Coal-Fired Power

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS –** Some 42% of the world's electricity production is based on coal combustion. The world's coal-fired capacity is 1440 GW_e out of a global capacity of 4509 GW_e (2007). In China, around 71% of the total installed capacity (502 GW_e out of 706 GW_e, 2007) is based on coal-fired power plants. Currently, super-critical pulverised coal (**SCPC**) power - a mature technology - is the dominant option for new coal-fired power plants. In a SCPC power plant, pulverised coal combustion generates heat that is transferred to the boiler to generate supercritical steam. The steam is then used to drive a steam turbine and an electricity generator. Pulverised coal-fired power plants produce a considerable amount of airborne emissions. A 1,000 MW_e supercritical plant emits about 5.2 million tonnes (Mt) of CO_2 per year, in addition to smaller but significant amounts of SO_2, NO_x, particulate matter (PM), and minor amounts of mercury. An alternative to the SCPC technology is the integrated gasification combined cycle (**IGCC**). In the IGCC plants, a thermo-chemical reaction with oxygen and steam is used to convert liquid or solid fossil fuels (e.g. hard coal) into a gas mixture of carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2), along with small amounts of hydrogen sulphide (H_2S). After cleaning, the gas is fired in a gas turbine to generate electricity. The exhaust gas is used to produce superheated steam (in the heat recovery steam generator, HRSG) that drives a steam turbine and generates further electricity. The IGCC technology is less mature than SCPC technology. Several IGCC plants have been built in the US and in Europe. They have efficiency similar to that of SCPC plants, but lower non-greenhouse gas (GHG) emissions.

- **PERFORMANCE AND COSTS –** Technological development aims to increase the efficiency and decrease the investment cost and the emissions of coal-fired power. The generating efficiency of SCPC plants is expected to increase from the current (2010) maximum value of 46% (lower heating value, LHV) to some 50% for 'ultra-supercritical' technology in 2020. Efficiency and reliability improvements are also expected for the IGCC technology. Its efficiency is estimated to grow from 46% in 2010 to 52% in 2020. In the IGCC plants, the production of CO_2 during the gasification process offers the opportunity for relatively low-cost CO_2 capture and storage (CCS), which may give the future IGCC plants some competitive and environmental advantages over SCPC. As far as costs are concerned, due to the increasing prices of materials, steel and equipment, the investment cost of a pulverised coal-fired power plant increased from \$1500/kW_e in 2000 to approximately \$2200/kW_e in 2008 (costs are quoted in US\$ 2008). Since the 2008 peak, investment costs have been slightly declining because of the reduction of the material cost induced by the economic crisis and the lower demand for new capacity. The IGCC investment cost is relatively high. It may be up to almost twice the cost of SCPC plants. The operation and maintenance cost (O&M cost, expressed in \$/kW_e per year) is estimated at 4% of the investment cost per year for both SCPC and IGCC, but the IGCC plants may face higher O&M costs because of a lower technology maturity. Average costs of electricity today from SCPC are \$60–70/MWh (typically \$65/MWh), of which \$15–25/MWh is for the fuel. For IGCC plants, corresponding figures are \$90–100 (typically \$95/MWh), with \$15–25/MWh for the fuel. In terms of cost projections, technology learning is not expected to dramatically reduce the SCPC investment costs as the technology is mature. Therefore, the costs of supercritical and ultra-supercritical pulverised coal power plants are expected to decline from \$2200/kW_e in 2010, to \$2000/kW_e in 2020, and to \$1800/kW_e in 2030. On the other hand, technology learning may significantly reduce the IGCC investment cost from \$3700/kW_e in 2010 (70% more than PC) to \$2800/kW_e in 2020, and to \$2200/kW_e in 2030 (20-25% more than PC).

