MANAGEMENT FRAMEWORK FOR SELECTION OF CLEAN COAL TECHNOLOGIES FOR POWER PLANTS IN PAKISTAN USING WORLD BANK GUIDELINES

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Head of Department	Dated	Dean / Commandant	Dated

DEDICATED

TO

MY PARENTS

WHOSE PRAYERS AND GUIDANCE ARE ESSENCE OF MY LIFE

ABSTRACT

Over the next two decades, the world will become increasingly dependent on electricity to meet its energy needs. Electricity is expected to remain the fastest growing form of end use energy worldwide through year 2030, as it has been over the past several decades. World net electricity generation will nearly double, from 17.3 trillion kwh in 2005 to 33.3 trillion kwh in year 2030. About 1.6 billion people or 25% of the world population is lacking access to electricity. It is essential that steps are taken to increase access to affordable energy supplies, while minimizing environmental impacts. Rapidly depleting reserves of oil and gas has diverted the world attention towards the coal fired power generation.

Pakistan is amongst the countries with lowest per capita energy availability and consumption. The nation is also amongst the most vulnerable economies on the energy security matrix because of high import dependence, inefficient GDP conversion and high price sensitivity. Pakistan's per capita per year energy use is 12.7 MMBTU compared with 65 MMBTU/capita/year for the world. Pakistan's energy mix is significantly different from that of the world comprising 48.4% gas, 30% oil mainly imported, 12.7% hydel, 7.4% coal and 1% nuclear compared with world average of 24% gas, 36% oil, 28% coal, and 6% each for hydro and nuclear.

Pakistan has the 6th largest coal reserves in the world equivalent to 185.5 billion tones of reserves of coal with heating value ranging from 5219Btu/lb to 15800 Btu/lb. Despite the huge coal reserves, the share of coal in Pakistan's power generation is only 0.1%. The Government of Pakistan asserts that exploitation of half of coal reserves in Pakistan is sufficient for generating 100,000MW electricity for 30 years. The government has focused its attention to use these reserves for power generation for which it has issued Letters of Interests (LOIs) to 3 companies for installing power plants each having 1550MW capacity. It has further planned to increase the coal based power generation capacity to 19900MW by 2030.

Government of Pakistan's approach to increase the share of coal in its primary energy supplies and use of coal as a fuel for power generation is in line with long wave penetration theory of new fuels which foresees that coal will rebound from 2015 and once again will become one of the dominant sources of energy approaching 50% by 2100.

Moreover indigenous coal can provide the second cheapest power tarrif in Pakistan after hydel, which certainly gives it an edge over the other energy sources.

Although Pakistan's environmental regulation does limit the emissions from a coal fired power plant, the concerned authorities possesses limited knowledge for achieving it. The conventional approach will a) use the available coal resources for power production at sub-optimal efficiencies and b) add considerable amounts of green house gases to the environment and cause environmental degradation. The research suggests that the use of clean coal technologies at pre-combustion, combustion and post combustion stages of power plants will not only save precious coal reserves but will also help GOP to remain within the limits prescribed by the treaties like Kyoto protocol or any other strict future legislation. The World Bank sponsored Fast Track Technology Selection Model (FTTSM) which involves the evaluation and optimization of large number of technical, environmental and economic parameters has been improved and enhanced to make a suitable framework of clean-coal technology selection for power sector of Pakistan.

ACKNOWLEDGEMENTS

Thesis writing is a long struggle and cannot be completed in isolation. Researcher has to get input from others that enable him to reach the destination. One requires the right technical advice as well as encouragement at each step. Through this page, I would like to express my gratitude to few persons.

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Maj Aamir Akram Kundi

Acronyms and Abbreviations

AFBC	Atmospheric Fluidised Bed Combustion
BP	British Petroleum
CO_2	Carbon Dioxide
CCS	Carbon Dioxde Capture and Storage
CCT	Clean Coal Technology
EIA	Energy Information Administration
ESP	Electrostatic Precipitator
EPC	Electricity Production Cost
FGD	Flue Gas Desulphurization
FTTSM	Fast Track Technology Selection Model
GOP	Government of Pakistan
GHG	Greenhouse Gas
IGCC	Integrated Gasification Combined Cycle
IEA	International Energy Agency
IEO	International Energy Outlook
IPCC	Intergovernmental Panel on Climate Change
kwh	Kilowatt Hours
MTDF	Medium Term Development Framework
Mwh	Megawatt Hours
M Tonnes	Million Tonnes
NOx	Nitrogen Oxides
N_2O	Nitrous Oxide
O&M	Operation and Maintenance
OECD	Organization for Economic Cooperation and Development
PCC	Pulverized Coal Combustion
PFBC	Pressurized Fluidised Bed Combustion
SCR	Selective Catalytic Reduction
SNCR	Selective Non Catalytic Reduction
SO_2	Sulphur Dioxide

TOE	Tonnes of Oil Equivalent
US $ 123M	123 Million United States Dollars
UNFCCC	United Nations Forum Convention for Climate Change
US DOE	United States Department of Energy
WBFTTSM	World Bank Fast Track Technology Selection Model
WCI	World Coal Institute

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CHAPTER 1
INTRODUCTION

1.1 Background

In the developing countries, strong economic growth resulted in growing demand for electricity. Increases in per capita income lead to improved standards of living, rising consumer demand for lighting and appliances and growing requirements for electricity in the industrial sector. Over the next two decades, the world will become increasingly dependent on electricity to meet its energy needs. Electricity is expected to remain the fastest growing form of end use energy worldwide through 2030, as it has been over the past several decades. Nearly one-half of the projected increase in energy consumption worldwide from 2005 to 2030 is attributed to electricity generation. Since 1990, growth in net generation has outpaced the growth in total energy consumption (2.9 and 1.9 % per year, respectively), and generation is expected to increase at an average annual rate of 2.6 % through 2030 as the growth in demand for electricity continues to outpace growth in total energy use. World net electricity generation will nearly double in 2030 [1]. With 25% of the world population lacking access to electricity, it is essential that steps are taken to increase access to affordable energy supplies, while minimizing environmental impacts.

World is facing the challenge of sustainable energy security in the 21^{st} century. Among the fossil fuels, oil and gas reserves are depleting rapidly and with current consumption will last for another 30 and 70 years respectively. Coal has still enough reserves to serve the world for 200 years before exhaustion. Coal is the cheapest and geographically most evenly distributed fuel in the world. It has remained the fastest growing fuel for the last 5 years and will remain dominant fossil fuel in the 21^{st} century. Coal has a share of 28% in the world energy mix and is forecasted to be at 25% in 2030 [2]. Besides others, the most important use of coal is the electricity generation. Currently 40% of the world's power generation needs are met through coal and will increase to 46% by 2030(British petroleum 2008). In countries like China, India and USA, having large coal reserves, this figure is higher i.e 78%, 68.5% and 50% respectively. The 3.1% projected annual growth rate for coal fired electricity generation worldwide is exceeded only by the 3.7% growth rate projected for natural-gas-fired generation. Non-OECD Asia led by China and India has the fastest projected growth in electric power generation worldwide, averaging 4.9 % per year from 2005 to 2030. The nations of non-OECD Asia, which includes Pakistan, are expected to see continued robust economic growth, with corresponding increases in demand for electricity in the building sector, as well as for industrial sector uses. Total electricity generation in non-OECD Asia is expected to double over the first decade of the projection, from 3.9 trillion kwh in 2005 to 7.8 trillion kwh in 2015. In 2030, total net generation in non-OECD Asia is projected to12.9 trillion kwh (US DOE 2008). Coal accounts for two-thirds of the electricity generation in non-OECD Asia dominated by generation in China and India.

The biggest challenge coal is facing is the global climate change. These include the release of pollutants, such as CO_2, oxides of sulphur and nitrogen (SOx and NOx), and particulate and trace elements, such as mercury. More recently GHG emissions, including CO_2 and methane, have become a global concern. The release of GHG emissions into the atmosphere from human activities is linked to climate change – this includes emissions from the use of fossil fuels, land-use, deforestation and agriculture. Growth based mainly on fossil fuels is by no means assured to be feasible, at least at the current level of fossil fuel price, and if feasible would lead to considerable increases in greenhouse gas emissions [3]. Coal is the most carbon intensive and the biggest emitter of CO_2 in the atmosphere among the fossil fuels. Coal's share of world carbon dioxide emissions grew from 39 % in 1990 to 41 % in 2005 and is projected to increase to 44 % in 2030. Due to their substantial use of fossil fuel-derived energy and influence on technology development, large industrialized nations are key to addressing the problem. The US emits more energy-related carbon dioxide per capita than any other OECD country [4], with current trends suggesting that emissions could rise 54% above 1990 levels by 2020 [5]. Australia, a major producer and user of coal, has the highest per capita greenhouse gas emissions in the industrialized world [6].

The issue of climate change contribution by coal is being tackled by the use of clean coal technologies. They offer use of coal in an environment friendly way and reduces the emissions to varying extents. The emissions can be reduced in three basic ways. Firstly; by using washed coal for combustion. Secondly; by increasing the efficiency of the power plant by using advanced technologies like PC supercritical, ultra supercritical and IGCC. And lastly; by the use of equipment for removal of SO_2, nitrogen oxides and particulates.

Pakistan has the 6th largest coal reserves in the world equivalent to 185.5 billion tones of reserves of coal, out of which almost 95% lies in Tharparkar desert of Sind [7]. Despite the huge coal reserves, the share of coal in Pakistan's power generation is less than 1%. GOP has planned to increase the coal based power generation capacity to 19900 MW by 2030 [8].

Pakistan is currently generating a total of 98,384 Gwh of electricity per year, 65% of which comes through the use of fossil fuels [9]. As per UN statistics division, Pakistan is the 30th biggest CO_2 emitter country in the world through the use of fossil fuels. Although Pakistan's environmental regulation provides the emission limits from coal fired power plants, however, the understanding of achieving it through the use of clean coal technologies is very limited in the government sector. Moreover the growing concern in the world about the use of coal indicates that there is going to be much stringent emission standards worldwide in the near future. Pakistan's plan to increase the use of coal for power generation and ratification of treaties like Kyoto protocol further necessitates the use of clean coal technologies for the power plants. Moreover in this context , the case of Pakistan , where 65% of the total electricity generation depends upon fossil fuels(coal, gas, oil), demands a rational base of making an assessment of the existing electricity policy [10].

1.2 World Energy Situation

Energy is vital to human development. It is impossible to operate a factory, to run a shop, deliver goods to consumers, or grow crops, for example, without some form of energy. Access to modern energy services not only contributes to economic growth and household incomes but also to the improved quality of life that comes with better education and health services. Unless access to energy is improved, many of the world's poorest countries will remain trapped in a circle of poverty, social instability and under development. The global energy system faces many challenges in this century. It will have to continue to supply secure and affordable energy in the face of growing demand. At the same time society expects cleaner energy and less pollution, with an increasing emphasis on environmental sustainability. Advancements in technology is the only way the human race will discover sustainable, renewable, safe, low-cost, and secure energy sources. There will be no single technology, but rather a combination of many technologies that collectively meet the globe's energy needs [11]. Improvements in energy efficiency have been suggested as both a measure of progress towards sustainable development and as a means of achieving sustainability [12]. The proportion of world primary energy supplies by fuel in 2006 is shown in figure 1.1.

Over the next 30 years it is estimated that global energy demand will increase by almost 60% [13]. Two thirds of the increase will come from developing countries – by 2030 they will account for almost half of total energy demand. However, many of the world's poorest people will still be deprived of modern energy in 30 years time. Electrification rates in developing countries will rise from 66% in 2002 to 78% in 2030 but the total number of people without electricity will fall only slightly, from 1.6 billion to just under 1.4 billion in 2030 due to population growth.

World coal consumption was about 6,743,786,000 short tons in 2006 [14] and is expected to increase 48% to 9.98 billion short tons by 2030 [15]. China produced 2.38 billion tons whereas India produced about 447.3 million tons of coal in 2006.

1.3 World Power Generation and Consumption 1990-2030

World net electricity generation will nearly double from 17.3 trillion kwh in 2005 to 24.4 trillion kwh in 2015 and 33.3 trillion kwh in 2030 as shown in figure 1.2. In general growth in the OECD countries is slower than in the non-OECD countries because electricity markets of the former are well established and consuming patterns are mature whereas in the later a large amount of demand remains unsatisfied. IEA OECD countries excluding non-OECD Europe and Eurasia, a total of about 1.6 billion people, do not yet have access to electricity [16]. With the strong economic growth projected for the developing non-OECD nations, substantial increase in electricity generation will be needed to meet the demand in the residential, commercial and industrial sectors. Although the non-OECD nations consumed 24% less electricity than the OECD nations in 2005, total non-OECD electricity generation in 2030 is projected to exceed OECD generation by 46% as shown in figure 1.2. In the developing countries, strong economic growth translates to growing demand for electricity. Increases in per capita income lead to improved standards of living, rising consumer demand for lighting and appliances and growing requirements for electricity in the industrial sector. As a result, total non-OECD electricity generation increases by an average of 4.0% per year as compared with a projected average annual growth rate in OECD electricity generation of 1.3% from 2005 to 2030.

1.3.1 World Electricity Generation by Energy Source

The mix of primary fuels used to generate electricity has changed significantly over the past two decades all over the world. Coal has continued to be the most widely used fuel for electricity generation, although generation from nuclear power increased rapidly from the 1970s through the 1980s, and natural-gas-fired generation grew rapidly in the 1980s and 1990s. The use of oil for electricity generation has been declining since the mid-1970s, when the oil embargo by Arab producers in 1973-1974 and the Iranian Revolution in 1979 produced oil price shocks. High world oil prices which have moved upward in every year since 2003 in combination with concerns about the environmental consequences of greenhouse gas emissions are raising renewed interest in nuclear power and renewable energy sources as alternatives to the use of coal and natural gas for electric power generation. Projections of future coal use are particularly sensitive to assumptions about future policies that might be adopted to mitigate greenhouse gas emissions.

1.3.2 World Coal Fired Power Generation

Coal fuels almost 40% of the world's electricity and in many countries this figure is much higher. For example Australia, China, India and South Africa, use their large indigenous coal reserves to generate most of their electricity as shown in table 1.1. With 1.6 billion people or 25% of the world population does not has access to electricity, it is essential that steps are taken to increase access to affordable energy supplies while minimizing environmental impacts.

For many countries, particularly those with large indigenous reserves such as China and India, this will mean continuing to use coal for power generation. Over the past 20 years, China has employed 700 million people in the electricity system. The country is now 99% electrified with around 80% of China's electricity fueled by coal. China is currently constructing the equivalent of two, 500MW coal fired power plants each week [17]. By 2030, India and China are predicted to account for more than 50% of installed coal power capacity globally [18].The USA consumes about 14% of the world total coal, using 90% of it for generation of electricity.

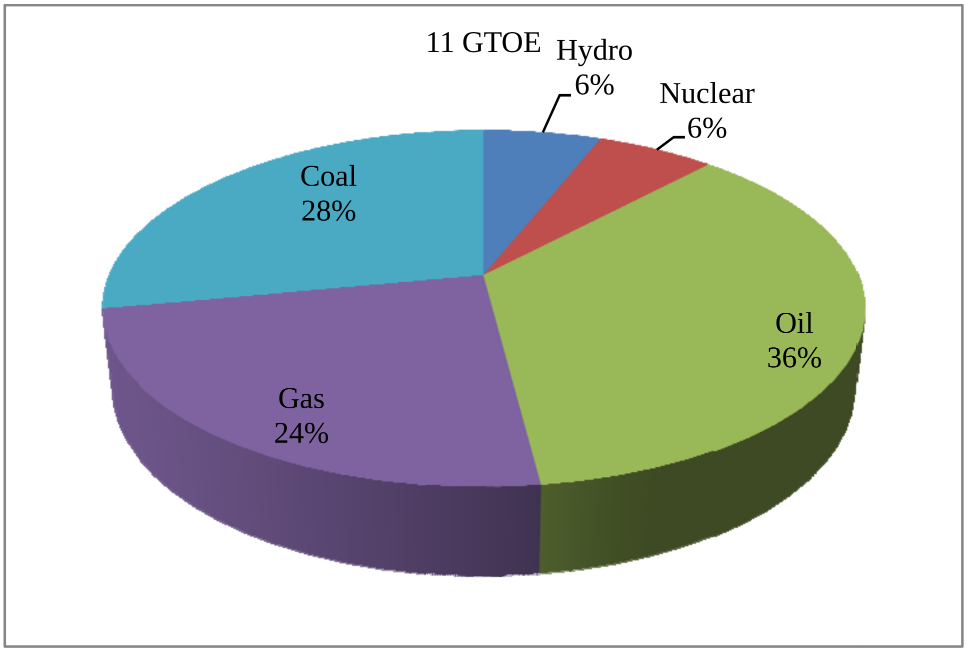

Figure 1.1 World Energy Mix

Source: Data extracted from World Energy Outlook 2006, EIA US DOE

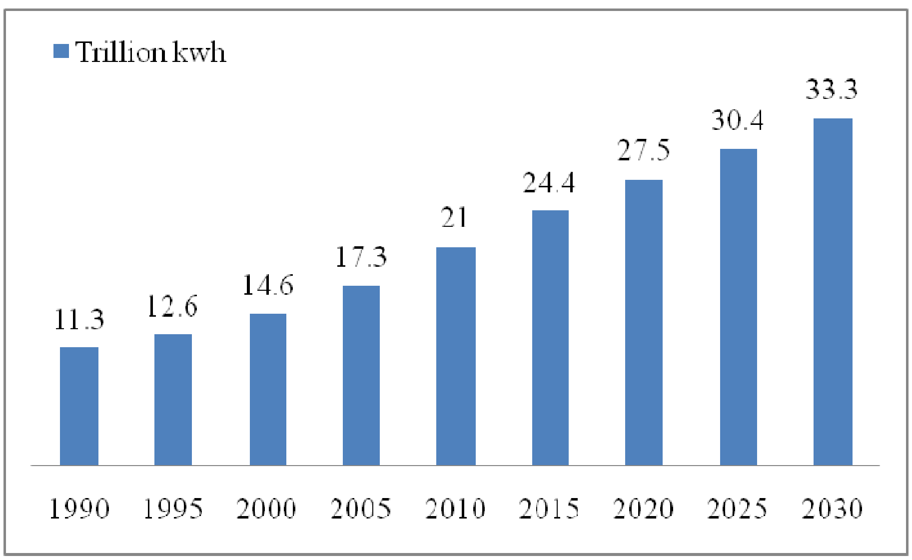

Figure1.2. World Net Electric Power Generation 1990-2030

Source: Data extracted from World Energy Outlook 2008,US DOE

As per IEO 2008, although natural gas is the fastest growing energy source for electricity generation worldwide, coal still provides the largest share of the energy used for electric power production as shown in figure 1.3. In 2005 coal fired generation accounted for 40% of world electricity supply whereas in 2030 its share is projected to be 46%. Sustained high prices for oil and natural gas make coal fired generation more attractive economically, particularly in nations that are rich in coal resources like China, India and the United States. The 3.1% projected annual growth rate for coal fired electricity generation worldwide is exceeded only by the 3.7% growth rate projected for natural gas fired generation. However, the outlook for coal-fired generation could be altered substantially by international agreements to reduce greenhouse gas emissions. The electric power sector offers some of the most cost-effective opportunities for reducing carbon dioxide emissions in many countries.

