2, SO_2 and NO_x have been mentioned above as some of the things that made coal "unclean". The good possibility of reducing the level of NO_x and SO_x are summarized in Tables 4, 5 and 8. Let's consider now the problem of CO_2. It is well known that recent Pulverized Coal Combustion (PCC) plants are characterized by a level of CO_2 emission in the range between 850 and 900 g/kWh. The level of 750 g/kWh can be reached both by means USC plants and IGCC plants. It is really difficult that the barrier of 750 g/kWh can be broken without any mitigation strategy. Coal (C) emits at least the double of CH_4. Emission factor from coal (EFc) can be calculated by

$$EF_C = \frac{CR \cdot CC \cdot CE \cdot 44}{HV \cdot 12} \tag{1}$$

where HV is the Heating Value of the fuel (12-32 MJ/kg), CC is the Carbon Content of coal (60-90%), CE is the Combustion Efficiency (0.9-0.95) and CR is an opportune conversion rate (0.2778 in case of MW and KWh). In usual conditions EFc is approximately in the range

between 0.3-0.4 $kgCO_2/kWh_{th}$. Considering the actually available efficiency values (0.35-0.45) it gives a level of emissions energy produced of 0.750-1 $kgCO_2/kWh_{el}$.
The advanced technologies for coal conversion like USC and IGCC can contribute to the CO_2 emission mitigation mostly due to the efficiency increase (USC technology) and to the different plant architecture (IGCC). Fig. 4 summarizes the range of specific CO_2 emission available with the various coal technologies in comparison with the reference level represented by CO_2 emission of Natural Gas Combined Cycle (NGCC) plants.

4.1 CO_2 emissions control and the mitigation technologies

To maintain the position of coal in the global energy mix in a CO_2-constrained world, the crucial question about the future of coal technologies remains the perspective of a considerable reduction of the CO_2 emissions from its utilization. To reduce CO_2 emissions from coal-fired power generation, two strategies can be perceived: improving efficiency or resorting to capture and storage of CO_2 from conventional plants. Three main strategies are analyzed in order to mitigate the CO_2 emissions produced by coal:

- Post-Combustion (removal of CO_2 from combustion flue gases).
- Oxy-Fuel Combustion (combustion with pure O_2 and Recycled Flue Gas)
- Pre-Combustion (separation of CO_2 from the fossil fuel)

Even if the second and the third are promising strategies, the control of CO_2 emissions from coal fired power plants is possible through end-of-pipe (post-combustion) processes.
The most suitable technology appears to be the chemical absorption, which is based on the CO_2 concentration and its partial pressure at the capture point. This method has been widely analyzed in literature, being the most applied one. Under an energetic point of view this technology requires a great amount of energy to achieve the CO_2 capture, with a great impact on the thermodynamic performance of the plant that seriously decreases power generation efficiency (Fig. 5). The CO_2 capture systems demand a significant amount of energy for their processes requiring more fuel per kWh generated, reducing net plant efficiency, increasing other environmental pollutants (ammonia, limestone). According to the currently available literature, a reduction of efficiency estimated in 7-8 point percentage (from 40% to 32%) can be estimated. [4]. Economically talking, the development of this technology without much modification to the plants can be a transitory short-term solution for existing plants. The estimated increase of costs is of the order of 35-40% (from 1100-1200 €/kW to about 1600-

1700 €/kW for conventional PCC plant with CO_2 capture). However several key questions remain, including cost and performance of integrated power and capture technologies about how sustainable could be CO_2 capture as a mitigation strategy.

In spite of the important research efforts and the great emphasis associated to the development of pollutant emission control, the concept of CO2 capture in power generation is still in a developing phase. The different options offer an enormous engineering challenge but do not seem to be valid solutions for existing power plants.

4.2. Research and development lines in the field of “Clean Coal Technologies”

Under the urgent need of advanced technologies for electricity generation using coal as fuel, projects related to clean coal technologies for power generation are undertaken worldwide, particularly in the United States and in Europe. Primary focus of these efforts is to develop innovative concepts for pollutant control. The projects concern new and advanced technologies for pollutant control (SO_x, NO_x, PM, etc.) including more economic and ecocompatible than the actually available, that can be retrofitted to existing baseload coal-fired power generating capacity. Major efforts include low-NO_x combustion, mercury control, fine particulate control, by-product utilization, water management, analysis on mercury formation during combustion and during the subsequent treatments. Other research lines concerns new materials and advanced diagnostics for USC plants, IGCC Plants with CO_2 capture and separation, “zero liquid discharge” plants. The promising EFCC technology is nowadays only at evaluation of proof concepts but it seems the only one strategy for promoting the development of low size plants (10-50 MW) based on coal as primary fuel.