- **POTENTIAL & BARRIERS –** Numerous coal-fired power plants are under construction or being planned in many countries. In the US, some 16 GW_e were under construction in January 2009 and a further 10 GW_e were approved for construction, some of which are to replace retired capacity. Coal-fired power offers advantages over gas-fired power if the natural gas price is high and/or volatile, or in light of supply security issues. New coal-fired power plants have higher efficiency and lower emission of CO_2 per kWh than existing plants. Emissions of airborne pollutants may be lower as well. A disadvantage is the high investment cost (compared to gas-fired power) that is compensated for by the lower fuel cost. The price of CO_2 may also be a barrier for new coal-fired capacity. The current price in the European emission trading system (some €13-14/tCO_2,) is not high enough to discourage the construction of new coal-fired capacity. However, uncertainties about future CO_2 prices can make it difficult to adopt new investment strategies. In the near future, the utilities that have to comply with emissions trading systems may consider implementing CO_2 capture and storage technologies (CCS). This may significantly increase the investment cost and reduce the efficiency of coal-fired power. Therefore, long-term emission reduction policies and high CO_2 prices are needed for CCS to become commercially available. Coal-fired power not only competes with gas-fired power, but also with nuclear and renewable power. While some renewable technologies are growing fast and will have an increasing impact on the electricity market, the competition with nuclear power will largely depend on licensing and regulatory aspects, environmental issues, social acceptance, and long-term CO_2 policies.

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PROCESS AND TECHNOLOGY STATUS – The key features of major types of coal used for power generation are listed in Table 1. **Pulverised coal (PC)** is the fuel used in about 97% of the world's coal-fired capacity (IEA, 2008). In a pulverised coal-fired power plant, coal is milled and burned with air in tall boilers that provide for complete burnout and efficient heat transfer. Radiant and convective heat is transferred to the boiler walls' pipes that carry pressurised water. In a few heating stages (single or double reheating), water is converted into superheated steam. Natural gas or fuel oil may also be used for the start-up phase of a pulverised coal-fired power plant, followed by gradual phase-in of coal.

Table 1 - Main features of four types of coal (Sources: EWG, 2007; Internet source 1)

Coal Type	C content, [%wt]	Ash content, [%wt]	LHV[a] [MJ/kg]
Anthracite	85 – 95	7 – 11	30
Bitum. coal: Illinois #6	60 – 61	11 – 14	18.8 – 19.3
Sub-bitum. coal: WY Powder River Basin	48 – 49	5.3 – 6.3	8.3 – 25
Lignite: N. Dakota	35 – 45	6.6 – 16	5.5 –14.3

a) **Low heating values (LHV) refer to coal types in EWG, 2007**

■ **Super-critical pulverised coal (SCPC)** power plants use supercritical[1] steam as the process fluid to reach high temperatures and pressures, and efficiencies up to 46% (lower heating value, LHV). New **ultra-supercritical** (**U-SCPC**) power plants may reach even higher temperatures and pressure, with efficiency up to 50% (Fig. 1). For example, the AD700 project aims to reach an efficiency of approximately 50%, in 2015-2020. Materials for state-of-the-art steam turbines and boilers can withstand maximum operating temperatures of 600-610°C for primary steam, and 610–620°C for reheated steam, and a maximum pressure of 30 MPa (Fig. 2, Susta, 2008). More than 570 SCPC or U-SCPC units are in operation, under construction, or planned worldwide (Fig. 3) in some 430 power plants (2008), with sizes ranging from 200 MW_e to 1300 MW_e and a total capacity in excess of 330 GW_e. The majority of these units operate at a steam pressure and temperature (i.e. below 24MPa/595°C) that are compatible with the use of all-ferritic steel for thick-wall boiler components. Further temperature increases require the use of Ni-based super-alloys and new designs. It is anticipated that above 650°C superalloys will replace traditional ferritic steels for steam turbine rotors. Because of the increased thermal expansion coefficients of these materials compared to ferritic steels, thermal stresses in forgings and castings become an important issue during start-up and load cycling, and rotor axial expansions require new design approaches (PC, 2004). Based on ongoing developments, steam turbines with ultra-supercritical conditions of 35MPa and 720-760°C – with net LHV efficiency above 52% (Fig. 2) – might be designed and tested in the next decade.

[1] Fluids become supercritical at temperature (T) and pressure (P) above the critical point. Close to the critical point, small changes in T and P result in large changes in density. SC fluids are used in industry and in power generation.