Table 1.1 Coal in World Electricity Generation

S.Africa	94%	Israel	71%	Czech Rep	62%
Poland	93%	Kazakhstan	70%	Greece	55%
Australia	76%	India	68%	USA	49%
PR China	81%	Morocco	57%	Germany	49%

Source: IEA 2009

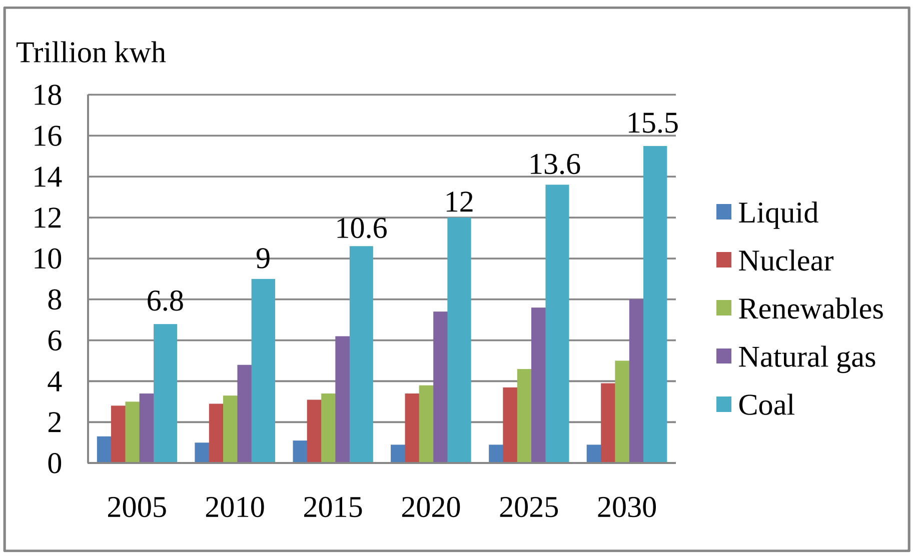

Fig. 1.3 World Electricity Generation by Fuel, 2005-30

Source: US DOE, 2008

1.3.3 Power Generation in Non-OECD Asia

Non-OECD Asia, led by China and India, has the fastest projected growth in electric power generation worldwide, averaging 4.9% per year from 2005 to 2030. The nations of non-OECD Asia are expected to see continued robust economic growth with corresponding increases in demand for electricity in the building and industrial sectors. As shown in figure 1.4, total electricity generation in non-OECD Asia is predicted to double from 3.9 trillion kwh in 2005 to 7.8 trillion kwh in 2015. In 2030, total net generation in non-OECD Asia will be 12.9 trillion kwh. Clearly, coal is used for two third of the electricity generation in non-OECD Asia, dominated by generation in China and India. Both countries already rely heavily on coal to produce electric power. In 2005, coal's share of generation was an estimated 77 % in China and 74 % in India. Despite efforts to diversify the fuel mix away from coal, it is likely that both countries will continue to use coal as the main fuel for electricity generation. In the IEO 2008, the coal share of electricity generation declines to 65 % in 2030 in India but continues rising to 84 % in China.

1.4 Pakistan Energy Overview

Pakistan's energy mix is 0.54% of the world's and both have different ratios of fuels. The fuel wise comparison is given in table 1.2 and shown in figure 1.5. Pakistan is a 'Gas Country' because half of its energy requirements are met through the use of natural gas. Pakistan's energy requirements are growing while supplies are not keeping up. The result is net shortage of energy supplies. It is reported that load shedding has caused a loss of approximately 6% of the value added in the manufacturing sector [19]. Pakistan's total energy requirements are going to increase to 110 mtoe by 2015 and to 198 mtoe by 2025 creating a net deficit of 50 and 122 mtoe in FY 2015 and FY 2025 respectively. Pakistan currently meets only 19.9% of its energy demand from indigenous production although it has considerable oil, gas and coal reserves but require exploitation. Reserve to production ratio for oil is 13, for gas 22 and for coal it is 720 [20].A brief detail of each energy resource is as follows:

1.4.1 Oil

"Historically, Pakistan is dependent on oil imports. The crude oil import for the year 2006-07 was about 8.2 million tones and that of petroleum products import was

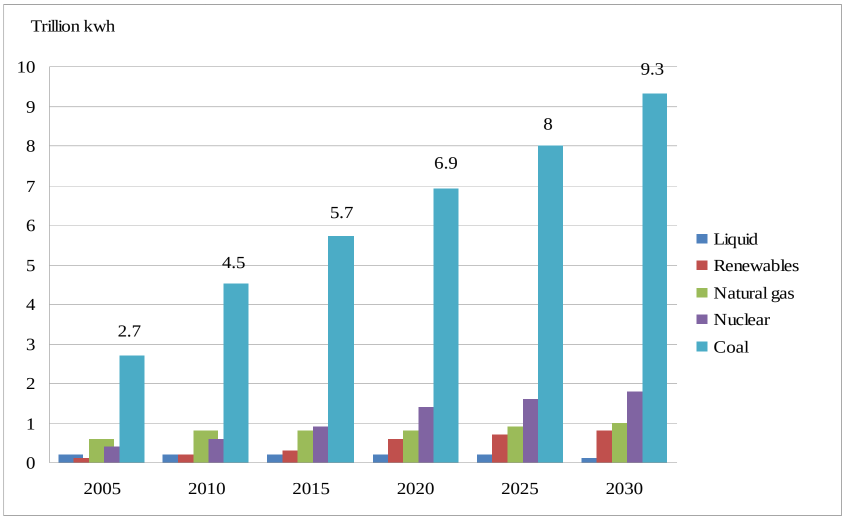

Fig. 1.4 Net Electricity Generation in Non-OECD Asia by Fuel, 2005-30

Source: Data extracted from IEO 2008, US DOE

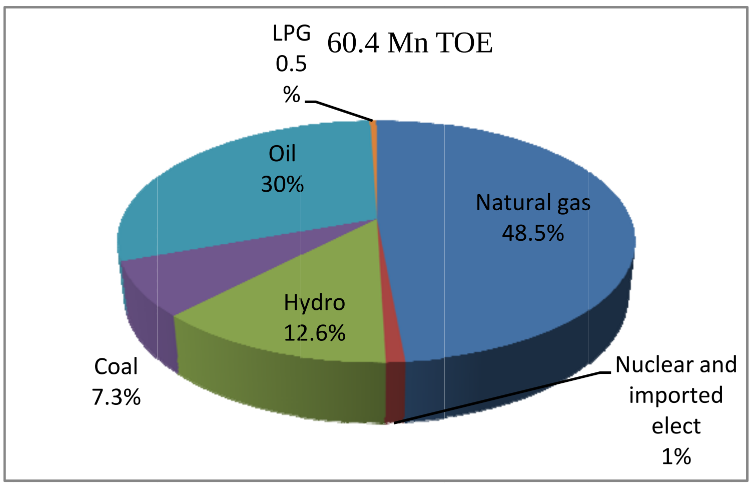

Figure 1.5 Pakistan Primary Energy Mix 2006-07

Source: Data extracted from Official Website Ministry of Petroleum and Natural Resources, GOP

Table1.2. Energy Mix: World vs Pakistan

Fuel	World(%)	Pakistan(%)
Oil	36	30.0
Gas	24	49.0
Coal	28	7.4
Hydro	6	12.6
Nuclear	6	1.0

Source: Data extracted from Pakistan energy year book 2006

8.3 million tonnes. The total annual import bill for the year 2006-07 was US$ 7,448 million. Annual oil refining capacity is 12.87 million tonnes.

Pakistan has an interesting Geo-dynamic history of large and prospective basin, both onshore and offshore, with sedimentary area of 827,268 sq. km. So far about 937 million barrels crude oil reserves have been discovered of which 583 million barrels have already been produced. A Prognostic potential of total endowment of hydrocarbons has been estimated as 27 billion barrels of oil and 282 trillion cubic feet of gas. Uptil now over 689 exploratory wells have been drilled by various national and international exploration and production companies, resulting in over 202 oil and gas discoveries. Indigenous production of crude oil during the year 2006-07 was 67,438 barrels per day. Sectoral oil consumption during the year 2006-07 was: Power 40%, transport 47.4%, agriculture 0.6%, industry 9.5%, domestic 0.6% and government 1.9%" [21].

1.4.2 Natural Gas

"Pakistan is among the most gas dependent economies of the world. Natural gas was first discovered in 1952 at Sui in Balochistan province which proved a most significant and largest gas reservoir. After successful exploration and extraction, it was brought to service in 1955. This major discovery at Sui followed a number of medium and small size gas fields in other part of the country. So far about 54 trillion cubic feet of gas reserves have been discovered of which 21.6 trillion cubic feet have already been produced. Natural gas production during 2006-07 was about 3.9 billion cubic feet per day. Pakistan has well developed and integrated infrastructure of transporting, distributing and utilizing natural gas with 9,916 km transmission and 81,698 km of distribution and service lines network developed progressively over 50 years. Natural gas sectoral consumption during 2006-07 was: power 35.5%, fertilizer 15.9%, cement industry 1.2%, general industry 25.0%, domestic 15.2%, commercial 2.6% and transport CNG 4.6%" (Ministry of water and power, GOP).

1.4.3 CNG as Transport Fuel

"Pakistan started Compressed Natural Gas (CNG) as a transport fuel program through establishment of research and demonstration CNG refueling stations by Hydrocarbon Development Institute of Pakistan (HDIP) at Karachi in 1982 and at Islamabad 1989. CNG has emerged as an acceptable vehicular fuel in place of oil.

Pakistan is second largest user of CNG in the world after Argentina. Large diesel vehicles like buses and trucks, being the major consumer of high speed diesel, are now being substituted by CNG for economic and environmental reasons” (Ministry of water and power,GOP). .

1.4.4 Coal

“In view of large indigenous reserves, Pakistan hopes to use coal as an alternative to imported oil. At present coal constitute only 7.3% of our primary energy supplies. Total coal resource potential of Pakistan is estimated to be around 185 billion tonnes, out of which about 175 billion tonnes are located in Thar desert, Sindh province which is the 5th largest single coal field in the world. The quality/rank of coal ranges from sub-bituminous to lignite. The Thar coal is lignite B but it is low in sulphur and ash content. Historically the coal consumption in Pakistan has come down with increase in gas consumption. There is a great scope for large scale utilization of coal in power generation. At present only one power plant of 150 MW capacity using Lakhra coal is in operation in Sindh province. Coal consumption during 2006-07 is shown in figure 1.6: Brick kilns 41.5%, Cement and other industry 52.5%, Domestic 0.01%, Power 2.1%, Coke use 3.9%.

Presently the cement and other industry is the biggest user of coal, consuming about 4.1 million tonnes annually. Coal briquettes could also find a ready market in domestic sector. An extensive campaign to utilize huge indigenous coal resource to meet ever-increasing national energy needs is on the way” (Ministry of water and power, GOP).

1.5 Pakistan Coal Reserves

“Allah has blessed Pakistan with immense coal resources of more than 185.5 billion tones with Thar alone 175 billion tones, and if half of these resources are exploited properly, it would be sufficient for generating 100,000 MW of electricity for 30 years. Energy contents of these resources are more then the energy contents of Saudi Arabia and Iran's joint oil resources. Coal reserves, together with heating values of all the four provinces are given in table 1.3

The presence of coal deposits in Pakistan was known before independence, but its economic value was highlighted in 1980 when large reserves of coal were discovered in the Lakhra and Sonda areas of Sindh province. The discovery of another

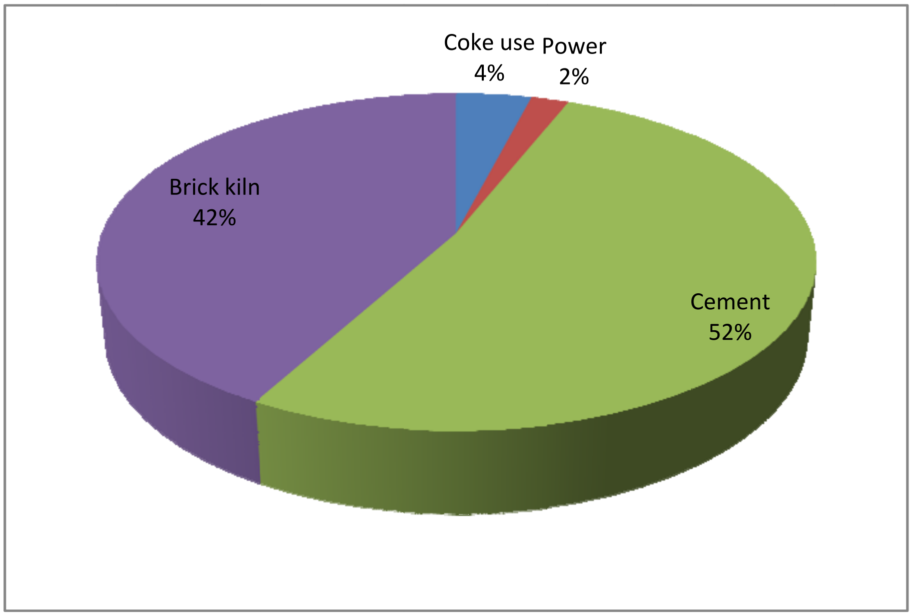

Figure 1.6 Coal Consumption by Sector in Pakistan

Source: Data extracted from Pakistan energy book 2007

Table 1.3 Pakistan Coal Reserves

Province	Resources(M Tons)	Heating value(Btu/lb)
Sind	184,623	5219-13,555
Balochistan	217	9637-15,499
Punjab	235	9472-15,801
NWFP	235	9386-14,217
Total	185,175 M Tonnes	

Source: “Pakistan Coal Power Generation Potential”, February 2008:PPIB.

huge deposits of 175.5 billion tonnes in an area of 10,000 square km in Tharparkar District of Sindh has provided a quantum increase in the coal resources of Pakistan.

After this discovery, Pakistan is now the 6th richest nation of the world in respect of coal resources. Pakistan did not appear even on the list of coal rich countries before the discovery of Thar coal" (PPIB Pakistan). The details of Pakistan coal reserves are given in Table 1.4.

1.5.1 Thar Coal

"The Thar coalfield is located in the south eastern part of Sindh. The first indication of the presence of coal beneath the sands of the Thar Desert was reported while drilling water wells by the British Overseas Development Agency (ODA) in coordination with the Sindh Arid Zone Development Authority (SAZDA), in 1992. The Thar coalfield, with a resource potential of 175.5 million tonnes of coal, covers an area of 9000 sq. km. in the Tharparkar Desert. The coal bearing area is covered by stable sand dunes. In order to establish the coal resources in the selected six blocks, a total of 239 holes were drilled at one kilometer spacing. Coal resources of the six blocks are estimated at 12,778 million tones" [22], and their chemical analysis is given in table 1.5.

1.5.2 Similarities between Thar Lignite and Other Countries

"Coal mining at Thar is not a big challenge. The stripping ratio of 6:1 is comparable to several other lignite coal fields in the world. The overburden of 150m at Thar is also not uncommon. In the world coal with 200m is being mined. The overburden comprises of loose material like sand, clay and 0.2 m thick sand stone layers. Removal of this type of overburden is achievable by excavators and no specialized machinery is required. The harsh climate in summers and looseness of soil do present a challenge in transportation and ability of machinery to operate in high temperature dusty environment" (PPIB, Pakistan Thar coal power potential). Table 1.7 provides the comparison and similarities of Thar lignite with some other countries using it for power generation.