5. CONCLUSIONS

Over the past decade, the role of coal as an energy source for the future has gained renewed interest and it is, therefore, likely that coal will remain in an important position among the primary resources. Concerning the emission control strategies it is possible to observe good success in controlling PM, NO_x and SO_x emissions. Advanced, low-cost emissions control systems have been successfully demonstrated and employed in several plants, but difficulties for the maintenance of standards during operating life of the plant is observed. Moreover the high sensitivity to the type of coal used and the problems with auxiliary material (ammonia, urea, limestone, gypsum) are well known.

Regarding the advanced technologies, it is clear that the clean coal technologies, which are likely to make serious contributions to energy sector in the next years are on the one hand supercritical pulverised coal firing and on the other hand integrated gasification combined cycles. A superiority of USC solution in a mid-term scenario can be evidenced. From a long-term perspective, the development of IGCC solutions appears interesting, due to the inherently cleaner process because coal is not combusted and pollutants can be removed with greater efficiency. About CO_2 capture and storage only early research work and promising strategies are available but uncertainty about perspectives is apparent. The application of CO2 capture technologies to the existing plants appears to be a quite critical task but it appears really interesting the development of power plants in which the removal systems be integrated into the process.

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Tables and captions

Year	Electric energy production [Twh]	Coal (%)	Natural Gas (%)	Oil (%)	Nuclear (%)	Renewable (%)
2005	18235	40.3	19.7	6.6	15.2	18.2
2030	26600	32	27	9	12	20

Table 1. Electric energy production by sources (the data of 2005 are from [5])

Central name	State and year of installation	Steam conditions
Eddystone I	USA ‘50	345 bar, 649℃/566℃/566℃
Kashira	Russia ‘60	306 bar, 650℃/565℃
Typical USA coal plants	USA ‘60	241 bar, 566℃/566℃
Typical Italian PCC plant	Italy ‘70	250 bar, 540℃,540℃
Kawagoe	Japan ‘90	311 bar, 566℃/566℃/566℃
Frimmesdorf	Germany ‘90	250 bar, 580℃/600℃
Averdore 2	Denmark ‘90	300 bar, 580℃/600℃
Torrevaldaliga Nord	Italy ‘00	250 bar, 600℃/610℃

Table 2. The thermodynamic evolution of coal plants

Indicator	Range
Efficiency	36-40%
Size (MW)	300-1000
CO_2 Emission (kg/MWh)	850-1000
NO_X Emission (kg/MWh)	0.5-1.5
SO_2 Emission (kg/MWh)	0.5-0.7
PM Emission (kg/MWh)	0.1
Capital cost (US$/Kw)	1100-1200

Table 3. Reference data for an installed coal plant: sub-critical units and conventional sulfur control

Control Technique	NO reduction potential (%)
Overfire air (OFA)	20-30
Low NO_x Burners (LNB)	35-55
LNB + OFA	40-60
Reburn	50-60
SNCR (Selective non Catalytic Reduction)	30-60
SCR (Selective Catalytic Reduction)	75-85
LNB with SCR	50-80
LNB with OFA and SCR	85-95

Table 4. Potential Reduction of NO_x control technologies [7]

Control Technique	SO reduction potential (%)
Pre combustion removal: Physical cleaning	(30-50% removal inorganic sulfur)
Chemical and biological cleaning	(90% removal organic sulfur)
Combustion configuration: Fluid Bed	
Post-combustion removal: Wet Flue Gas Desulfurization (FGD)	(80-98%)
In situ sulfur capture: Dry Sorbent Injection (DSI)	(50%)

Table 5. Potential Reduction of SO_x control technologies [7]

Control Technique	Reduction potential (%)
Electrostatic precipitator (ESP)	99% (for 0.1<d (mm)<10)
Filters	As high as 99.9%
Wet scrubber	95-99%
Cyclone	90-95% (d(mm)>10)

Table 6. Potential Reduction of PM control technologies [7]

Project – Location	Start-Up	MW	Products - Feedstock	Availability (h/y)
Cool Water	1984	120	Power – syngas / Coal	
Bugghenum – The Netherlands	1994	250	Power / Coal	6000-8000
Wabash – USA	1995	260	Repower / Coal, Pet Coke	< 6000
Tampa Elec. Company – USA	1996	250	Power / Coal, Petroleum Coke	< 8000
Puertollano – Spain	1998	320	Power / Coal, Coke	> 5000
Pinon Pine – USA	1998	107	Power / Coal	< 1000
Schwarze Pumpe – Germany	1996	40	Power and Methanol / Lignite	
Shell Pernis – Netherlands	1997	120	Cogen and H_2 / Visbreaker Tar	
ISAB: ERG/Mission – Italy	2000	510	Power / Asphalt	
Sarlux: Saras – Italy	2001	545	Power, Steam, H_2 / Visbreaker Tar	> 8000
Exxon Chemical – Singapore	2001	160	Cogeneration / Ethylene Tar	
API Energia – Italy	2001	280	Power and Steam / Visbreaker Tar	
Motiva LLC – Delaware, USA	2002	160	Repower / Pet Coke	
Nippon Refining – Japan	2003	342	Power / Asphalt	