■ **Integrated gasification combined cycles (IGCC)** are an alternative coal-fired power technology in which a thermo-chemical reaction with oxygen and steam is used to convert coal (or liquid fossil fuels) into a high-pressure gas consisting of carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2), with small amounts of hydrogen sulphide (H_2S). After cleaning, the gas is fired

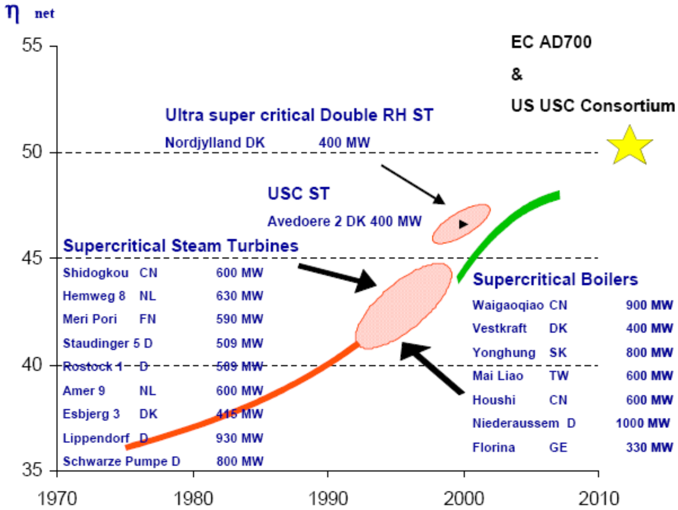

Fig. 1 - Efficiency of PC power plants (Otter, 2002; Susta, 2008)

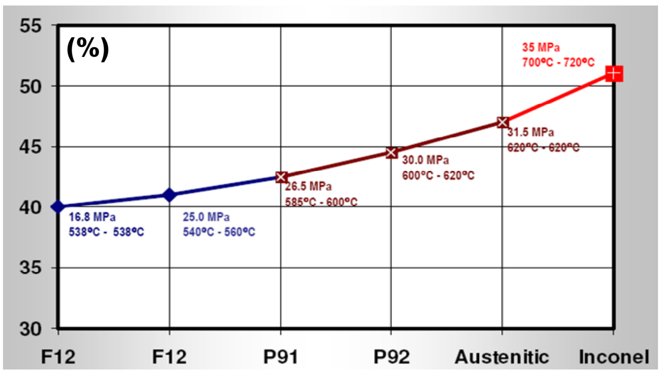

Fig. 2 - PC plants efficiency (%) vs. steam parameters and materials (Susta, 2008)

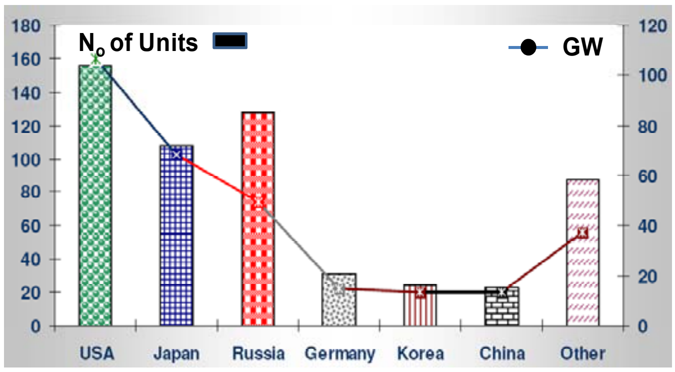

Fig. 3 – Super/ultra critical capacity (Susta, 2008)

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in a gas turbine and exhaust is used to generate superheated steam in the heat recovery steam generator (HRSG) and to drive a steam turbine (Fig. 4). Eight IGCC plants in the US and Europe use coal or pet-cokes (Table 2). Another seven IGCC plants – four of which are in Italy – use residual oil (Higman, 2008). Table 3 provides technical and environmental data for four coal-based IGCC plants. Designed as demonstration plants, they have a relatively small capacity (250–300 MW_e). Their efficiency varies from 39% to 45% (LHV), which is comparable to state-of-the-art pulverised coal-fired power. Table 3 also shows that the IGCC specific SO_2 emission is very low, i.e. ≤ 0.6 g/kWh (98–99+% desulphurisation), and the same applies to NO_x (0.24–0.40 g/kWh) and particulate matter (0.005–0.02 g/kWh).