Quality and Coal Resources of Pakistan

Province/Coal Field	Seam Thickn-ess (metres)	Reserves (million tonnes)			Status	Coal Quality Proximate Analyses (in percent)					Rank ASTM Classification	Heating Value (mmmf) Btu/lb	Average Annual Production 2000-2001 (tonnes)
		Total	Meas-ured	Mineable		Moisture	Volatile Matter	Fixed Carbon	Ash	Total Sulphur			
SINDH													
Lakhra	0.3-3.3	1,328	244	146	Developed	9.7-38.1	18.3-38.6	9.8-38.2	4.3-49	1.2-14.8	ligB to SubC	5,503-9,158	1,112,406
Sonda-Thatta	0.3.-1.5	3,700	60	36	Non-Developed	22.6-48.0	16.1-36.9	8.9-31.6	2.7-52.0	0.2-15.0	SubC to hvBb	8,878-13,555	-
Jherruk	0.3-6.2	1,823	106	64	Non-Developed						SubC to hvCb	8,800-12,846	-
Ongar	0.3-1.5	312	18	11	Non-Developed	} 9.0-39.5	20.0-44.2	15.0-58.8	5.0-39.0	0.4-7.7	LigB to SubA	5,219-11,172	-
Indus East	0.3-2.5	1,777	51	31	Non-Developed						LigA to SubC	7,782-8,660	-
Meting-Jhumpir	0.3-1.0	161	10	6	Developed	26.6-36.6	25.2-34.0	24.1-32.2	8.2-16.8	2.9-5.1	LigA to SubC	7,734-8,612	-
Badin	0.55-3.1	16	3	2	Non-Developed						SubA to hvCb	11,415-11,521	-
Thar	0.2-22.8	175,506	2,700	1,620	Non-Developed	29.6-55.5	23.1-36.6	14.2-34.0	2.9-11.5	0.4-2.9	LigB to SubA	6,244-11,054	-
BALOCHISTAN													
Khost-Shahrig-Harnai	0.3-2.3	76	13	8	Developed	1.7-11.2	9.3-45.3	25.5-43.8	9.3-34.0	3.5-9.55	SubB to hvAb	9,637-15,499	227,784
Sor Range-Deghari	0.3-1.3	50	15	9	Developed	3.9-18.9	20.7-37.5	41.0-50.8	4.9-17.2	0.6-5.5	SubA to hvBb	11,245-13,900	279,564
Duki	0.2-2.3	50	14	8	Developed	3.5-11.5	32.0-50.0	28.0-42.0	5.0-38.0	4.0-6.0	SubB to hvAb	10,131-14,164	278,518
Mach Abegum	0.6-1.3	23	9	5	Developed	7.1-12.0	34.2-43.0	32.4-41.5	9.6-20.3	3.2-7.4	SubA to hvCb	11,110-12,937	317,004
Pir Ismail Ziarat	0.4-0.7	2	2	1.2	Developed	6.3-13.2	34.6-41.0	19.3-42.5	10.3-37.5	4.0-5.5	SubA to hvVb	10,786-11,996	384,108
Chamalong-Bala Dhaka	0.3-2.0	1	1	0.6	Developed	1.1-2.9	24.9-43.5	19.4-478.1	9.1-36.5	3.0-8.5	hvCb to hvAb	12,500-14,357	NA
PUNJAB													
Salt Range	0.15-1.2	235	50	30	Developed	3.2-10.8	21.5-38.8	25.7-44.8	12.3-44.2	2.6-10.7	SubC to hvAb	9,472-15,801	221,964
Makarwal	0.3-2.0	-	5	3	Developed	2.8-6.0	31.5-48.1	34.9-44.9	6.4-30.8	2.8-6.3	SubA to hvAb	10,688-14,029	47,928
NWFP													
Hangu/Orakzai	1	82	1	0.6	Developed	0.2-2.5	16.2-33.4	21.8-49.8	5.3-43.3	1.5-9.5	SubA to hvAb	10,500-14,149	77,000
Cherat/Gulla Khel	0.3-1.2	9	0.5	0.3	Developed	0.1-7.1	14.0-31.2	37.0-76.9	6.1-39.0	1.1-3.5	SibC to hvAb	9,388-142,171	36,060
AJK													
Kotli	0.25-1.0	8	1	-	Developed	0.2-6.0	5.1-32.0	26.3-69.5	3.3-50.0	0.3-4.8	ligA to hvCB	7,336-12,338	-
TOTAL		185,174	3,303	1,982									2,982,336

hvAb =high volatile A bituminous coal　**Sub A** =Sub bituminous A coal　**Sub C** = Sub bituminous C coal　**Btu** = British Thermal Unit
hvBb =high volatile B bituminous coal　**Sub B** = Sub bituminous B coal　**lig B** = Lignite B coal　**ASTM** = American Society For Testing and Materials
hvb =high volatile C bituminous coal　**Sub B** = Sub bituminous B coal　**mmmf** = moist mineral matter free　**Kg** =kilogram

Mineable Reserves = 60 % of the proved reserves
Measured Reserves: having a high degree of geological assurance, coal lies within a radius of 0.4 km from a point of coal measurement.
Indicated Reserves: having a moderate degree of geological assurance, coal lies within a radius of 0.4 to 1.2 km. from a point of coal measurement.
Inferred Reserves: having a low degree of geological assurance, coal lies within a radius of 1.2 to 4.8 km from a point of coal measurement.
Hypothetical Resources: undiscovered coal resources and are generally extension of inferred reserves in which coal lies beyond 4.8 km from a point of coal measurement.
To convert Btu to Kcal/Kg multiply by 0.556.　To convert Kcal/Kg to Btu/lb multiply by 1.798

Source:

1. Ahmad and others, (1986), Coal Resources of Pakistan, GSP, Rec. Vol. 73
2. Kazmi and Siddiqui, (1990). Significance of the Coal Resources of Pakistan, GSP/USGS Pub.
3. Jaleel and others, (1999), Coal Resources of Sindh, Pakistan,GSP, Rec. Vol.110.
4. Javed & others (2000), Coal Resources of Eastern Salt Range, Pakistan (unpublished)

Table 1.5 Weighted Average Chemical Analysis of the Thar Coal Individaul Blocks

S No	Area	As Received values(%)					Heating Values(Btu/lb)				Volatile matter (%)
		Moisture	Ash	Volatile Matter	Fixed Carbon	Sulphur	As Received	Dry	Dry Ash Free	mmmf	Dry Ash Free
1	Block I	43.13	6.53	30.11	20.11	0.92	6,398	10,461	11,605	6,841	60.00
2	Block II	48.89	5.21	26.55	19.37	1.05	5,780	11,353	12,613	6,106	57.72
3	Block III	45.41	6.14	28.51	19.56	1.12	5,875	10,880	11,789	6,268	59.76
4	Block IV	43.24	6.56	29.04	21.13	1.20	5,971	10,723	12,111	6,413	57.67
5	Block V	38.82	8.92	38.24	28.22	1.20	4,748				
6	Block VI	38.32	7.62	36.22	20.13	1.52	10,514				

Source: “Pakistan Thar coal power generation potential” July 2008: PPIB

Table1.6. Comparison of Thar Lignite with other Countries

	Stripping Ratio(m^3:t)	Heating value (Btu/kg)	Total generation (MW)
India Neyvelli	7:1	5200	2740
Germany Rhineland	4.9:1	4514-11054	10,289
Hungary	9:1	3035	1852
Pakistan Thar	6:1	6200-11000	0

Source: Data extracted from “Pakistan coal power generation potential”, February 2008:PPIB

1.6 Power Generation Potential of Indigenous Coal Resources

"The bulk of Pakistan's indigenous coal resources lie in Sindh. The largest reserve, 175 billion tonnes of lignite coal, is located in the Thar Desert of Sindh. Thar coal is yet to be developed for mining and power generation. In addition to this, there are lignite coal reserves in Lakhra, Sonda, Indus East and other coalfields of Sindh. The Lakhra coal field is thoroughly investigated and developed. Several public and private mining companies are mining coal from Lakhra. It has been confirmed that Lakhra coal is suitable for power generation. A 150 MW FBC plant is currently being operated by WAPDA on Lakhra coal. The Sonda and other coal-fields of Sindh are yet to be investigated and developed.

In Balochistan and Punjab, coal has been continuously mined since before independence. Good quality Sub-bituminous coal is available in various coal fields of Balochistan and Punjab, which coalfields are considered suitable for power generation. Some small coal reserves are also located in NWFP and AJK, and are being mined on a small scale" (PPIB, Pakistan Thar coal power potential).On the basis of available mineable coal reserves, a tentative estimate of power generation potential and quantity of required coal is given in table 1.7.

1.7 Power Sector in Pakistan- An Overview

"Electricity plays a key role in the national growth and economic development of any country. Presently, in Pakistan only about 40% of the population has access to electricity**.** However increasing urbanization and industrialization in the country provide a great opportunity for expansion of the power sector. Pakistan, a progressive nation with a buoyant economy, is situated in one of the most important economic zones of the world and offers an excellent combination of natural and human resources for the prospective investor. Spread over almost 800,000 square kilometers, with a population of approximately 170 million, the country is located on the crossroads of Africa, Middle East and Central Asia.

The generation, transmission, distribution and retail supply of electricity in Pakistan is presently undertaken by two vertically integrated public sector utilities, with significant contribution to generation from various private Independent Power Producers (IPPs). These utilities are the Pakistan Water and Power Development Authority (WAPDA) and the Karachi Electricity Supply Corporation (KESC).

Table1.7.Power Generation Potential and Consumption

Province	Coal Fields	Generation Potential (MW)	Consumption (Mn tons/ year)
Sind	Thar	100,000	536.00
	Lakhra	1000	4.00
	Sonda	500	2.30
Balochistan	Sor-Range-Degari	50	0.13
	Sharigh-Khost	50	0.13
	Mach	25	0.06
	Duki	25	0.06
Punjab	Salt Range	80	0.35
	Makarwal	50	0.13
NWFP	Hangu/Cherat	10	0.03

Source: PPIB, “Pakistan coal power generation potential”, February 2008.

WAPDA supplies power to all of Pakistan, except the metropolitan city of Karachi and some of its surrounding areas which are supplied by KESC. Power Wing of WAPDA is being restructured with the ultimate goal of privatizing it to make Power Sector strong and vibrant through enhancing efficiency to meet the needs of the consumers. The transmission systems of WAPDA and KESC are interconnected through 220 kV double circuit transmission line. Presently, the total installed electricity generation capacity in the country is about 19420 MW.

In the total installed capacity, the share of public sector is around 70%, and the private sector is 30% The rising share of private sector in electricity generation and presence of some of the leading foreign and local companies in this business, speak volumes about Pakistan being an ideal investment destination. Currently, there are 16 IPPs in the country, which have been implemented on a Build, Own and Operate (BOO) basis, mainly under the private power policy announced by the GOP in 1994.

Transmission of electricity takes place at voltages of 500kV, 220kV, 132kV, 66kV and 33kV and distribution to at 11kV. It is envisaged that in near future there will be a huge gap between demand and supply of electricity. Electricity generation during 2006-07 increased by 4.9% including 3.5% increase in hydel generation over the last year and reached 98,834 GWh including 171 GWh of electricity imported from Iran. Electricity generation includes 65.1% thermal comprising 28.5% oil, 36.4% gas, 0.1% coal and 32.5% hydel, 2.3% nuclear while 0.2% of the electricity was imported. These figures are indicated in figure 1.7.

These shortages are expected to increase to 5500 MW in the year 2010 as shown in figure 1.8" and further to 14,000MW by 2020. As per GOP statement of 2 Jan 2009, the present electricity supply demand gap in the country is around 4500 MW.

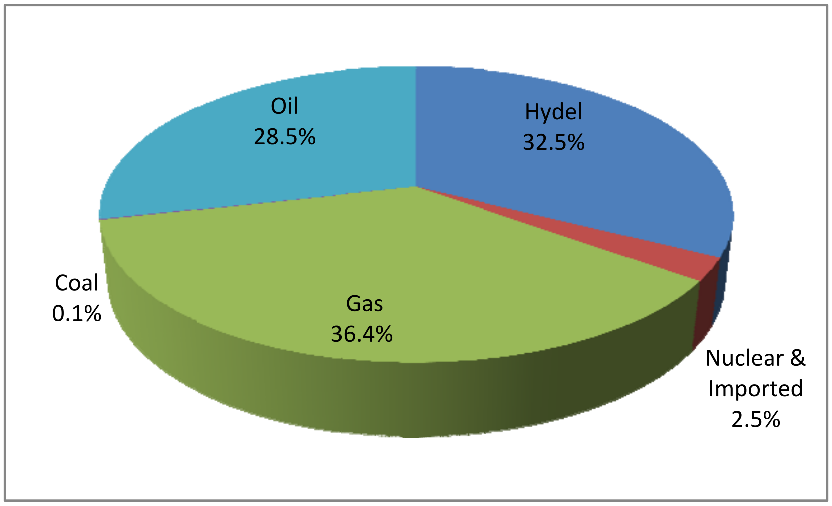

Figure 1.7 Power Generation by Fuel 2006-07

Source: Ministry of Water and Power,GOP

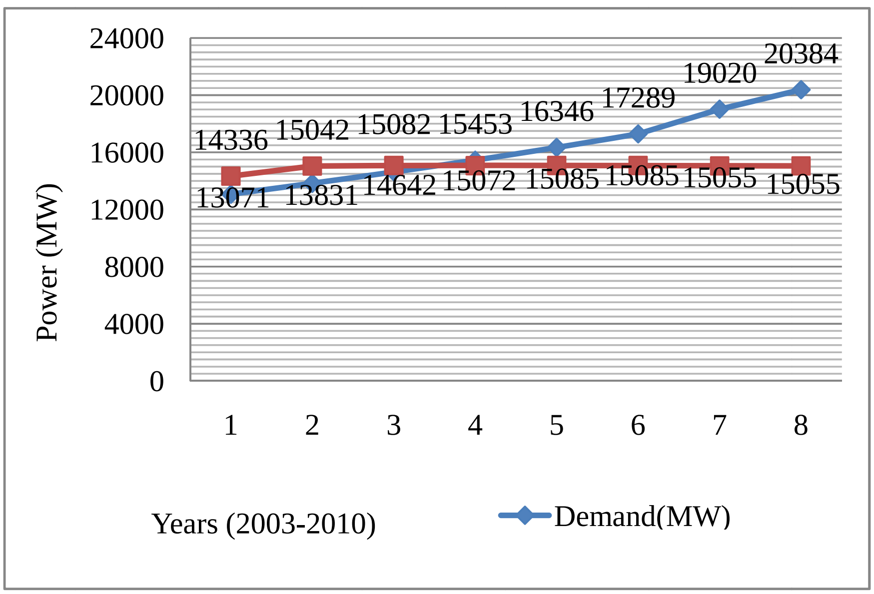

Fig.1.8 Electricity Demand-Supply Curve of Pakistan (Indicative)

Source: Ministry of Water and Power,GOP

1.8 Pakistan Environmental Overview

"Pakistan is facing following two environmental issues

- High levels of toxic emissions; and
- Lack of energy efficiency standards.

In Pakistani widespread consumption of low-quality fuel, combined with large expansion in the number of vehicles on the roads, has led to significant air pollution problems. Lead and carbon emissions are major air pollutants in urban centers such as Karachi, Lahore, and Islamabad. A lack of energy efficiency standards has contributed to Pakistan's high CO_2 intensity. Currently, government vehicles and taxis that have been using liquefied petroleum gas (LPG) are being converted to CNG" [23].

1.8.1 Environmental Statistics

- As per Country Analysis Brief [24], CO_2 emissions related to Pakistan are
  - Energy-Related Carbon Dioxide Emissions (2003E): 104.4 million metric tons, of which Oil 46%, Natural Gas 45%, Coal 9%;
  - Per-Capita, Energy-Related CO_2 Emissions(2003E): 0.7 metric tons
  - Carbon Dioxide Intensity (2004E): 0.3 Metric tons per thousand;
  - Environmental issues are water pollution from raw sewage, industrial wastes, and agricultural runoff; limited natural fresh water resources; a majority of the population does not have access to potable water; deforestation; soil erosion; desertification; and
  - Major Environmental Agreements: Pakistan is party to Biodiversity, Climate Change, Climate Change-Kyoto Protocol, Desertification, Endangered Species, Environmental Modification, Hazardous Wastes, Law of the Sea, Marine Dumping, Ozone Layer Protection, Ship Pollution.
- Pakistan was ranked 30^{th} [25] amongst CO_2 emitting countries from fossil fuels in year 2007. The figure indicates 142.659 Million metric tonnes of CO_2 emission annually, which is 0.5% of the world total CO_2 emissions.

All the above discussion reveals that world and especially Pakistan is running short of energy. Domestic coal, being in abundance, is an attractive option for Pakistan for producing electricity. But while doing that it is necessary to utilize coal in a cost effective and environment friendly manner so that we are not trapped in some accord like Kyoto protocol in future.

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CHAPTER 2

RESEARCH DESIGN AND METHODOLOGY

2.1 Aim of Research

The aim of this research is to recommend a framework for selection of clean coal technologies for power generation in Pakistan based on World Bank guidelines.

2.2 Objectives of Research

The objectives of this research are as follows

- Compare CCTs worldwide with special emphasis on their maturity level, emission control capability and cost effect
- Suggest a framework to the power planners of Pakistan for selection of CCTs
- Recommend combination of CCTs that can meet local and World Bank environmental standards
- Suggest effective use of indigenous coal to GOP
- Bring out the environmental concerns of the coal use in Pakistan
- Suggest GOP to remain within the the Kyoto Protocol and any other strict future legislation
- To suggest a logical and speedy method of selecting clean coal technologies for power sector in Pakistan;

2.3 Research Question

During the 20th century the demand for energy has increased manifold because of economic growth backed by industrialization. Fossil fuels including oil, gas and coal had been the major energy resources contributing to the world energy supply. Among the three, present world oil and gas reserves are not enough to last longer and are depleting quickly. Coal on the other hand has enough reserves to last for more than a century. As per long wave penetration theory of new fossil fuels coal will rebound from 2015 onwards and by the end of 21st century will fulfill 50% of world energy demands. A major portion of world coal reserves is consumed by the power generation sector.

Pakistan has the world's 6th largest coal reserves and GOP has planned to increase the share of coal in electricity generation from less than 1% to 12% by 2030, but unfortunately the progress is very slow. On the other hand electricity supply demand gap has reached 4500 MW and is further widening.

Main drawback of coal use for power generation is its environmental impact. Coal is the most carbon intensive fossil fuel and is the biggest source of carbon dioxide emission in the atmosphere. As per UN statistics division, Pakistan is 33rd in the ranking of carbon dioxide emitting countries from the use of fossil fuels. The problem of coal emissions is being reduced by using clean coal technologies in the power plants. Pakistan's environmental regulation dictates the emission limits from coal fired power plants but the understanding of achieving it through the use of clean coal technologies is very limited in the government sector. Moreover; the growing concern in the world about the use of coal indicates that there is going to be much stringent emission standards worldwide in the near future. Pakistan's plan to increase the use of coal for power generation and Pakistan ratification treaties like Kyoto protocol further necessitates the use of clean coal technologies for the power plants. In spite of all these worthy reasons nothing worthwhile has been done so far on the adoption of clean coal technologies in Pakistan.

The selection of clean coal technologies for a power plant is a complex task. It involves evaluation and optimization of a large number of technical, economic and environmental parameters. There are a number of technologies available for clean utilization of coal in power plants. This research endeavors to evolve a method / framework for selecting the environment friendly and cost effective clean coal technologies for the power plants in Pakistan based on World Bank guidelines.

2.4 Research Methodology A logical research methodology was adopted. Step wise approach is given below and presented in figure 1.1

- An extensive literature review on coal and clean coal technologies was carried out to develop the basic knowledge and establish a firm base;
- Identification of the need for research and arriving at the research question.
  - While studying the RWE feasibility study, it was found that only mining portion has been covered in detail and no feasibility study has been carried out for the proposed Thar coal power plant. As per the report a separate study has to be carried out for the power plant. The power tarrif calculated by the NEPRA for Thar coal based on RWE study does include the emission control equipment cost but it is nowhere mentioned which technology will be used therein;
  - During the course of literature review, it was found that a number of CCTs are available for use in power plants. However these are used keeping in view their cost effect, environmental regulations and suitability to the type of coal being used. An optimization of all these parameters has to be carried out while selecting a suitable technology; and

- WBFTTSM provides a solution to the above mentioned problem and help select environment friendly and cost effective CCTs for the power plants.

- Framework was evolved for selection of CCTs for power plants. It consists of two parts
  - A comparison of the available CCTs including technical, environmental and economic parameters was carried out and the results were compiled in tabular form; and
  - Enhanced WBFTTSM. WBFTTSM is given in a very generic and sketchy form in the original document. A few improvements and additions were made to make it suitable for Pakistan.