Table 7. The experience on the IGCC plants

	PF	PF+FGD	SCPF	CFBC	IGCC	NGCC
SO_X (mg/m^3)	2250	200	150	150	25	0
NO_X (mg/m^3)	650	200	150	220	45	45

Table 8. Emission level of NO_x and SO_x for the various advanced coal plants

Figure captions

Fig. 1. A schematic view of a classic PCC power plant with end-of-pipe emission control

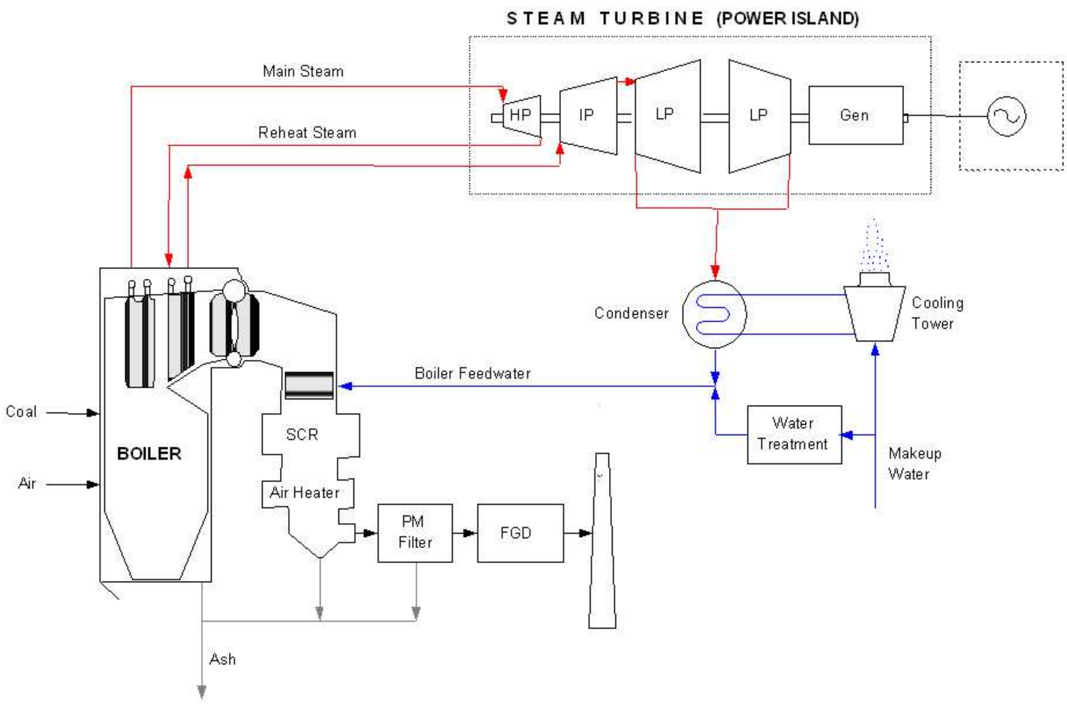
Fig. 2. Advanced technologies for coal conversion

Fig. 3. Integrated Gasifier Combined Cycle: schematic

Fig. 4. Emission level of CO_2 for the various technologies coal plants

Fig. 5. Comparison of CO_2 emissions for plants with and without capture (kg/kWh)