Table 4 shows technical and environmental parameters of a new SCPC plant in the Netherlands and a new IGCC plant in the US. The IGCC plant can more easily attain very low levels of SO_2 and NO_x emissions than an ultra-SCPC plant. In both cases, low-NO_x burners and, if requested by environmental regulations, selective catalytic reduction (SCR) systems are applied to reduce the NO_x emissions to the required level. Other environmental impacts relate to the ashes produced in the case of coal combustion or gasification. Waste can be minimised both prior to, and during, coal combustion. Coal cleaning prior to combustion is a very cost-effective method of providing high quality coal. It reduces power station waste, SO_x emissions, and increases thermal efficiencies. The residual waste can then be reprocessed into construction materials (WCI, 2004). In accordance with the target efficiency of the AD700 project, it is assumed that technological learning will entail slow efficiency gains for U-SCPC, namely 46% (LHV) in 2010, and 50% (LHV) in 2020. With regard to coal-based IGCC, it is assumed that these plants may have a net generating efficiency of 46% in 2010 (equal to SCPC plants). However, more learning potential for IGCC may result in a higher efficiency in 2020 (52%, LHV).

The electrical capacity in the European Union is approximately 800 GW_e, (2007) of which 18% is based on hard coal and 10% on lignite. In China, the electrical capacity in 2007 was 706 GW_e, (with an annual growth rate of 14.1%) of which 502 GW_e was based on coal. According to the International Energy Agency (IEA, 2008), the average coal consumption in the Chinese plants is more than 50 gce/kWh higher than the consumption in best available U-SCPC plants. This is equivalent to an additional coal consumption in China of 100 Mtce per year (2930 PJ per year). In the US, the total electrical capacity is approximately 1039 GW_e, with 335 GW_e based on coal, generating almost 50% of the electricity. At present, the global coal-fired capacity is some 1440 GW_e out of a global capacity of 4509 GWe. China is now installing SCPC power plants as the standard technology and the Indian government is also intensively promoting both SCPC and U-SCPC technologies. In the US, about 16.3 GW_e new coal-fired capacity – mostly SCPC and U-SCPC plants – are under construction and an additional 10 GW_e are going to be built or have building permission (Shuster, 2009).

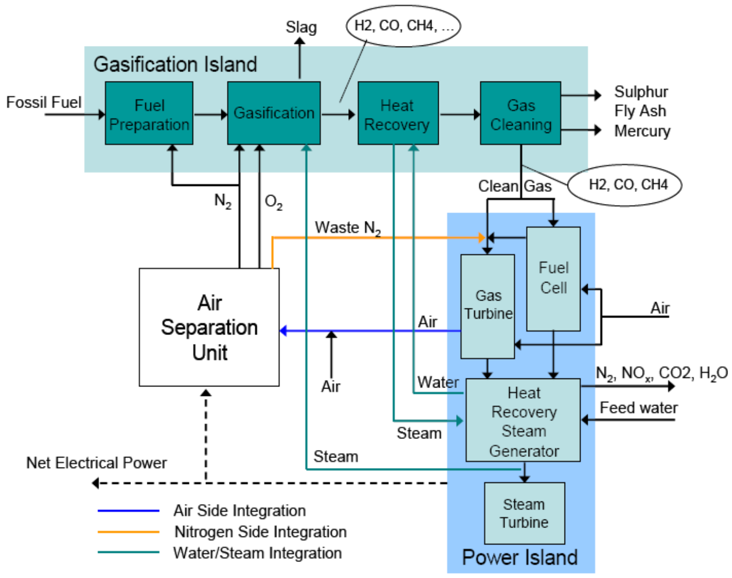

Fig. 4 - IGCC power plants (Purdue University, 2007)

Table 2 - Characteristics of IGCC plants (Sources: Ely Field, 2008; Stiegel, 2008).

Plant	Location	Operation	Size (MW_e)	Fuel
SCE Cool Water	Barstow (California)	1984–1988	120	Bit. coal
LGTI (Destec/Dow)	Plaquemine (Louisiana)	1987–1995	160	S.bit.coal & n. gas
NUON (Demkolec)	Buggenum (Netherlands)	1994-now	253	Bit. coal
Global Energy Wabash River	Terre Haute (Indiana)	1996-now	261	Bit. coal & pet-coke
TECO Polk Power Station	Polk (Florida)	1996-now	252	Bit. coal pet-coke
Frontier Oil & Refining Co.	El Dorado (Kansas)	1996-now	40 [a]	Pet-coke
Elcogas S.A.	Puertollano (Spain)	1997-now	298	Coal & Pet-coke
Motiva Enterpr. Refinery	Delaware City (Delaware)	2002-now	160 [a]	Pet-coke

a) Co-generation

Table 3 - IGCC technical and environmental characteristics (Sources: EPA, 2006; Fowler, 2008; Swift, 2008; Stiegel, 2008)