- Use of evolved framework to select CCTs for Thar coal fired power plant mentioned in RWE feasibility comprises of five steps. It includes the step wise elimination of technologies. During the process detailed technical, environmental and economic analysis of the CCTs is carried out. Last step results in a combination of two sets of technologies that are recommended for detailed feasibility study. Thus making the job of power plant designer easier;

- Results were analyzed and recommendations made;

- Verification of the achieved results from a coal expert at PPIB; and

- Compilation and documentation of thesis.

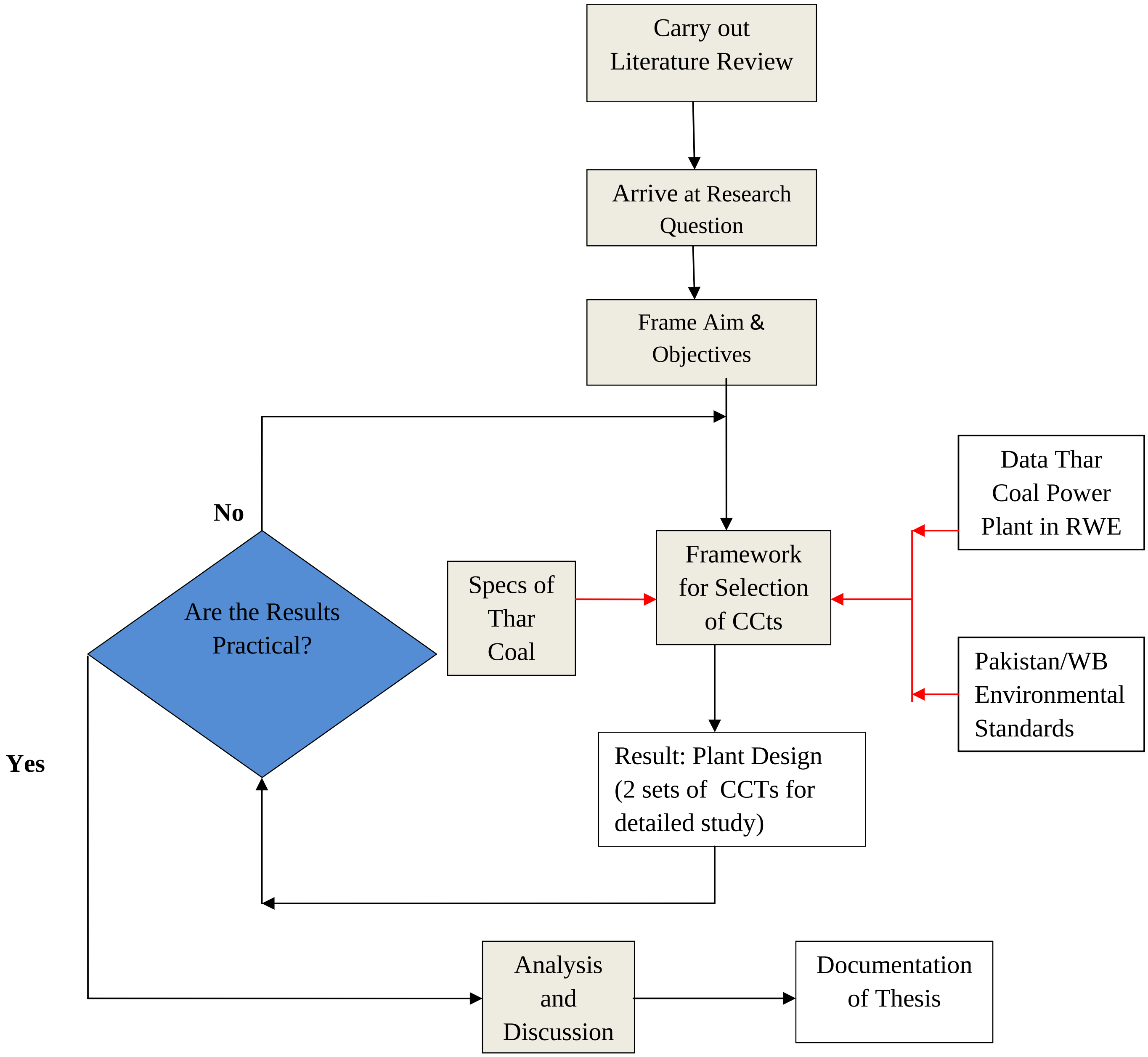


Figure 2.1 Research methodology

2.5 Structure of Thesis

The structure of the thesis has been developed in a very logical and interwoven pattern for an easy understanding of the research study. The format of thesis is in accordance with the "Guidelines for the Preparation of B.E. Project Report / MS Thesis", issued by the National University of Sciences and Technology (NUST), Rawalpindi, Pakistan. The thesis comprises of 5 chapters

For building the research foundation, energy overview and the climate change of world and Pakistan have been discussed in Chapter 1. It includes the Statistics related to World and Pakistan's energy, Pakistan coal resources, their coal characteristics & chemical analysis and Pakistan coal power generation potential from authentic resources.

Research design including aim/objectives, research question and research layout have been discussed in Chapter 2**.**

Literature review, Chapter 3 consists of three sections. First section contains the basic facts of coal, i.e its composition, energy value, uses and environmental effects etc. Second section contains the details of different CCTs and their selection criterias. Third section explains the emission limits set by the World Bank, WHO and GOP for the coal fired power plants.

Management framework including enhanced WBFTTSM has been explained and applied to RWE study Thar coal fired power plant in Chapter 4. Evaluation and optimization of large number of technical, economic and environmental parameters of CCTs is carried out for the selection of clean coal technologies. The results are documented and analyzed.

Finally recommendations are given and research is concluded in Chapter 5**.**

References

CHAPTER 3

LITERATURE REVIEW

3.1 Basics of coal

3.1.1 Types of Coal

The degree of change undergone by a coal as it matures from peat to anthracite, known as coalification, has an important bearing on its physical and chemical properties and is referred to as the 'rank' of the coal. "As geological processes apply pressure to dead biotic matter over time, under suitable conditions it is transformed successively into

- Peat, considered to be a precursor of coal, has industrial importance as a fuel in some countries, for example, Ireland and Finland;
- Lignite, also referred to as brown coal, is the lowest rank of coal and used almost exclusively as fuel for electric power generation. Jet is a compact form of lignite that is sometimes polished and has been used as an ornamental stone since the Iron Age;
- Sub-bituminous coal, whose properties range from those of lignite to those of bituminous coal and are used primarily as fuel for steam-electric power generation. Additionally, it is an important source of light aromatic hydrocarbons for the chemical synthesis industry;
- Bituminous coal, a dense mineral, black but sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke;
- Anthracite, the highest rank; a harder, glossy, black coal used primarily for residential and commercial space heating. It may be divided further into metamorphically altered bituminous coal and petrified oil, as from the deposits in Pennsylvania; and
- Graphite, technically the highest rank, but difficult to ignite and is not so commonly used as fuel: it is mostly used in pencils and, when powdered, as a lubricant.

Low rank coals, such as lignite and sub bituminous coals are typically softer, friable materials with a dull, earthy appearance. They are characterized by high moisture levels and low carbon content, and therefore a low energy content. Higher rank coals are generally harder and stronger and often have a black, vitreous lustre. They contain more carbon, have lower moisture content, and produce more energy. Anthracite is at the top of the rank scale and has a correspondingly higher carbon and energy content and a lower level of moisture" [26]. This information is summarized in figure 3.1.

3.1.2 Classification as per Contents

The classification of coal is generally based on the content of volatiles. However, the exact classification varies between countries. According to the German classification, coal is classified as given in table 3.1. The middle six grades in the table represent a progressive transition from the sub-bituminous to bituminous coal, while the last class is an approximate equivalent to anthracite. Cannel coal, sometimes called candle coal, is a variety of fine-grained, high-rank coal with a large amount of hydrogen.

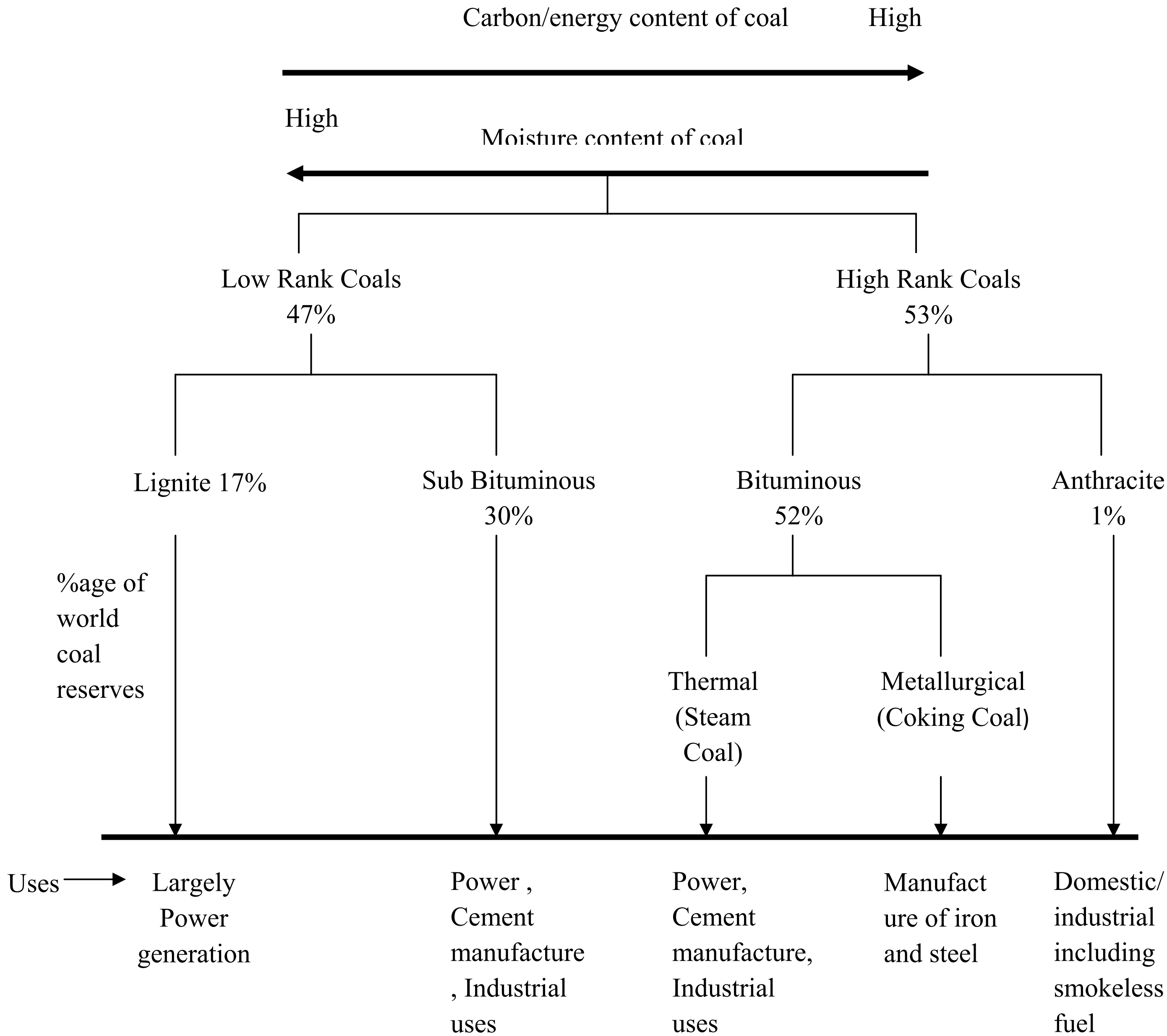


Fig 3.1.Types of coal

Source: Reproduced from Section I Coal Book,WCI

Table 3.1. Classification of Coal (German Standard)

Type	Volatiles %	Carbon %	Hydrogen %	Oxygen %	Sulfur %	Heat content kJ/kg
Braunkohle (Lignite)	45-65	60-75	6.0-5.8	34-17	0.5-3	<28470
Flammkohle (Flame coal)	40-45	75-82	6.0-5.8	>9.8	~1	<32870
Gas flammkohle (Gas flame coal)	35-40	82-85	5.8-5.6	9.8-7.3	~1	<33910
Gaskohle (Gas coal)	28-35	85-87.5	5.6-5.0	7.3-4.5	~1	<34960
Fettkohle (Fat coal)	19-28	87.5-89.5	5.0-4.5	4.5-3.2	~1	<35380
Esskohle (Forge coal)	14-19	89.5-90.5	4.5-4.0	3.2-2.8	~1	<35380
Magerkohle (Non baking coal)	10-14	90.5-91.5	4.0-3.75	2.8-3.5	~1	35380
Anthrazit (Anthracite)	7-12	>91.5	<3.75	<2.5	~1	<35300

Source: Eberhard Lindner; Chemie fur Ingenieure; Lindner Verlag Karlsruhe, S 258

3.1.3 Coal Combustion

Combustion of coal, like any other fossil fuel, occurs due to an exothermic reaction between the components of the fuel source and the components of the air surrounding it. Coal is made primarily of carbon, but also contains sulfur, oxygen and hydrogen. The reaction between coal and the air surrounding it produces oxides of carbon, usually carbon dioxide in a complete combustion, along with oxides of sulfur, mainly sulfur dioxide and various oxides of nitrogen. Because of the hydrogen and nitrogen components of air, hydrides and nitrides of carbon and sulfur are also produced during the combustion of coal in air. These could include hydrogen cyanide HCN, sulfur nitrate SNO_3 and many other toxic substances.

Coal and its waste products including fly ash, bottom ash, and boiler slag, contain many heavy metals, including arsenic, lead, mercury, nickel, vanadium, beryllium, cadmium, barium, chromium, copper, molybdenum, zinc, selenium and radium, which are dangerous if released into the environment. Coal also contains low levels of uranium, thorium, and other naturally occurring radioactive isotopes whose release into the environment may lead to radioactive contamination. While these substances are trace impurities, enough coal is burned that significant amounts of these substances are released resulting in more radioactive waste than nuclear power plants.

3.1.4 Combustion Efficiency

CO_2 emissions from coal combustion are being reduced through improvements in the thermal efficiencies of coal fired power stations. Thermal efficiency measures the overall fuel conversion efficiency for the electricity generation process. The higher the efficiency levels, the greater the energy produced from less amount of fuel. The global average thermal efficiency of coal fired power stations is around 30%, with the OECD average at around 38%. In comparison China in spite of steadily improving to 33% in the year 2003, coal-fired efficiency of China is still lower than the United States 37%, Western Europe 39% and Japan 42% [27].

“New supercritical technology allows coal fired power plants to achieve overall thermal efficiencies of 43-45%. These higher levels are possible because supercritical plant operate at higher steam temperatures and pressures than conventional plant. Ultra supercritical power plants can achieve efficiency levels of up to 50% by operating at even higher temperatures and pressures.

An alternative approach is to produce a gas from coal, this is achieved in IGCC systems. These systems operate at high efficiencies, typically in the mid 40s but plant designs offering close to 50% efficiencies are available. They also remove 95-99% of NOx and SOx emissions. Work is being undertaken to make further gains in efficiency levels, with the prospect of net efficiencies of 56% and more in the future". [28]

3.1.5 Energy density

The energy density of coal, i.e its heating value, is roughly 24 megajoules per kilogram [29].The energy density of coal can also be expressed in kilowatt hours for unit of mass, the units most commonly used, to estimate how much coal is required to power electrical appliances. One kilowatt-hour is 3.6 MJ, so the energy density of coal is 6.67 kwh/kg. The typical thermodynamic efficiency of coal power plants is about 30% i.e 2.0 kwh/kg can successfully be turned into electricity; the rest is waste heat. So coal power plants obtain approximately 2.0 kwh/kg of burned coal.

As an example, running one 100 watt computer for one year requires 876 kwh (100 W × 24 h/day × 365 {days in a year} = 876000 Wh = 876 kwh). Converting this power usage into physical coal consumption: It takes 438 kg or 966 lb of coal to power a computer for one full year [30]. One should also take into account transmission and distribution losses caused by resistance and heating in the power lines, which is in the order of 5–10%, depending on distance from the power station and other factors.

3.1.6 Relative carbon cost

" Because coal is at least 50% carbon by mass, then 1 kg of coal contains at least 0.5 kg of carbon, which is where 1 mol is equal to N_A (Avogadro Number) particles. This combines with oxygen in the atmosphere during combustion, producing carbon dioxide, with an atomic weight of 12 + 16 × 2 = mass(CO_2) = 44 kg/kmol, so $^1/_{24}$ kmol of CO_2 is produced from the $^1/_{24}$ kmol present in every kilogram of coal, which once trapped in CO_2 weighs approximately.

This can be used to put a carbon cost of energy on the use of coal power. Since the useful energy output of coal is about 30% of the 6.67 kwh/kg, we can say about 2 kwh/kg of energy is produced. Since 1 kg coal roughly translates as 2.93 kg of CO_2, we can say that using electricity from coal produces CO_2 at a rate of about 1.47 kg/kwh, or about 0.407 kg/MJ. This estimate compares favourably with the US Energy Information Agency's 1999 report on CO_2 emissions for energy generation [31], which quotes a specific emission rate of 950g CO_2/kwh. By comparison, generation from oil in the US was 881g CO_2/kwh, while natural gas was 569g CO_2/kwh. Estimates for specific emission from nuclear power, hydro and wind energy vary, but are about 100 times lower". (Wikipedia encyclopedia)

3.2 <u>Uses of Coal</u>

Coal has many important uses worldwide. The most significant uses are in electricity generation, steel production, cement manufacturing, industrial processes and as a liquid fuel.

3.2.1 Coal as Fuel for Electricity Generation

"Steam coal, also known as thermal coal, is used in power stations to generate electricity. The earliest conventional coal fired power stations used lump coal which was burnt on a grate in boilers to raise steam. Nowadays, the coal is first milled to a fine powder, which increases the surface area and allows it to burn more quickly. In these pulverised coal combustion (PCC) systems, the powdered coal is blown into the combustion chamber of a boiler where it is burnt at high temperature. The hot gases and heat energy produced converts water in tubes lining the boiler into steam. The high pressure steam is passed into a turbine containing thousands of propeller like blades. The steam pushes these blades causing the turbine shaft to rotate at high speed. A generator is mounted at one end of the turbine shaft and consists of carefully wound wire coils. Electricity is generated when these are rapidly rotated in a strong magnetic field. After passing through the turbine, the steam is condensed and returned to the boiler to be heated once again. The whole process is shown in figure 3.2.