Figures and captions



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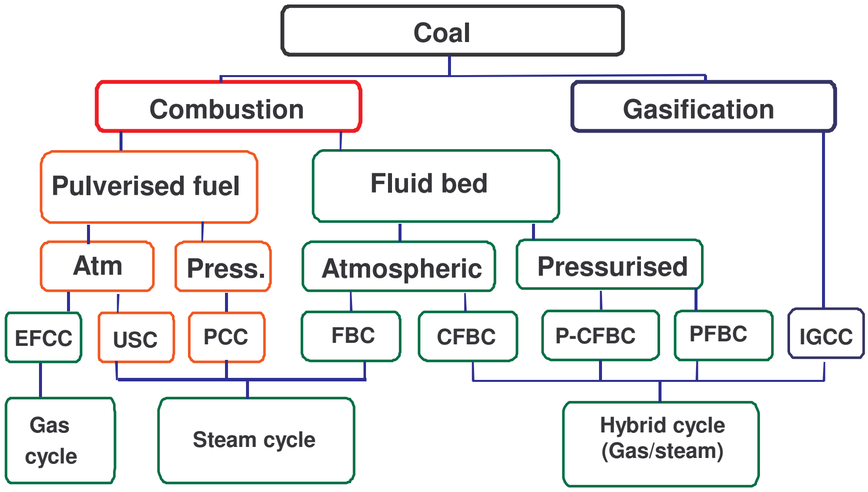
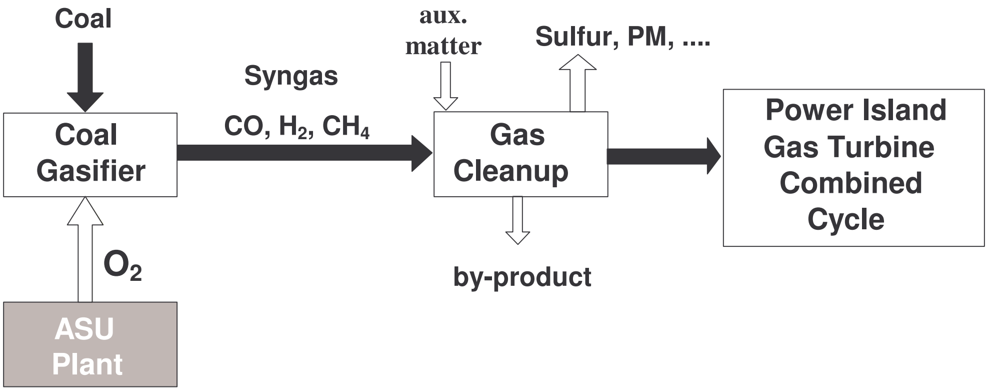


Fig. 2. Advanced technologies for coal conversion



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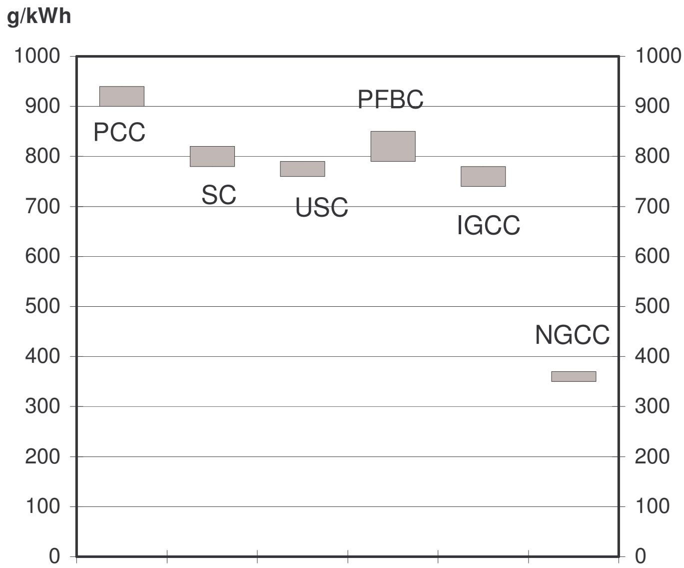

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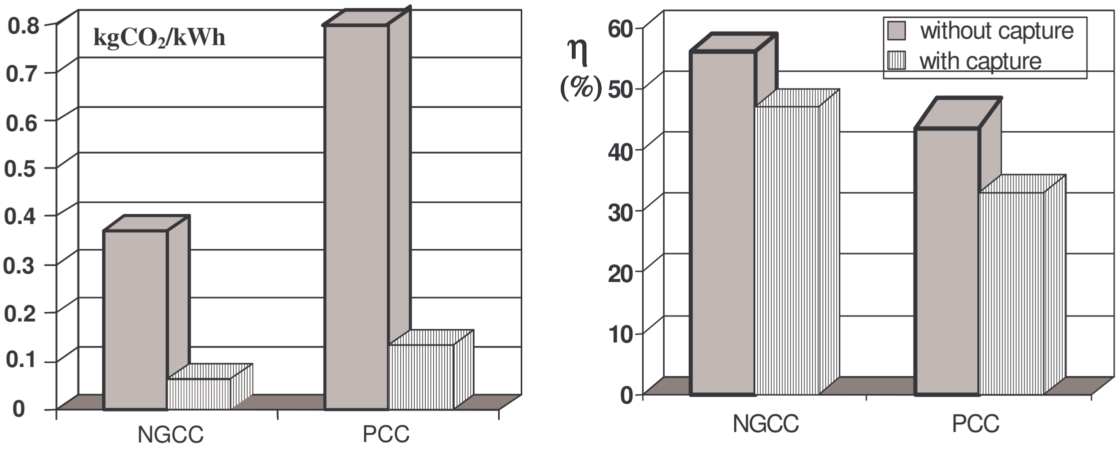

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