Technical Performance	NUON (NL)	Elcogas (Spain)	TECO (Florida)	Global Energy (Indiana)
Service	1994	1997	1996	1996
Fuel	Bit.. coal	Bit. coal/ Pet-cokes	Bit. coal/ Pet-cokes	Bit. coal/ Pet-cokes
Availability, %	≥80		≥85	≥70
Gas turbine power, MW_e	156	182	192	192
Steam turb. power, MW_e	128	135	120	105
Internal load, MW_e	31	35	60	36
Net capacity, MW_e	253	298	252	261
Net effic.,%	43.2	45.0	39.1	41.9
Coal use, t/day	2,000	2,175	2,270	2,300
SO_2, g/kWh	0.20	0.07	< 0.61	0.49
DeSOx, %	> 99	99,9	> 98	> 98
NO_x@15%O_2, g/kWh (ppmv)	0.32 (<10)	0.40 (<10)	0.24 (15)	0.49 (25)
PM emissions, g/kWh	0.005	0.02	< 0.02	< 0.05

COSTS – In the last few years, the investment cost of the **SCPC plants** increased rapidly due to high prices of steel, other materials, and equipment. Around the year 2000, the specific investment cost was approximately $1500/kW$_e$ (2008 US$). In 2008, the investment cost of state-of-the-art SCPC power plants was approximately $2200/kW$_e$ (Internet source 2). As the SCPC is a mature technology, its investment cost may decrease moderately based on technology learning. The following costs are predicted over the next two decades: $2200/kW$_e$ in 2010 (based on current experience), $2000/kW$_e$ in 2020, and $1800/kW$_e$ in 2030 (based on learning effects). It should be said that the current global economic crisis is resulting in significantly lower material prices and lower demand for new capacity. This may result, in turn, in lower investment costs and prices of power technologies.

If compared to pulverised coal, the investment cost of **coal-based IGCC plants** is high, i.e. $3700/kW$_e$ (Sears, 2007 and 2008; Power Engineering, 2009). The figure refers to the 632 MW$_e$ IGCC plant in Edwardsport, Indiana. Technological learning is expected to have a more important impact on future IGCC investment costs. Projections suggest a decline from some $3700/kW$_e$ in 2010 (70% more than PC power) to $2800/kW$_e$ in 2020 (40% more than PC power) and to $2200/kW$_e$ in 2030 (20–25% more than PC power). Technology learning effects rely on the future availability of high-capacity gasifiers, more efficient gas cleaning systems, and high-efficiency gas turbines. The operation and maintenance (O&M) cost (expressed in $/kW$_e$ per year) is estimated at 4% of the investment cost per year for both SCPC and IGCC plants. For (U-)SCPC plants, the O&M cost is estimated at $88/kW$_e$ per year in 2010, $80/kW$_e$ in 2020, and $72/kW$_e$ in 2030, while for IGCC plants, the O&M cost is estimated at $148/kW$_e$ per year in 2010, $112/kW$_e$ in 2020, and $88/kW$_e$ in 2030. Projected figures (2015) of the incremental levelised cost of electricity for pulverised coal power plants as a function of the CO_2 cost, are given in Table 4.