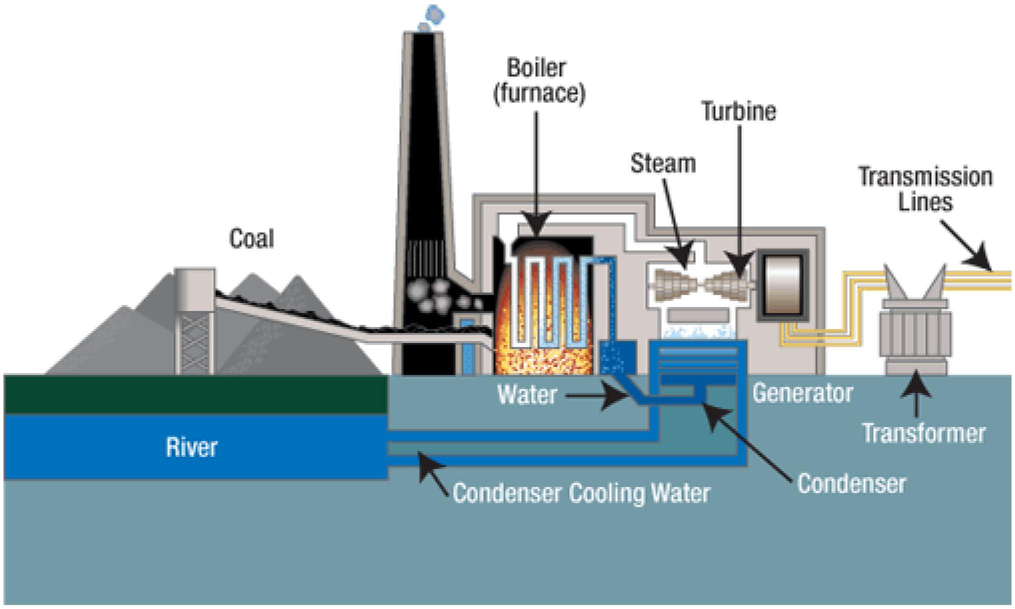


Figure 3.2 Converting Coal into Electricity

Source: World Coal Institute

The electricity generated is transformed into the higher voltages up to 400,000 volts used for economic, efficient transmission via power line grids. When it nears the point of consumption, such as our homes, the electricity is transformed down to the safer 100-250 volts systems used in the domestic market" [32].

3.2.2 Coking and use of coke

"Coke is a solid carbonaceous residue derived from low-ash, low-sulfur bituminous coal from which the volatile constituents are driven off by baking in an oven without oxygen at temperatures as high as 1,000 °C or 1,832 °F so that the fixed carbon and residual ash are fused together. Metallurgic coke is used as a fuel and as a reducing agent in smelting iron ore in a blast furnace. Coke from coal is grey, hard, and porous and has a heating value of 24.8 million Btu/ton or 29.6 MJ/kg. Some coke making processes produce valuable by products that include coal tar, ammonia, light oils and coal gas. Petroleum coke is the solid residue obtained in oil refining, which resembles coke but contains too many impurities to be useful in metallurgical applications" (Wikipedia, encyclopedia).

3.2.3 Gasification

" Coal gasification can be used to produce syngas, a mixture of carbon monoxide and hydrogen gas. This syngas can then be converted into transportation fuels like gasoline and diesel through the Fischer-Tropsch process. Currently, this technology is being used by the SASOL chemical company of South Africa to make gasoline from coal and natural gas. Alternatively, the hydrogen obtained from gasification can be used for various purposes such as making ammonia or upgrading fossil fuels.

During gasification, the coal is mixed with oxygen and steam while being heated and pressurized. During the reaction, oxygen and water molecules oxidize the coal into carbon monoxide while releasing hydrogen gas. This process has been conducted in both underground coal mines and in coal refineries.

$$\text{(Coal)} + O_2 + H_2O \rightarrow H_2 + CO$$

If the refiner wants to produce gasoline, the syngas is collected at this state and routed into a Fischer-Tropsch reaction. If hydrogen is the desired end-product, however, the syngas is fed into the water gas shift reaction where more hydrogen is liberated.

$$CO + H_2O \rightarrow CO_2 + H_2$$

High prices of oil and natural gas are leading to increased interest in "BTU Conversion" technologies such as gasification, methanation and liquefaction” (Wikipedia encyclopedia).

In the field of energy conversion , the integrated systems, also known as energyplexes, are highly efficient, incorporate advanced technologies that may have fuel flexibility and allow for product flexibility e.g various combinations of electricity,liquid fuels, hydrogen, chemicals and heat [33]. The energyplexes would permit the application of polygeneration strategies. Poly-generation, or co-production, schemes have been highlighted in the literature as promising alternatives for the simultaneous production of electricity, hydrogen, synthetic liquid fuels, heat and/or chemicals [34]. Poly-generation schemes may contribute to improve the economic attractiveness of the different products and have the potential to reduce the costs of carbon capture and sequestration [35].In order to achieve these multiple purposes, a combination of technologies is required. Thus, “energyplexes” could incorporate hybrid systems that could take advantage of the characteristics of the individual components. The hybrid system could achieve higher conversion efficiencies and fulfill more purposes than the component technologies alone. For instance, a hybrid system could combine a gas turbine with a high-temperature fuel cell for electricity generation [36].

3.2.4 Liquefaction – Coal To Liquids (CTL)

Coal can also be converted into liquid fuels like gasoline or diesel by several different processes. In the direct liquefaction processes, the coal is either hydrogenated or carbonized. Hydrogenation processes are the Bergius process, [37] the SRC-I and SRC-II (Solvent Refined Coal) processes and the NUS Corporation hydrogenation process. [38-39] In the process of low temperature carbonization coal is coked at temperatures between 680 °F (360 °C) and 1,380 °F (750 °C). These temperatures optimize the production of coal tars richer in lighter hydrocarbons than normal coal tar. The coal tar is then further processed into fuels. Alternatively, coal can be converted into a gas first, and then into a liquid, by using the Fischer-Tropsch process. An overview of coal liquefaction and its future potential has been done by others [40].

Coal liquefaction methods involve carbon dioxide emissions in the conversion process. If coal liquefaction is done without employing either carbon capture and storage technologies or biomass blending, the result is lifecycle greenhouse gas footprints that are generally greater than those released in the extraction and refinement of liquid fuel production from crude oil. If CCS technologies are employed, reductions of 5-12% can be achieved in CTL plants and up to a 75% reduction is achievable when co-gasifying coal with commercially demonstrated levels of biomass (30% biomass by weight) in CBTL plants [41]. For most future synthetic fuel projects, Carbon dioxide sequestration is proposed to avoid releasing it into the atmosphere. Sequestration will, however, add to the cost of production. Currently all US and at least one Chinese synthetic fuel projects, [42] are including sequestration in their process designs.

Coal liquefaction is one of the backstop technologies that could potentially limit escalation of oil prices and mitigate the effects of transportation energy shortage that some authors have suggested could occur under peak oil. This is contingent on liquefaction production capacity becoming large enough to satiate the very large and growing demand for petroleum. Estimates of the cost of producing liquid fuels from coal suggest that domestic U.S. production of fuel from coal becomes cost competitive with oil priced at around US$ 35 per barrel [43] (break-even cost). With oil prices back at around US$ 40 per barrel as on 15 December, 2008, liquid coal once again lost much of its economic allure (Wikipedia encyclopedia)].

3.2.5 Refined Coal

Refined coal is the product of a coal upgrading technology that removes moisture and certain pollutants from lower rank coals such as sub-bituminous and lignite (brown) coals [44]." It is one form of several pre combustion treatments and processes for coal that alter coal's characteristics before it is burned. The goals of pre combustion coal technologies are to increase efficiency and reduce emissions when the coal is burned. Depending on the situation, pre-combustion technology can be used in place of or as a supplement to post combustion technologies to control emissions from coal fueled boilers” [24].

3.2.6 Coal as a traded commodity

The price of coal has gone up from around $30 per short ton in 2000 to around $150.00 per short ton on 26 September, 2008. As on 31 October, 2008, the price per short ton declined to $111.50 [45].

3.2.7 Coal and Cement

“Cement is critical to the construction industry, when mixed with water and gravel it forms concrete which is the basic building element in modern society. More than 1350 million tonnes of cement are used globally every year. Cement is made from a mixture of calcium carbonate, generally in the form of limestone, silica, iron oxide and alumina. A high temperature kiln, often fuelled by coal, heats the raw materials to a partial melt at 1450°C, transforming them chemically and physically into a substance known as clinker. This grey pebble like material is comprised of special compounds that give cement its binding properties. Clinker is mixed with gypsum and ground to a fine powder to make cement. Coal is used as an energy source in cement production. Large amounts of energy are required to produce cement. Kilns usually burn coal in the form of powder and consume around 450g of coal for about 900g of cement produced. In Japan the rate of effective use of ash has been raised from 51 to 96%in the same period mainly due to use in the cement sector, approximately 70% [46].

Coal combustion products (CCPs) can also play an important role in concrete production. CCPs are the by products generated from burning coal in coal fired power plants. These by products include fly ash, bottom ash, boiler slag and flue gas desulphurisation gypsum. Fly ash, for example, can be used to replace or supplement cement in concrete. Recycling coal combustion products in this way is beneficial to the environment, acting as a replacement for primary raw materials”. [47]

3.2.8 Coal & Renewable Energy

"The continued development and deployment of renewable energy will play an important role in improving the environmental performance of future energy production. However, there are a number of practical and economic barriers that limit the projected rate of growth of renewable energy. Renewable energy can be intermittent, unpredictable and 'site-dependent', which means they are only available at specific locations. Wind energy, for example, depends on whether and how strongly the wind is blowing and even the best wind farms do not normally operate for more than about one third of the season and are difficult to transport.

Coal fired electricity can help support the growth of renewable energy by balancing out their intermittencies in power supply. Coal can provide convenient, cheap base load power while renewables can be used to meet peak demand. The economics and efficiency of biomass renewables can also be improved by co-firing with coal. While clean coal technologies are improving the environmental performance of coal fired power stations, its role as an affordable and readily available energy source offers wider environmental benefits by supporting the development of renewables". [48]

3.2.9 Other Uses

"Other important users of coal include alumina refineries, paper manufacturers, and the chemical and pharmaceutical industries. Several chemical products can be produced from the by products of coal. Refined coal tar is used in the manufacture of chemicals, such as creosote oil, naphthalene, phenol and benzene. Ammonia gas recovered from coke ovens is used to manufacture ammonia salts, nitric acid and agricultural fertilizers. Thousands of different products have coal or coal by-products as components: soap, aspirins, solvents, dyes, plastics and fibres, such as rayon and nylon. Coal is also an essential ingredient in the production of specialist products like:

- Activated carbon - used in filters for water and air purification and in kidney dialysis machines;
- Carbon fibre – an extremely strong but light weight reinforcement material used in construction, mountain bikes and tennis rackets; and

- Silicon metal is used to produce silicones and silanes, which are in turn used to make lubricants, water repellents, resins, cosmetics, hair shampoos and toothpastes". [49]

3.3 Environmental Effects

There are a number of adverse environmental effects of coal mining and burning, especially in power plants.

These effects include:

- release of carbon dioxide and methane, both of which are greenhouse gases, which are causing climate change and global warming according to the IPCC. Coal is the largest contributor to the human made increase of CO_2 in the air [50];
- generation of hundred of millions of tons of waste products, including fly ash, bottom ash, flue gas desulfurization sludge, that contain mercury, uranium, thorium, arsenic, and other heavy metals;
- interference with groundwater and water table levels;
- impact of water use on flows of rivers and consequential impact on other land-uses;
- dust nuisance;
- subsidence above tunnels, sometimes damaging infrastructure;
- rendering land unfit for other uses;
- coal-fired power plants without effective fly ash capture are one of the largest sources of human-caused background radiation exposure;
- coal-fired power plants shorten nearly 24,000 lives a year, including 2,800 from lung cancer [51];
- coal-fired power plant releases emissions including mercury, selenium, and arsenic which are harmful to human health and the environment [52]; and
- Acid rain. It may occur when the sulfur dioxide produced in the combustion of coal, reacts with oxygen to form sulfur trioxide (SO_3), which then reacts with water molecules in the atmosphere to form sulfuric acid. The sulfuric acid (H_2SO_4) is returned to the Earth as acid rain. However, another form of acid rain

is due to the carbon dioxide emissions of a coal plant. When released into the atmosphere, the carbon dioxide molecules react with water molecules, to produce carbonic acid (H_2CO_3). This, in turn, returns to the earth as a corrosive substance. This cannot be prevented as easily as sulfur dioxide emissions and adversly affects the environment and human health. Currently, about 30–40% of China's territory, especially the southwest, is suffering from acid rain and respiratory system disease are continuously increasing [53].

3.4 Greenhouse Gases in Atmosphere

In order, Earth's most abundant greenhouse gases are:

- Water vapor;
- Carbon dioxide;
- Methane;
- Nitrous oxide;
- Ozone; and
- Carbon Fluro Chlorides(CFCs)

When these gases are ranked by their contribution to the greenhouse effect, the most important are:

- Water vapor, which contributes 36–70%;
- Carbon dioxide, which contributes 9–26%;
- Methane, which contributes 4–9%; and
- Ozone, which contributes 3–7%

3.5 Natural and Anthropogenic Emissions

Aside from purely human produced synthetic hydrocarbons, most greenhouse gases have sources from both the ecosystem i.e natural and from human activities i.e anthropogenic. During the pre-industrial era, concentrations of existing gases were roughly constant. In the industrial era, human activities have added greenhouse gases to the atmosphere, mainly through the burning of fossil fuels and clearing of forests [54].

Some of the main sources of greenhouse gases due to human activity include:

- Burning of fossil fuels and deforestation leading to higher carbon dioxide concentrations. Land use change, mainly deforestation in the tropics, accounts for up to one third of total anthropogenic CO_2 emissions [55];
- Livestock enteric fermentation and manure management, paddy rice farming, land use and wetland changes, pipeline losses and covered vented landfill emissions leading to higher methane atmospheric concentrations. Many of the newer style fully vented septic systems that enhance and target the fermentation process also are sources of atmospheric methane;
- Use of chlorofluorocarbons (CFCs) in refrigeration systems, and use of CFCs and halons in fire suppression systems and manufacturing processes; and
- Agricultural activities, including the use of fertilizers, that lead to higher nitrous oxide concentrations;

The seven sources of CO_2 from fossil fuel combustion with percentage contributions from 2000–2004 are [56]:

- Solid fuels e.g. coal, 35%;
- Liquid fuels e.g. gasoline, 36%;
- Gaseous fuels e.g. natural gas, 20%;
- Flaring gas industrially and at wells, <1%;
- Cement production, 3% ;
- Non-fuel hydrocarbons, <1%; and
- The "international bunkers" of shipping and air transport not included in national inventories, 4%.

Carbon dioxide, methane, nitrous oxide and three groups of fluorinated gases i.e sulfur hexafluoride, HFCs, and PFCs are the major greenhouse gases and the subject of the Kyoto Protocol. The intergovernmental panel on climate change has consistently documented scientific consensus on a link between anthropogenic GHG emissions and climate change [57]. The US National Academy of Science, in response to a request from the Office of the President in 2001, also confirmed the existence of significant evidence of a link between recent anthropogenic GHG emissions and climate change

[58]. If unabated, human-induced climate change threatens large and enduring impacts on human communities and ecosystems [59]. Moreover, these effects may result in highly inequitable patterns of harm, affecting poor populations and future generations in disproportion to their GHG emissions [60 - 61- 62]. Climate change threatens significant impacts on global ecosystems and human populations. To address this challenge, industrialized nations have ratified the Kyoto Protocol and undertaken commitments to reduce emissions of greenhouse gases, the primary agents linked to anthropogenic alteration of earth's climate [63].

3.6 Clean Coal Technologies

Clean coal is an umbrella term used in the promotion of the use of coal as an energy source by emphasizing methods being developed to reduce its environmental impact.

The threat posed by the coal fired power plants to the environment is being tackled with the help of CCTs. These technologies facilitate the use of coal in an environmentally satisfactory and economically viable way. Among other aspects, they meet various regulations covering emissions, effluents, and residues. In some situations, CCTs offer the possibility of satisfying even more stringent standards, at an acceptable cost.

CCTs are introduced at pre-combustion, combustion and post- combustion stages of the coal fired power plants, whereas they are used to reduce/control different emissions. Therefore CCTs can be classified on the basis of

- Stage of use; and
- Type of emission reduced/controlled.

A basic approach to the cleaner use of coal is to reduce emissions by reducing the formation of pollutants such as NOx and/or cleaning the flue gases after combustion. A parallel approach is to develop more thermally efficient systems so that less coal is used to generate the same amount of power, together with improved techniques for flue gas cleaning, for effluent treatment and for residues use or disposal. Thermal efficiency may be increased by using a higher grade coal.

The concept of clean coal is said to be a solution to climate change and global warming by coal industry groups, while environmental groups maintain that it is greenwash, a public relations tactic that presents coal as having the potential to be an environmentally acceptable option.Greenpeace is a major opponent of the concept because emissions and wastes are not avoided, but are transferred from one waste stream to another.

The rapid growth of electric power consumption worldwide, especially in developing countries calls for planning and building of cost efficient power plants. They provide technological solution to the environmental pollution by coal combustion. A database of CCTs compiled from different sources is attached as Appendix A. The details of technologies covered by FTTSM and few others are given in succeeding paras for understanding and application in chapter 4. It has to be read in conjunction with the information contained in tables 4.1- 4.6.

3.6.1 Coal Washing

"The use of washed coal is a first cost-efficient step towards increased plant efficiency and availability, reduced investment and O&M costs. It is also known as coal cleaning, coal preparation and coal beneficiation. As mined coal is of variable quality and contains impurities, coal beneficiation is the process by which these impurities are removed to produce a cleaner product. Coal washing increases the heating value and the quality of the coal, by lowering the level of sulphur and mineral constituents. Following are some of the advantages of washed coal use:

- increases the efficiency of power generation, mainly due to a reduction in the energy loss associated with the combustion of inert material;
- increases plant availability;
- reduces investment costs, less cost for fuel and ash handling equipment;
- reduces operation and maintenance costs as a result of reduced plant wear and tear and reduced costs for fuel and ash handling;
- energy savings in the transportation sector and lower transport costs;
- reduces impurities and results in more even coal quality;

- reduces the load on the particulate removal equipment in existing plants; and
- reduces the amount of solid waste that has to be taken care of at the plant.

Coal washing can reduce the ash content of coal by over 50%, reduce SO_2 emissions and improve thermal efficiencies leading to lower CO_2 emissions" [64].

3.6.1.1 Coal Quality Impact on Power Generation Cost

"The degree of coal cleaning e.g. ash content has an impact on power plant economics. The investment cost and the O&M costs are affected by the coal quality. A break even cost analysis established the following:

- Premium of about $0.55/ton could be paid for each percentage point reduction in the ash content of the typical high ash bituminous coals fired in older, existing power plants [65] ;
- A premium of about $0.40/ton for each percentage point reduction in a coal's ash content could be paid for cleaning high ash coals for use in newer plants (Sachdev et. al). Projected savings derive mainly from reduced maintenance costs within the power plant, increased plant availability and reduced fuel transportation costs.

An example from an Indian mine with an annual capacity run-of-mine of 6.5 million tons shows the following: the specific investment cost for coal cleaning was $24/ton, the ash content in washed coal was 34% and the moisture content was 8% [66]. The effect of using washed coal with a reduction in ash content from about 40 to 34 %, compared to run-of-mine coal, was evaluated. The plant load factor increases in the order of 5-10% when the ash content is reduced from 40 to 34%. When designing a plant for lower ash content or for washed coal, the reliability of the coal washing plant has to be close to 100%. It is also important to establish a correlation between the contracted coal price and the quality of the coal". (Karin Oskarson et.al)

3.6.1.2 Efficiency vs Coal Consumption

An efficient power plant is the one which produces more Mwh of electricity with less amount of coal. Type of combustion technology used in power plant determines the efficiency of power plant. "A major concern in developing countries is the inefficient use of coal in the power industry due to low plant efficiencies typically 33 to 36%. Older power plants might have efficiencies as low as 25%. Higher plant efficiencies reduce the emissions of SO_2, NOx, particulates and the waste production per Mwh. In addition to these advantages, coal consumption is reduced per Mwh produced. This is illustrated in Figure 3.3 where the hard coal consumption per kwh of electricity produced is shown as a function of unit efficiency. For example, the figure shows that when the efficiency of a hard coal fired power plant is increased from 34-42%, coal consumption is decreased from 0.42-0.34 kg/kwh of electricity produced, or around 20%, if the hard coal has a lower heating value (LHV) of 25 MJ/kg. Not only the coal consumption is decreased, but emissions and waste are also reduced by 20%" (Karin Oskarson et.al). Another advantage of reduced consumption is the lessened amount of CO_2 emissions which is the real driving force behind the efficiency increase.

3.7 Combustion Technologies

3.7.1 Pulverized Coal Combustion

"Pulverized coal technology is the oldest and most commonly used technology for thermal power generation worldwide. Pulverized coal technology requires flue gas cleaning in order to be environmentally friendly, since the emissions of SO_2 and NOx, become unacceptably high. Pulverized coal boilers can be divided into three groups based on steam data: subcritical PC boilers, where the live steam pressure and temperature are below the critical values 221.2 bar absolute pressure and 374.15°C; and supercritical PC boilers with steam data above the critical values. The current trend is to increase the steam data in order to increase plant efficiency.

They can be designed for any coal from lignite to anthracite, but a given boiler must be designed for one type of coal (lignite, bituminous or anthracite). This means that once designed for a specific coal, PC units are somewhat more sensitive to changes in fuel quality than fluidized bed combustion technology. Uncontrolled emissions from PC firing are high compared to other technologies, which means that emission reduction equipment is necessary and can be rather expensive.

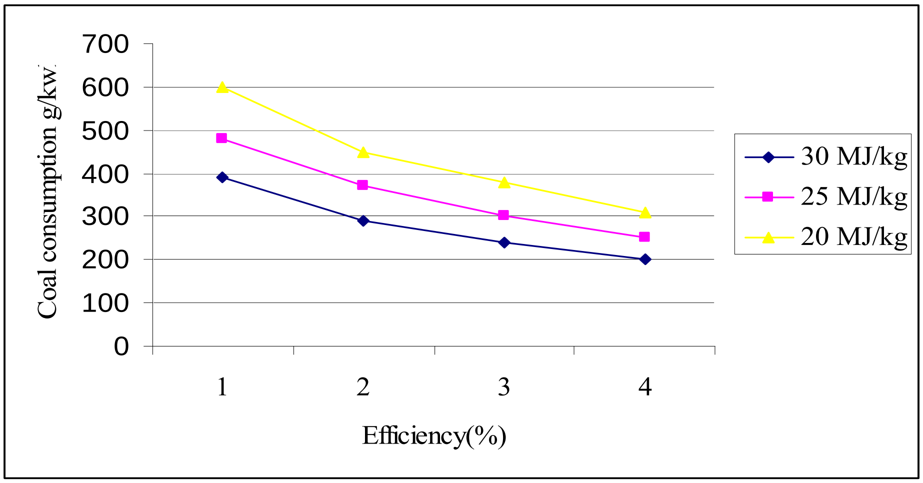


Figure 3.3 Hard coal consumption per kwh of electricity produced for 3 different coals

Source: Data extracted from World Bank Technical paper no 387, 1997.

Table 3.2 Limits for coal parameters for PC boiler designed for normal bituminous coal

Coal Parameter	Limit(Approximate values)
Lower Heating value	>20MJ/kg
Ash Content	<10 %
Moisture	<10 %
Chlorides	<0.3 %
Volatile Matters	>25 %
Sodium + Potassium(Na + K)	<2.5%

Source: Data extracted from World Bank Technical paper no. 387,1997

Table 3.3 Efficiency data for PC boilers

	Sub critical Boilers	Super critical Boilers	Super critical High Temperature Boilers	Ultra Super critical Boilers
Steam Pressure (Bar)	140	240	300	350
Steam temperature C)	540/540	540/540	590	650
Unit Efficiency (%)	36-38	40-42	45	close to 50

Source: Data extracted from World Bank Technical paper no. 387,1997

In boilers operating at high steam temperatures, above 540°C, corrosion becomes more of an issue. When high steam temperatures are used, coals with a high corrosion potential are less suited and should be avoided. Due to the more complex design of supercritical boilers, the requirements on O&M routines are higher than those for a subcritical boiler. Also the demands on water quality and instrumentation and controls equipment are high. Table 3.2 shows the limits for some coal parameters for a normal PC boiler. A PC boiler can be designed for wider variations in coal parameters than indicated in Table 3.2, but this generally results in increased capital cost and lower efficiency during off design operation. Operational flexibility, such as turn down, can also be compromised if the plant is designed for too wide a range of coal qualities" (Karin Oskarson et.al).

3.7.1.1 Efficiency

The theoretical efficiency i.e Carnot efficiency is defined as follows

$$\text{Efficiency} = 1 - T_o / T$$

Where T_o is the steam temperature in K and T is the ambient temperature i.e 15^oC or 288K.

The theoretical efficiency of a Rankine cycle is a function of both steam temperature and pressure with the dependence on temperature being much stronger. The practical maximum efficiency is the efficiency including irreversible losses through additional components, internal consumption etc. However, this practical maximum efficiency is not economically achievable. Therefore net efficiency is the generating efficiency that is economically feasible. Table 3.3 summarizes steam parameters and efficiency data for typical PC plants.

The average efficiency of coal-fired generation in the OECD is 36% in 2002 compared with 30% in developing countries. As a result, one kilowatt-hour produced from coal in developing countries emits 20% more carbon dioxide than in industrialised countries [67]. In the 1990s highly efficient pulverised coal power plants were built in Denmark, Germany and the Netherlands. The most efficient coal power plants, dating from 1998-2000, built in Denmark, is generating an efficiency of 46%. The Japanese

Electric Power Development Company (EPDC) operates a 1,000 MW cross compound plant with maximum steam temperatures of 600/610ºC in Shikoku, Japan. The maximum steam temperature of the unit is 610ºC and the generating efficiency is 49% [68].

The increase in plant net efficiency achieved by increasing steam parameters is shown in Figure 3.4. Conventional sub critical PC plants are shown to the left, followed by supercritical plants with efficiencies above 42%, and slightly higher steam parameters than shown in Table 3.3. Increasing steam data and the introduction of double reheat can increase efficiency still further. The future potential for an ultra supercritical boiler is shown to the right. Higher steam pressures and temperatures require improvements in high-strength alloys. Beyond 2010, advanced alloys for pipes, boiler, and headers may become available. In 2010, the generating efficiency of a pulverised coal power plant may be 48-50%. Development of new alloys for steam boilers and steam turbines could push the generating efficiency to 50-53% in 2020, and further development could offer 51-55% efficiency in 2050 (P.Lako, ECN Policy studies). Presently more than 400 supercritical coal fired power plants are currently operating around the world [69]. The current and future trend of steam temperatures and pressures in PC boilers with the maturity of technology is shown in Figure 3.5.

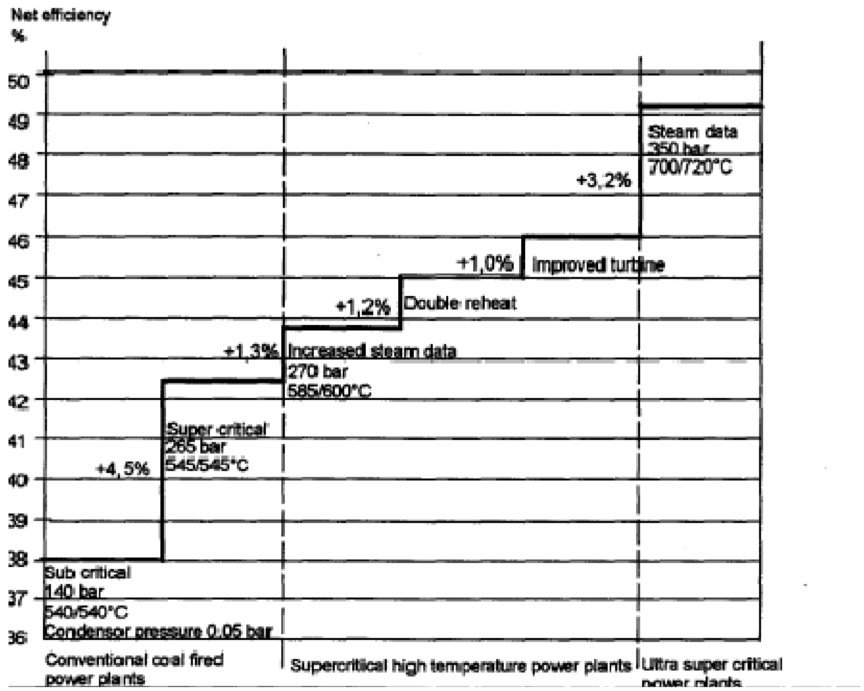


Figure 3.4 Plant net efficiency increase achieved by increasing steam parameter

Source: VGB KraftwerkstechnikUniversitat- GH, Essen, Germany.

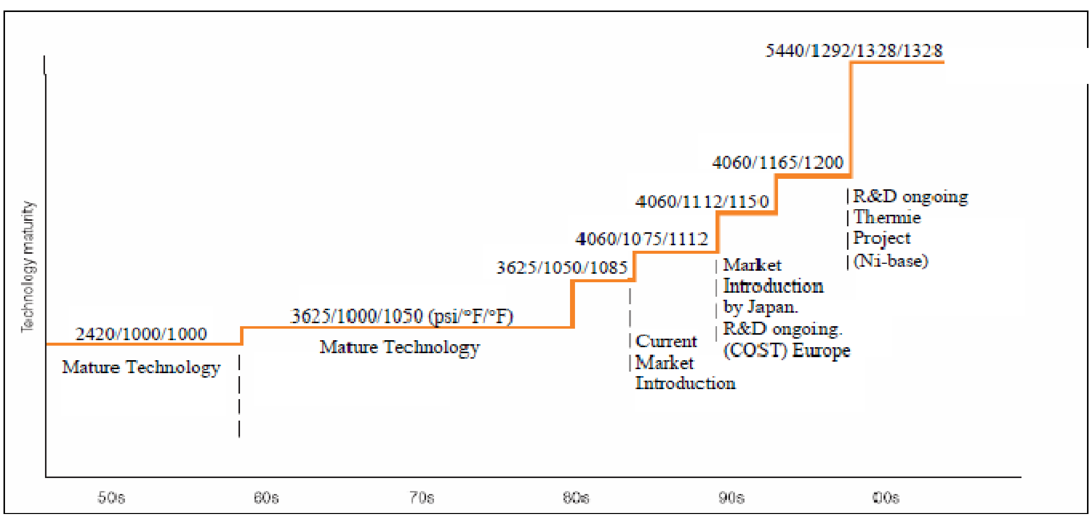


Figure 3.5 Trends in Steam Conditions of Coal Fired Power Plants

Source: Black & Veatch FPL. "Selection of clean coal technologies Final Report".

3.7.1.2 Investment costs

In Figure 3.6, the cost is given for a complete one unit plant that includes everything from fuel storage to waste handling. No emission reduction equipment is included with the exception of low NOx burners. The investment cost for a boiler only amounts to approximately 30% of the investment cost for a complete plant. The cost per kw decreases with increase in plant capacity and is highly dependent on the state of the market, the size of the plant, number of units, the extent to which manufacturing can be carried out in low wage rate areas etc.

According to Henderson, 2003, there is a reasonable likelihood of only moderate additional specific capital requirements for ultra-supercritical plants over current supercritical pulverised coal plants. For the timeframe 2000-2050, following has been assumed:

- From 2000 to 2020, the specific investment cost decreases by approximately 8%; and
- Towards 2050, the specific investment cost decreases by another 4-5%.

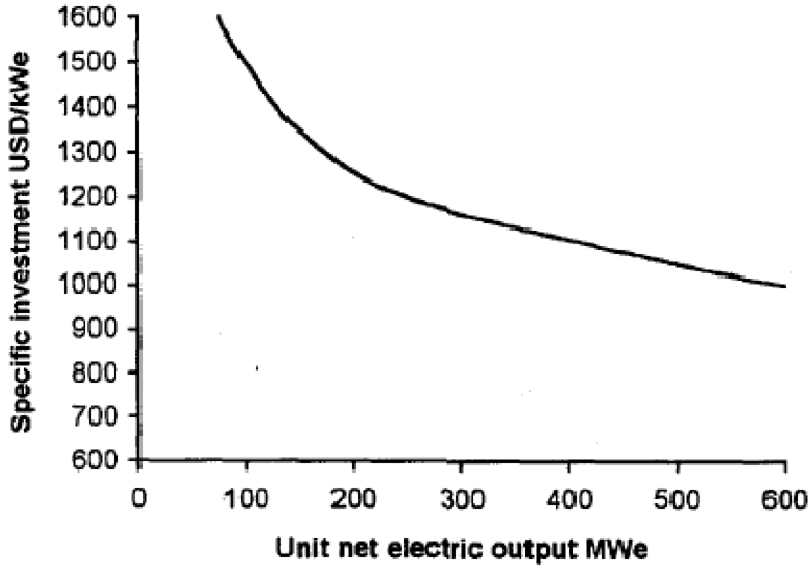


Figure 3.6. Investment costs for PC boiler plants

Source: US Department of Energy, 1994

3.7.2 Fluidized Bed Combustion (FBC)

During the 1980s, fluidized bed combustion (FBC) rapidly emerged as an alternative to PC fueled units for the combustion of solid fuels. Initially used in the chemical and process industries, FBC was applied to the electric utility industry because of its perceived advantages over competing combustion technologies.

Unlike pulverized coal, fluidized-bed boilers can combust larger pieces of coal (sized to about 3 mm) by creating a combustion-zone bed using pressurized air. The coal bed becomes fluidized (suspended) when the air flow is strong enough to match the bed's weight [70]. With enough air flow into the bed, the bed particles get agitated and well-mixed, resulting in a uniform combustion temperature along the bed. Similar to pulverized-coal boilers, this heat is then used to convert water into steam. There are several benefits to FBC technology in comparison to pulverized coal [71]:

- lower costs due to reduced crushing of coal,
- ability to burn a wide variety of coals including low-quality coals, waste coal, biomass and other feedstock,
- in-combustion sulfur removal by mixing crushed limestone/dolomite along with coal,
- reduced NOx production due to lower combustion temperature (800-900 deg C), and
- lower overall cost in comparison to PC with FGD and SCR systems.

Additionally, slagging and fouling tendencies were minimized in FBC units because of the low combustion temperatures.

A typical CFB arrangement is illustrated schematically on Figure 3.7. In a CFB, primary air is introduced into the lower portion of the combustion chamber, where the heavy bed material is fluidized and retained. The upper portion of the combustor contains the less dense material that is entrained with the flue gas from the bed. Typically, secondary air is introduced at higher levels in the combustor to ensure complete combustion and to reduce NO_x emissions. The combustion gas generated in the combustor flows upward, with a considerable portion of the solids inventory entrained.

These entrained solids are separated from the combustion gas in hot cyclone-type dust collectors or in mechanical particulate separators and are continuously returned to the combustion chamber by a recycle loop. The cyclone separator and recycle loop may include additional heat recovery surface to control the bed temperature and steam temperature and to minimize refractory requirements.

Ash removal from the CFB boiler is from the bottom of the combustor and also from fly ash that is entrained in the flue gas stream, similar to PC boilers. With a CFB boiler, the ash split between bottom ash and fly ash is roughly 50 % bed ash and 50 % fly ash. All of the ash drains from CFB boilers are typically retained in a dry condition .

A key disadvantage of FBC in comparison to PC is the increased production of solid waste, not only because of use of lower quality feedstock, but also because of the sorbents added to the combustion reaction. In some cases, the resulting solid waste can also be used as construction material, cement manufacturing, structural fills, etc. [55] Secondly, although NOx emissions are reduced due to lower temperatures, there are increased emissions of N_2O – a powerful greenhouse gas – which, however, can be reduced in several ways [72]. Also, fluidized bed burners are sensitive to changes in feed quality, although they are able to use lower quality coals than PC boilers; and if the quality of feedstock is highly variable, it may not be possible to use this for power generation [73].