POTENTIAL & BARRIERS – There are a number of competing technologies and potential barriers for coal-fired power. They relate to either coal-fired power or – more specifically – SCPC and IGCC power plants. In general, coal-fired power plants have to compete with other base-load power technologies, notably nuclear and gas-fired power. Renewable technologies also grow fast and their impact on electricity generation has to be taken into account. Competition with nuclear power largely depends on nuclear licensing and social acceptance issues. If these issues are solved, then nuclear power may be an economic competitor for coal-fired power as nuclear has in general lower variable costs (e.g. fuel). If compared to gas-fired power, coal plants generally have lower fuel costs per kWh and therefore dispatching priority over gas-fired power. New coal-fired power plants may also be favoured over gas-fired power in terms of supply security as natural gas prices are higher and more volatile than coal prices. In addition, in some regions, gas supply relies significantly on pipelines. In terms of dispatching priority, existing low-efficiency coal-fired plants are ranked lower than new, highly-efficient plants, that are obviously less flexible with respect to load variations. As a consequence, operation of existing low-efficiency plants may be stopped when the electricity demand is low (e.g. the weekend). In the industrialised countries, the increasing share of renewables driven by incentives and promotion policies may cause delay or cancellation of coal-fired plants. Some renewable technologies may be affected by intermittency issues (e.g. wind, photovoltaics), but geothermal power, biomass-fired power, and concentrating solar power (CSP) with thermal storage may also have attractive characteristics for base-load service. Utilities analyse and exploit the synergies between renewable and fossil-based power generation (including combined heat and power) as they may result in reliability and supply security advantages as well as in cost and environmental benefits.

Table 4 - Technical parameters for SCPC and IGCC plants (Sources: Seebregts&Daniëls, 2008; KEMA, 2007; Sears, 2007-2008; EPRI, 2007; Power Eng. 2009)

Plant Parameters	EOn Maasvlakte Netherlands	Edwardsport, Indiana - USA
Type of plant	SCPC	IGCC
In service	2012	2012
Fuel	Bitum.coal	Bitum. coal
Availability, %	91	85
Turbine power, MW$_e$	1,100	795
Internal load, MW$_e$	45	163
Net capacity, MW$_e$	1,055	632
Net efficiency, %	46.0	44.0
Coal use, t/day	7,350	
SO_2 emissions, mg/Nm^3 (g/kWh)	40 (0.11)	NA (0.05)
DeSOx, %	98	99+
NO_x SCR@15%O_2, mg/Nm^3 (g/kWh)	65 (0.18)	NA (0.07)
PM emissions mg/Nm^3, (g/kWh)	3 (0.008)	NA (0.026)

In many countries, **biomass co-firing** in coal-fired power plants is already common practice. In existing coal-fired power plants, biomass may be co-fired with coal up to 10–20% (in energy content), with no significant impact on plant operation. In general, the efficiency of biomass combustion can be 10 percentage points lower than efficiency of coal combustion at the same installation, but the efficiency of biomass co-firing in large-scale coal plants is higher (35%–45%) than the efficiency of biomass-dedicated plants (IEA, 2007). Higher percentages of biomass co-firing are technically achievable by investment in supply systems and burners. Co-firing investment costs for new coal-fired power plants may be relatively modest. Biomass may also be used in coal-based IGCC power plants. Biomass co-firing may also reduce SO_2 emissions of coal-fired power while NO_x emissions do not change significantly.

In the near future, the **price of CO_2** may be a barrier to coal-fired power. Today's prices are low and do not preclude new coal-based capacity. However, uncertainty about future prices of fuels (coal and natural gas) and CO_2 make it difficult to identify clear investment strategies. To comply with the Emissions Trading

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System (ETS) and more demanding emission regulations, in the industrialised regions electric utilities will be considering the implementation of CO_2 capture and storage (CCS) systems as soon as this technology becomes mature enough to enter the market. Because CCS is expected to increase the investment cost and to reduce the plant efficiency considerably, it will become commercially affordable only under clear and stable emissions mitigation policies and high CO_2 prices. As for non-greenhouse gas emissions, modern coal-fired power plants have very low emission levels. Nevertheless, hazardous air emissions such as mercury must be carefully monitored and controlled (Internet Source 3). The use of NOx selective catalytic reduction (SCR) systems depends on national or regional environmental regulations and may be mandatory in some countries. With regard to **IGCC** plants, their performance (efficiency and SO_2 and NO_x emissions) compare favourably with SCPC power plants, but the investment costs remain high. If Governments do not provide financial incentives, only large utilities and power companies may bear the cost of demonstrating IGCC with a view to its future benefits including potential for more efficient and less expensive CO_2 capture and storage (CCS).