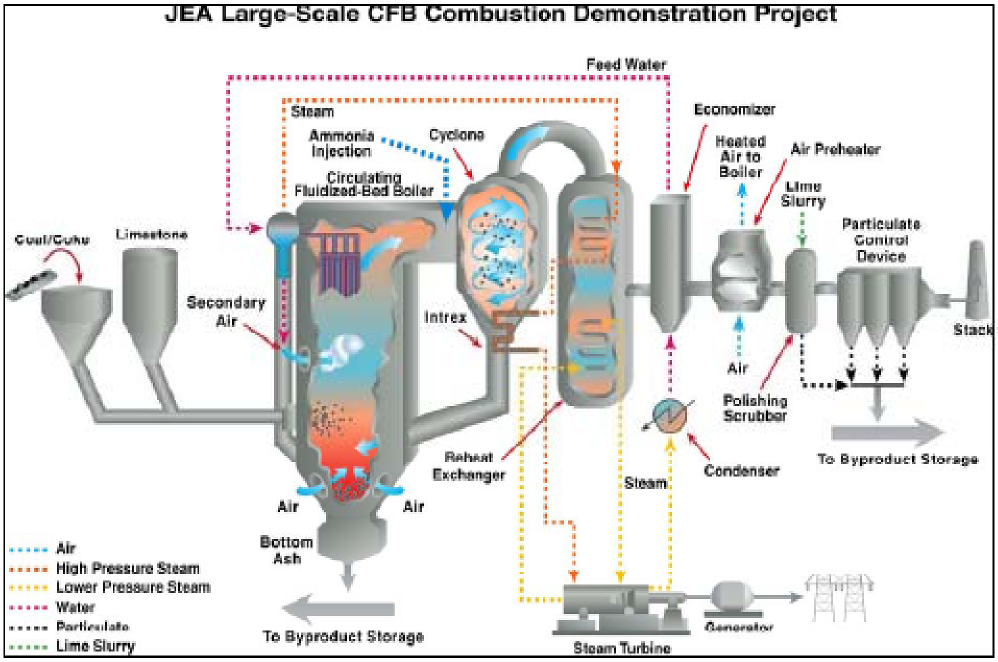


Figure 3.7 Typical CFB Unit

Source: Black & Veatch FPL. "Selection of clean coal technologies Final Report".

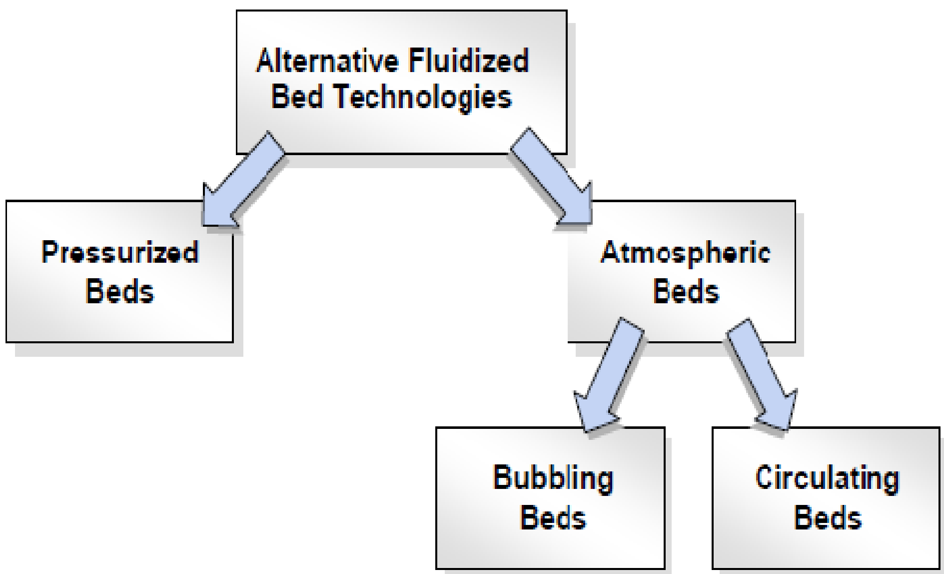


Figure 3.8 Fluidized Bed Technologies

Source: Black & Veatch FPL. "Selection of clean coal technologies Final Report".

The types of fluidized bed technologies, are illustrated in Figure 3.8. Atmospheric FBC (AFBC) is generally divided into two categories: bubbling and circulating.

3.7.2.1 Bubbling Fluidized Bed Combustion

A typical AFBC is composed of fuel and bed material contained within a refractory-lined, heat absorbing vessel. The composition of the bed during full-load operation is typically in the range of 98% bed material and only 2% fuel. The bed becomes fluidized when air or other gas flows upward at a velocity sufficient to expand the bed. At low fluidizing velocities (3 to 10 ft/sec), relatively high solid densities are maintained in the bed and only a small fraction of the solids are entrained from the bed. A fluid bed that is operated in this velocity range is referred to as a bubbling fluidized bed (BFB).

Generally, the unit size of BFBC boilers are small-to-medium range of 30-300 MW, and they are used mainly in industries – particularly in the pulp and paper industry for generating steam. BFBC technology is quite mature with a wide variety of local and international manufacturers, and so there is little prospect for dramatic improvements in the technology. Future market for the technology might be limited to India and China, where industrial use of coal is still quite prevalent (Ghosh, 2005).

3.7.2.2 Circulating Fluidized Bed Combustion

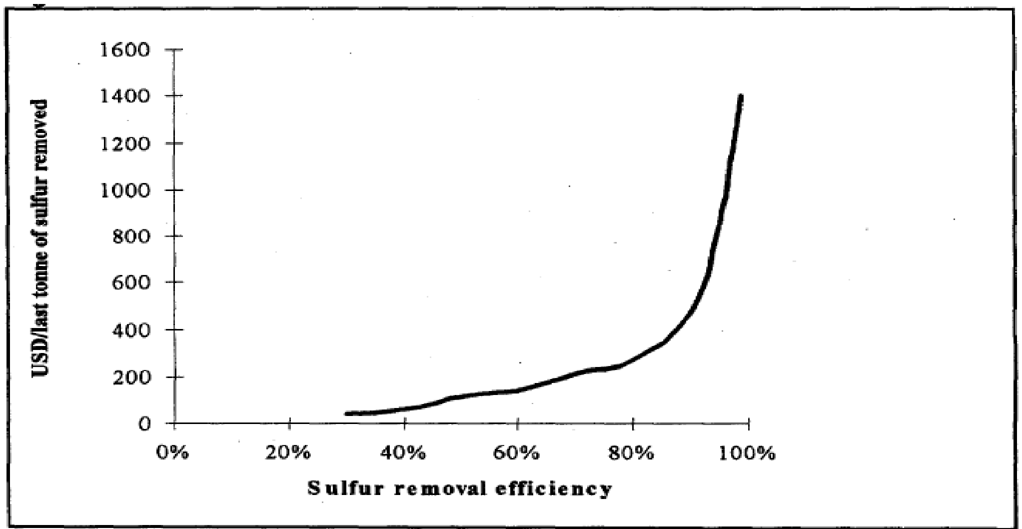
If the fluidizing velocity is increased, smaller particles are entrained in the gas stream and transported out of the bed. The bed surface, well defined for a BFB combustor, becomes more diffuse; solids densities are reduced in the bed. A fluid bed that is operated at velocities in the range of 13 to 22 ft/sec is referred to as a circulating fluidized bed, or CFB. The CFB has better environmental characteristics and higher efficiency than BFB and is generally the AFBC technology of choice for fossil fuel applications greater than 50 MW.

CFBC is a mature technology with more 1000 units installed worldwide with a total capacity greater than 65 GWh, with more than 50% of these units being installed in Asia (Ghosh, 2005). Generally, unit sizes range between 30 to 400 MW, with several hundred units in the 250-300 MW range. The technology, although developed only in the late 1970s, has proven its reliability. Some of the key companies involved in technology development include Alstom, Babcock and Wilcox, Foster-Wheeler, and Mitsui-Babcock.

The ease of operation that comes with the opportunistic ability of CFBC to use a wide variety of coals, combined with the many number of world-wide manufacturers, have helped to sustain this technology. The technology is also relatively simple, without the need for pulverizers or many add-on pollution control devices, that small CFBC plants can be installed relatively quickly (Ghosh, 2005)]. There are opportunities for retrofitting CFBC technology on old PC plants as well to take advantage of the CFBC's fuel-flexibility. Studies have indicated that the repowering PC plants with CFBC can be economically viable by using low-grade (cheap) fuel, eliminating pulverizers, and reducing auxiliary power consumption [74].

The efficiency of CFBC units mostly is comparable to equivalent PC units, although they may be 3-4 percentage points lower than equivalent PC in the 100-200 MW range. The use of low-grade coal combined with heat lost in the cyclone and by the removal of ash and spent sorbent, leads to some loss of efficiency (IEA 2005a). Furthermore, the use of subcritical steam cycle limits the overall thermal efficiency; although there are plans to develop advanced supercritical-based CFBC technology to increase efficiency. The 460 MW Lagisza plant in Poland (currently under construction) is expected to be the first supercritical CFBC power plant, with efficiency greater than 41% HHV [75].

CFBC-based power plants can have lower overall costs in comparison to PC-based systems. Although the capital cost for CFBC can be higher by 5-10% in comparison to a PC plant without pollution control devices for SOx and NOx, the costs can be 8-15 % can lower than a PC system with FGD and SCR. Operating costs can also be 5-10% lower than PC plants, especially in units less than 150 MW (Ghosh, 2005). Finally, fuel costs for a CFBC plant are lower not only because of the use of lower rank coal, but also because CFBC's fuel flexibility allows the use of a wider range of feedstock. Future government RD3 support for the development of CFBC technology is somewhat limited in the major developed countries. The United States ended its RD3 support for the CFBC technology in the early 1990s, although it played an important role at the initial stages of technology development in the 60s and 70s (Ghosh, 2005). U.S. RD3 supported various demonstration plants that focused on emission reduction and technology scale-up. Although the market in the United States is rather limited for the CFBC technology, the lessons from the demonstration plants will be useful for future technology development. The EU has also supported CFBC demonstration plants in Spain and France. Although the European Commission does not plan on future support, Electricité de France (EdF) is investing in CFBC R&D with focus on scale-up and fluid dynamics modeling (DTI 2000a).



Note: *The limestone cost used is 20 USD per ton.*

Figure 3.9 Costs for last ton of sulfur removed as a function of the sulfur removal efficiency

Source: World Bank Technical Paper No. 387,1997

3.7.3 Pressurized Fluidized Bed Combustion

Pressurized FBC permits a combined cycle, in which the pressurized hot flue gas, after particulate removal, is expanded through a gas turbine to drive the combustion air compressor and generate additional electric power. Typically, pressures in the range of 1.2-1.6MPa are employed, which correspond to the pressure ratios of conventional heavy-duty combustion turbines. In contrast to CFBC and BFBC, where combustion takes place at atmospheric pressure, the boiler and cyclone of a PFBC system are placed in a pressurized chamber, so that combustion can take place under high pressure. The underlying combustion process for the PFBC can be based on either bubbling or circulating fluidized-bed systems, although most of PFBC systems have been based on the bubbling-bed technology. Pressures of 12-16 bars can be reached with temperatures in the range of 800-900 deg C [76]. The high-pressure hot flue gas from combustion process is then cleaned and expanded in a gas turbine, allowing for a combined cycle operation. Generally, the gas turbine accounts for 20% and the steam turbine 80%, of the total electricity generation. The environmental performance of PFBC is similar to other FBC systems, except for the increased efficiency.

Combustion takes place at temperatures from 800-900°C resulting in reduced NOx formation compared with PCC. N_2O formation is, however, increased. SO_2 emissions can be reduced by the injection of sorbent into the bed, and the subsequent removal of ash together with reacted sorbent. Limestone or dolomite are commonly used for this purpose. As indicated above, hot gas filtration may be needed before the flue gases are passed through the turbine.

The key advantage of PFBC is the increased efficiency that results from both the pressurized combustion and the combined cycle operation. The efficiency of PFBC is higher than of CFBC, and it can reach as high as 40% (Ghosh, 2005). Advanced PFBC (APFBC) systems add a carbonizer before the PFBC boiler to generate fuel gas and char. The char is sent to the PFBC boiler and the fuel gas is cleaned and burned in a topping combustor. The vitiated flue gas from the PFBC boiler and from the topping combustor is then sent into the gas turbine for power generation. The efficiency of such advanced systems can be as high as 47% (Ghosh, 2005). In fact, the most advanced Karita supercritical PFBC plant in Japan (360 MW) already has a net efficiency of 42% HHV [77].

Key disadvantages of the PFBC technology include: the need to pressurize the input feedstock and sorbents, depressurize the ash and spent sorbent, and the complexities associated with the pressure vehicle. While the APFBC is more efficient compared to PFBC, its combined cycle operation is not as efficient as that in the case of NGCC or IGCC. Furthermore, the advanced-PFBC systems with a topping combustor add to the complexity of the system. Rather than partially carbonizing the coal, it might be better to gasify it completely, as in an IGCC. There have been five 80 MW PFBC demonstration plants in the US, Europe and Japan using the technology developed by Sweden’s ABB Carbon, which is now part of Alstom Sweden [78]. Other suppliers are Ahlstorm in Finland, Lurgi-Lentjes-Babcock in Germany and Ebara,Hitachi and Mitsubishi in Japan. (Ghosh, 2005). These demonstration plants indicated several problems in the clean up of hot gas, high erosion in the heat exchanger and overheating of the bed due to agglomeration [79]. The future development of this technology is reliant primarily on efforts by Japan and possibly China.

3.7.4 Integrated Gasification Combined Cycle

The technology is relatively new in connection with power generation. Among the coal fired options, Integrated Gasification Combined Cycle (IGCC) systems have the best environmental performance and are potentially suitable candidates [80]. IGCC uses a combined cycle format with a gas turbine driven by the combusted syngas, while the exhaust gases are heat exchanged with water/steam to generate superheated steam to drive a steam turbine. Using IGCC, more of the power comes from the gas turbine. Typically 60-70% of the power comes from the gas turbine with IGCC, compared with about 20% using PFBC. A typical IGCC plant can be visualized from figure 3.10.

Coal gasification takes place in the presence of a controlled 'shortage' of air/oxygen, thus maintaining reducing conditions. The process is carried out in an enclosed pressurized reactor, and the product is a mixture of CO + H_2 (called synthesis gas, syngas or fuel gas). The product gas is cleaned and then burned with either oxygen or air, generating combustion products at high temperature and pressure. The sulphur present mainly forms H_2S but there is also a little COS. The H_2S can be more readily removed than SO_2. Although no NOx is formed during gasification, some is formed when the fuel gas or syngas is subsequently burned.

Three gasifier formats are possible, with fixed beds (not normally used for power generation), fluidized beds and entrained flow. Fixed bed units use only lump coal, fluidized bed units a feed of 3-6 mm size, and entrained flow gasifiers use a pulverised feed, similar to that used in PCC. IGCC plants can be configured to facilitate CO_2 capture. The new gas is quenched and cleaned. The syngas is 'shifted' using steam to convert CO to CO_2, which is then separated for possible long-term sequestration.

Emissions from an IGCC plant are lower than combustion-based PC plants. IGCC essentially has no particulate emissions, since almost all of the particulates have to be removed before the syngas enters the gas turbine. Unlike in a PC plant, gas cleaning is part of the process, rather than an “add-on”. Using the metric of mass emissions per energy content of input (e.g. lbs/MMBTU or g/kcal), it is expected that U.S IGCC plants are expected to emit about 3-5 times less SO_2 than PC plants with FGD and 2-3 times less NOx than PC plants with SCR [81]. IGCC also uses at least 70% less water than standard PC plants (Khan et. al 2005). Hence, the environmental performance of IGCC plants can be quite close to NGCC plants, despite using coal. Similar to the PC plants, the overall efficiency of IGCC is dependent on coal quality [82]; a U.S. EPA study suggests a drop of three percentage points in efficiency for IGCC using lignite instead of bituminous coals (Khan et. al 2005) . IGCC is part of future ‘zero emission’ program by the US government.

The demonstration plants in Europe and U.S. have operated with efficiencies ranging between 38-43% HHV (Khan et.al 2005). Other studies have indicated that IGCC with entrained-flow gasifiers can have efficiencies in the range of 35-40% (HHV). It is expected that the efficiency of IGCC technology will improve significantly with increasing operational experience. R&D efforts to improve gas turbines, hot-gas-cleanup

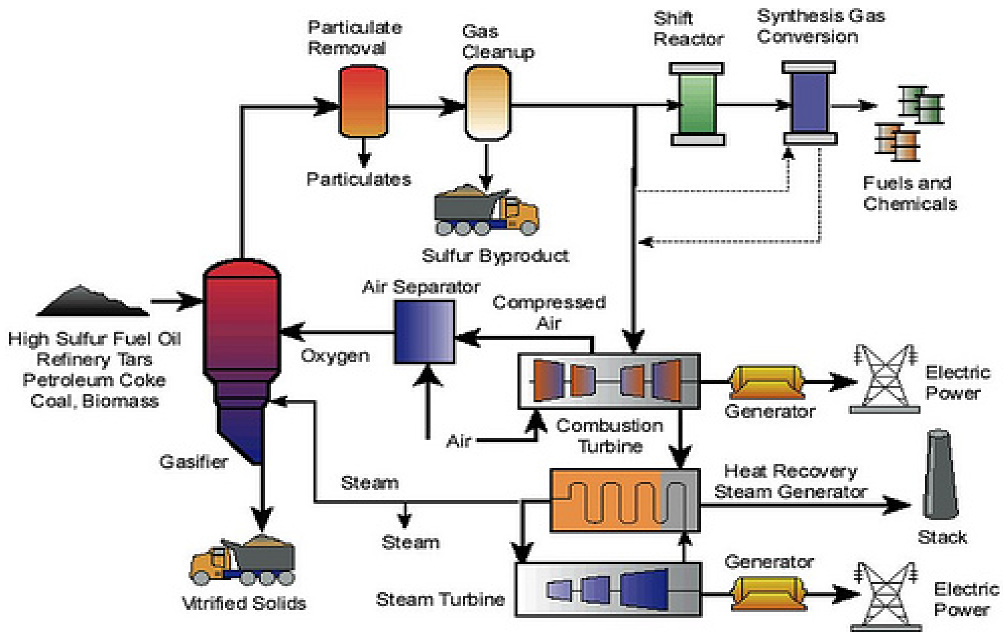


Figure 3.10 Typical IGCC unit

Source: World Coal Institute, Coal Book

systems, and materials technologies are expected to increase efficiency of IGCC plants to 45-50% HHV by 2010-2015, and further to 50-60% HHV by 2015-2025 [83] .

3.7.5 Oxy fuel Combustion

Oxy fuel combustion is an emergent technology that also offers an opportunity to produce a concentrated carbon dioxide stream that can then be more readily captured for storage. The process is very similar to conventional PCC generation but near pure oxygen is used instead of air in the boiler. This significantly reduces the dilution of carbon dioxide in the exhaust gas stream by removing nitrogen (80% in air) from the system.