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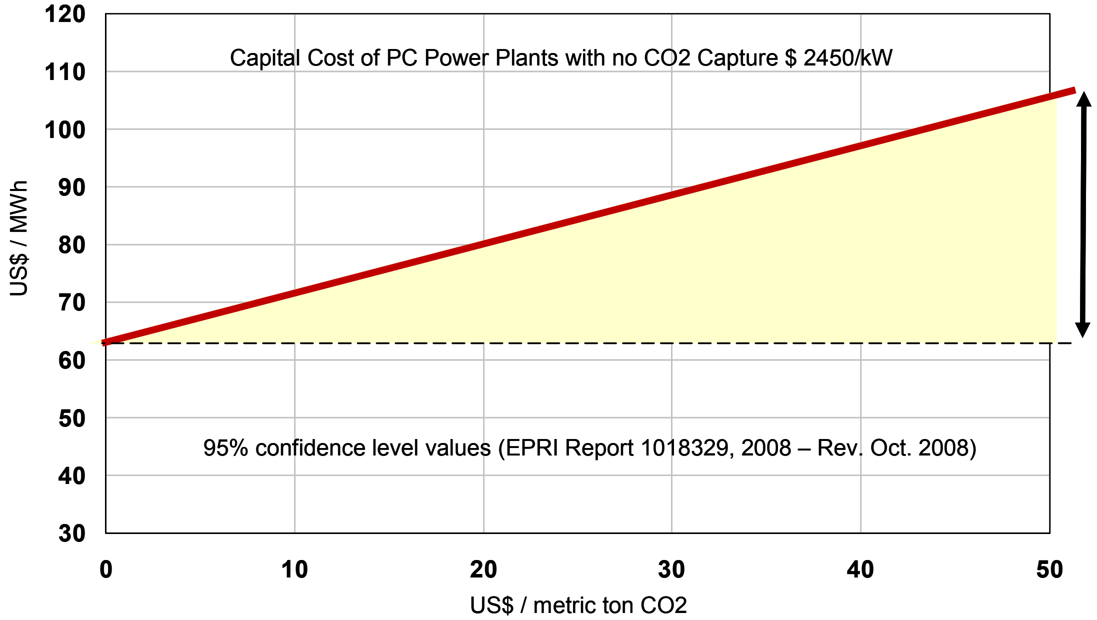
Table 5 – Summary Table - Key Data and Figures for Coal-based Power Technology

Technical Performance	Typical current international figures	
Energy input	Hard coal or lignite; possible biomass co-firing up to 10–20% of energy	
Output	Electricity	
Technologies	(Ultra)supercritical plants (U)SCPC	IGCC
Efficiency, %	46%	46%
Construction time, months	Minimum 42; Typical 48; Maximum 54	
Technical lifetime, yr	40	
Load (capacity) factor, %	Typical 75–85; Maximum 90	
Max. (plant) availability, %	92	
Typical (capacity) size, MW_e	600–1100	250–1200
Installed (existing) capacity, GW_e	1,260	1
Environmental Impact		
CO_2 and other GHG emissions, kg/MWh	730–850	700–750 (new IGCC plant)
SO_2, g/MWh	110–250	50
NO_x, g/MWh	180–800	70
Particulates, g/MWh	8–25	5–25
Solid waste (fly ash), kg/MWh	60–70	60–70
By-products	Gypsum	Sulphur
Costs		
Investment cost, including interest during construction, $/kW (PC / IGCC)	2000 – 2500; Typical 2200 (2010)	3500 – 4000; Typical 3700 (2010)
O&M cost (fixed and variable), $/kW/a	88	148
Fuel cost, $/MWh	15–25	15–25
Economic lifetime, yr	25	
Interest rate, %	10	
Total production cost, $/MWh (PC / IGCC)	60 – 70 / Typical 65	90 – 100; Typical 95
Market share	40% of global electricity output	Currently negligible

Projected Levelized Cost of Electricity for Pulverized Coal Combustion vs. Cost of CO2 - 2015 (US$ Dec. 2007)



Data Projections	2010		2020		2030		
Technology	(U)SCPC	IGCC	(U)SCPC	IGCC	SC(USC)	IGCC	
Net Efficiency (LHV)	46%	(46)	50%	52%	50%	52%	
Investment cost, including interest during construction, $/kW (PC / IGCC)	2200	3700	2000	2800	1800	2200	
Total production cost, $/MWh	65	95	62.5	75	60	65	
Market share, % global electricity output	35		30 – 35		25 – 35		

Please send comments to Paul Lako, Author (lako@ecn.nl), and to
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