Almost pure oxygen will be available for the combustion process in the boiler. This means that it will be possible to control and optimize the combustion process through the injection of oxygen in dedicated areas inside the boiler, which is not possible in air-fired boilers [84]. This means that the boiler design will have an additional degree of freedom compared to conventional air-fired boilers, which can be taken advantage of to control combustion conditions, emission formation and temperature distribution. When oxyfuel combustion is applied to a CFB boiler, opportunities to significantly reduce the amount of flue gas recycle exist. In a CFB boiler, the combustion temperature can be controlled through the recirculation of bed material, meaning that CO_2 recycle need not be very high, and that the boiler size and cost can be reduced in an easier manner than for the PF case. Alstom [85] have reported that pilot scale testing of oxyfuel CFB with O_2 concentrations of up till 70% is being performed. This technology has only been demonstrated at pilot scale at present. Research and development effort is under way to demonstrate this technology at a larger scale.

3.7.6 Integrated Coal Gasification Fuel Cell Combined Cycle

IGFC is a hybrid power generation technology and is being developed. It is a triple combined power generation system in that the power generation efficiency is improved using the coal combustion energy three times for power generation by installing fuel cells at the upper stream of the gas turbines. It is expected that this system is a technology being able to develop a high efficiency of 55% or more at transmission terminal, HHV.

The world is facing two main energy-related problems: lack of secure energy so in this context, fuel cells are considered excellent devices for future power plants, expected to produce clean electrical energy at high conversion rates and low emissions [86]. Solid oxide fuel cells(SOFC) are electrochemical devices based on a solid ion-conducting electrolyte which require operational temperatures up to 1000 °C. Such temperatures impose some constraints on SOFC manufacturing materials, but make them very suitable for co-generation and/or coupling with gas turbines. The coupling of an SOFC stack system with GTs (gas turbines) is considered the best integration option since an SOFC–GT hybrid system can reach net electrical and global efficiencies close to 70% and 85%, respectively [87].

3.7.7 Next-generation, High-efficiency Integrated Coal Gasification Electric _Power Generating Process (A-IGCC/A-IGFC)

In addition to IGFC, by returning the steam generated by exhausted heat from gas turbines and fuel cells to the gasification furnace where efficient gasification is performed using heat and steam i.e energy regeneration, the efficiency may be raised up to 57% on IGCC while using 1700◦C class gas turbine and approximately 65% on IGFC. These two are now being researched and known as A-IGCC and A-IGFC respectively [88].Unlike the existing IGCC/IGFC system that integrates partial oxidation gasifiers, fuel cells, and gas and steam turbines using a cascade method of energy utilization, the A-IGCC/A-IGFC i.e Advanced IGCC/IGFC systems direct recycled heat from gas turbines or fuel cells back into steam reforming gasifiers that employ endothermic reactions. This next generation exergy recovery-type IGCC/IGFC being studied. Thus, this technology is expected to have the potential to bring about a dramatic increase in system efficiency, contributing, in the future, to the provision of energy resources and a reduction in CO_2 emissions. The expected commercialization timings of these two technologies is year 2022 and 2025 respectively [89].

3.7.8 Underground Coal Gasification

Underground coal gasification is a promising technology as it is a combination of mining, exploitation and gasification. The main motivation for moving toward UCG as the future coal utilizing technique is the environmental and other advantages over the conventional mining process. Some of these benefits include increased worker safety, no surface disposal of ash and coal tailings, low dust and noise pollution, low water consumption, larger coal resource exploitation and low methane emission to atmosphere [90-91]. UCG is particularly advantageous for deep coal deposits and steeply dipping coal seams since at these conditions less gas leakages to the surroundings and high pressures favor methane formation. The gas composition of UCG-syngas is very similar in calorific value to that produced in surface gasifiers, but with higher methane content [92]. But UCG involves some environmental impacts such as land subsidence and groundwater reserve pollution, which serve as disadvantages. Thus before the UCG site is selected there is a need for a thorough environmental impact assessment and complete risk analysis [93]. UCG is relatively well developed in countries like USA, Russia, France, Spain and China [94].

3.8 Carbon Capture and Storage(CCS)

The processes described above for controlling the emissions of some pollutants cannot remove CO_2 from plant emissions and as such are not a means of combatting climate change. The technology behind the development of zero-carbon emissions coal is Carbon Capture and Storage (CCS), which is a means of separating out carbon dioxide when burning fossil fuels, collecting it and subsequently “dumping” it underground or in the sea. CCS is an integrated concept consisting of three distinct components: CO_2 capture, transport and storage (including measurement, monitoring and verification). All three components are currently found in industrial operation today, although mostly not for the purpose of CO_2 storage. Some capture technologies are economically feasible under specific conditions, while others remain in the research stages. To date, there has not been a single application of CCS to large scale (> 500 MW) power stations [95]. Carbon sequestration is a term used for the long term isolation of carbon dioxide from the atmosphere through physical, chemical, biological, or engineered processes [96].With regard to power generation, there are three major systems that are amenable to carbon capture: post-combustion (PC, FBC), oxy-fuel combustion (PC, FBC), and pre-combustion(APFBC, IGCC) [97].The technology is known to be the future of coal based power generation in 21st century.

Highly efficient power plants are also a prerequisite for the development of new technologies in capturing and storing CO_2 [98]. "The first step in the CCS process is removal of CO_2 from either IGCC synthesis or combustion exhaust gases. Relatively small scale CO_2 separation systems are commercially available today and are serving the industrial market for CO_2, but major improvements in the cost, performance and operating characteristics will be required before its deployment for large powder plants. One promising new CCS technology is chilled ammonia process. Early data from the laboratory scale equipment indicate that removing CO_2 from a PC plant using chilled ammonia process may reduce electricity output by 10% compared to 29% for the monoethanolamine process" (EPRI Journal Summer 2006). "Efforts are underway to launch large scale broadly collaborative demonstrations of the chilled ammonia process for capturing CO_2 from the flue gases of coal fired power plants. The two phase demonstration program would scale up the technology currently being tested in a pilot project at the We Energies Pleasant Prairie power plant and would also involve injection of the captured CO_2 into a secure geologic formation" [99].

3.8.1 Cost of CCS

According to the U.S. Department of Energy, it is not economical to retrofit existing coal plants with carbon capture technology. Existing CO_2 capture technologies are not cost-effective when considered in the context of large power plants. Economic studies indicate that carbon capture will add over 30 % to the cost of electricity for new

(IGCC) units and over 80 % to the cost of electricity if retrofitted to existing pulverized coal (PC) units. A recent study from the National Energy Technology Laboratory (NETL) confirms that additional alternatives need to be pursued to bring the cost of carbon capture down. In addition, the net electricity produced from existing plants would be significantly reduced - often referred to as parasitic loss - since 20 to 30 % of the power generated by the plant would have to be used to capture and compress the CO_2 [100].

Adding carbon and capture technology to new coal plants makes electricity from coal more expensive than energy from solar thermal and wind power, even when "firming costs" are included for alternatives.Capturing and compressing CO_2 requires much energy, significantly raising the running costs of CCS equipped power plants. In addition there are added investment or capital costs. The process would increase the energy needs of a plant with CCS by about 10 to 40 %. The costs of storage and other system costs are estimated to increase the costs of energy from a power plant with CCS by 30 to 60 %, depending on the specific circumstances.

3.8.2 Schwarzenegger Clause

In October 2008, the European Parliament's Environment Committee voted to support a limit on CO_2 emissions for all new coal plants built in the EU after 2015. The so-called "Schwarzenegger clause" applies to all plants with a capacity over 300 MW, and limits their annual CO_2 emissions to a maximum of 500 grams per kilowatt hour. The new emissions standard essentially rules out traditional coal plant technologies and mandates the use of Carbon Capture and Storage technologies. The Committee also adopted an amendment to support the financing of 12 large scale commercial CCS demonstration projects, at a cost that could exceed €10 billion [101-102]. Different CCS technologies are explained below and illustrated in figure 3.11.

3.8.3 Geological Storage

Injection of CO_2 into the earth's subsurface offers potential for the permanent storage of very large quantities of CO_2. The CO_2 is compressed to a dense state, before being piped deep underground into natural geological 'reservoirs'. Provided the reservoir site is carefully chosen, the CO_2 will remain stored (trapped in the bedrock or dissolved in solution) for very long periods of time and can be monitored. A number of options for the geological storage of CO_2 are being researched. it has been decided that the oxygen combustion technology being researched and developed by Japanese researchers is to be applied to the Callide, a power plant in Australia, for proving the test, which is the world's first project including recovery of CO_2 from a thermal power plant and storage of the recovered CO_2 underground [103].

3.8.4 Depleted Oil & Gas Reservoirs

An obvious site for geological storage is depleted oil and gas reservoirs. In the USA, it is estimated by the US DOE that the storage capacity of depleted gas reservoirs is about 80-100 Gigatonnes, or enough to store US emissions of CO_2 from major stationary sources (e.g. power stations) for 50 years or more.

3.8.5 Saline Aquifers

Storing large amounts of CO_2 in deep saline water-saturated reservoir rocks also offers great potential. One major project is already being conducted by the Norwegian company Statoil. This is at the Sleipner field in the Norwegian section of the North Sea, where about 1 million tonnes a year of CO_2 are being injected into the Utisira Formation at a depth of about 800-1000 metres below the sea floor. CO_2 storage can have ancillary economic benefits, by enabling improved oil and coal bed methane extraction which may provide economic incentives to accelerate the initial development of the process.

3.8.6 Enhanced Oil Recovery

CO_2 is already widely used in the oil industry to increase oil production – the CO_2 is injected to 'push' the oil out of the underground strata, so increasing the level of recovery from the field. Without such methods of enhanced production, many oil fields can only produce half or less of the original resource.

3.8.7 Enhanced Coal bed Methane

It is a potential opportunity for storing CO_2 in unmineable coal seams and obtains improved production of coal bed methane as a valuable by product.

3.8.8 Zero Emission Technology

A concept of zero-emission coal technology, proposed by ZECA Corporation, is presented and discussed. The process can produce electricity at 60–70% efficiency with zero emission to the atmosphere. The carbon dioxide is produced as concentrated, clean stream, which is easy to sequestrate. The process uses CaO/CaCO3 reaction to enhance hydrogen production and to separate carbon dioxide. Hydrogen feeds a stack of solid oxide fuel cells (SOFCs), which produce electricity. High-temperature byproduct heat from the SOFC drives the calcination reaction, which restores CaO [104]. The idea itself is very attractive. It is claimed that electricity can be produced with efficiency around 70% without any emission into the atmosphere [105].

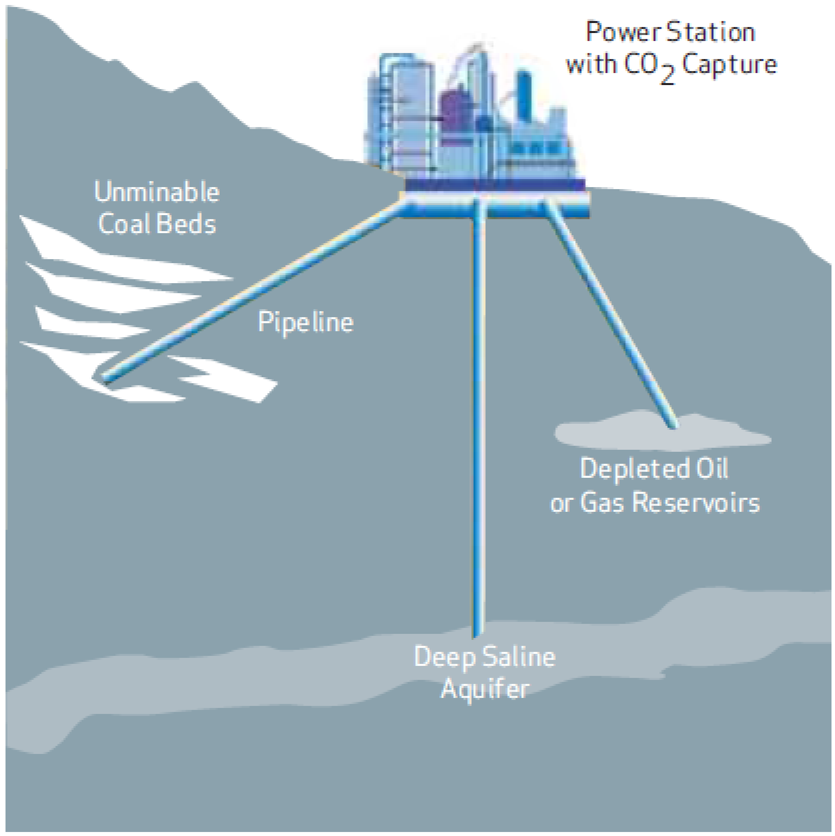


Figure 3.11 CO_2 Capture and Storage

Source: WCI, Coal Book

3.9 SO_2 Emission Control Technologies

"The simplest way to reduce SO_2 emissions in industrializing countries is to switch to a coal with lower sulfur content. The benefits are obvious: it requires no change in operating procedures, and no additional by-products are generated. The capital investment can range from none to considerable. In some cases, modification to coal handling equipment is necessary. Switching to low sulfur coal alone is rarely sufficient to meet regulatory requirements, but it can be a first step in an emission reduction program, reducing the cost of following control technologies. Since the inception of the Clean Air Act in 1970, SO_2 emissions in the United States declined by 50% at less than 10%of the originally estimated cost (Kerr 1998). Much of this reduction appears to have occurred through substitution at electric utilities from high-sulfur coal to cleaner-burning inputs of low-sulfur coal from the Powder River Basin (PRB) of Wyoming and Montana [106].

For large power plants tied to local suppliers for political or economic reasons, fuel switching may be difficult. In such cases an alternative is coal cleaning by physical separation. Although sulfur removal is not the primary aim, physical coal cleaning techniques remove inorganic sulfur compounds in the coal, resulting in a SO_2 removal of 10 - 40%. Coal cleaning at the mine site also reduces the cost of transportation and has the advantage of reducing the amount of by-products generated at the power plant; less sorbent is needed for SO_2 removal, hence reducing the cost of waste disposal. The major drawback is that with a lower sulfur content, the fly ash resistivity may increase. This affects the ESP performance. ESP modifications may be necessary.

Nonetheless, coal cleaning remains the most cost-effective route to reduce SO_2 emissions. When fuel switching and coal cleaning are not possible or not sufficient to meet desired emission levels, an SO_2 removal technology must be introduced. The choice of SO_2 removal technology depends on a number of factors: emission requirements, plant size and operating conditions, sulfur content in the fuel(s), and the cost of various technology options, all of which are unique to each site. Wet scrubbing has become the most commonly used technology for large base load, coal-fired power plants. It has a market share of 85% of the installed capacity.

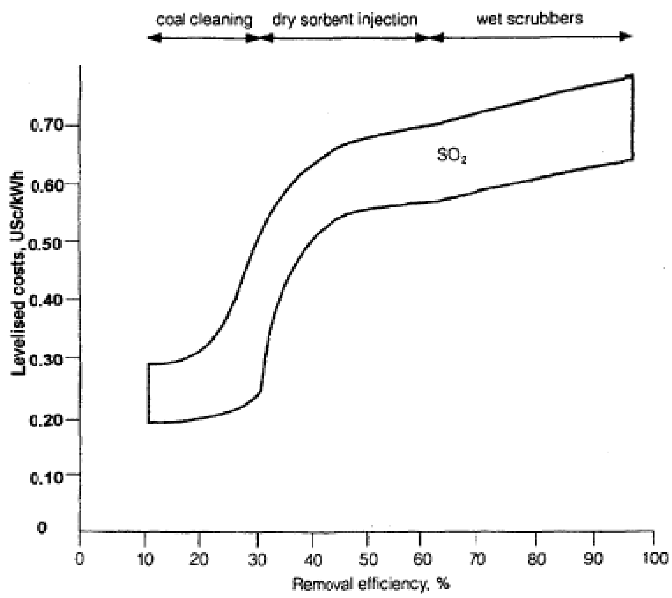


Figure 3.12 Levelized costs in UScents/kwh of electricity produced for different SO_2 removal technologies

Source: IEA(1995)

Capital costs for FGD have come down in the last few years due to improved design and simplified processes and they can be expected to decrease further as a result of a greater demand in the emerging markets of Asia and Eastern Europe. High capital costs result in high overall costs for smaller boilers and boilers with few operating hours due to peak load operation. The most economical choice for these boilers is either fuel switching, coal cleaning or a sorbent injection method with low capital requirements. This is also true for boilers with short residual lifetime. Therefore, when choosing a sulfur removal system, it is important to have realistic assumptions about annual operating hours and the lifetime of the plant. Assumptions which are too optimistic may result in incorrect conclusions. Despite the considerable variations in capital cost and increased EPC, the actual dollar costs per ton of SO_2 removed do not vary much for different methods. This can be seen in Figure 3.13. Coal cleaning is the most cost efficient route to reduce SO_2 emissions.

Sorbent injection processes, which have lower capital costs than wet scrubbers, require larger quantities of sorbent resulting in higher overall costs. The relatively low operating costs of wet scrubbers, combined with high sulfur removal efficiency, makes the overall sulfur removal cost lower than for sorbent injection processes despite the higher investment. In countries with a need for immediate removal of SO_2 emissions under tight economical constraints, a stepwise approach can be considered. Low-cost sorbent injection is an appropriate first step that can be implemented rapidly. It can be followed later by further upgrading to a hybrid system with higher removal efficiencies. Another option is to upgrade by adding a conventional wet scrubber, with the sorbent injection process and the scrubber sharing the same limestone storage and transport system.

When evaluating sulfur removal methods, it is important to use the actual average sulfur content of the coal for estimation of the required SO_2 removal. If the maximum sulfur content is used in the evaluation, the result may be totally misleading. One important aspect to be considered, particularly in the case of countries with a shortfall in power capacity, is the parasitic power consumption required by the SO_2 removal process.

As shown in Figure 3.14, sorbent injection systems have the lowest parasitic power demand (up to 0.5% of the electricity production). Spray dry scrubbers have a higher power demand, but only about half of that of wet scrubbers.

Wet scrubbers, the most widely used FGD technology, can remove as much as 99% of SO_2.Wet scrubbers take the lead followed by spray dry scrubbers and sorbent injection systems in the FGD market throughout the world. Regenerable and combined SO_2/NOx processes have a small share and the trend is not expected to change in the short term according to current plans for new FGD installations. New developments in sorbent injection technologies are in progress and this type of FGD is expected to become more widely used in older coal-fired plants" (Karin Oskarson et. al)

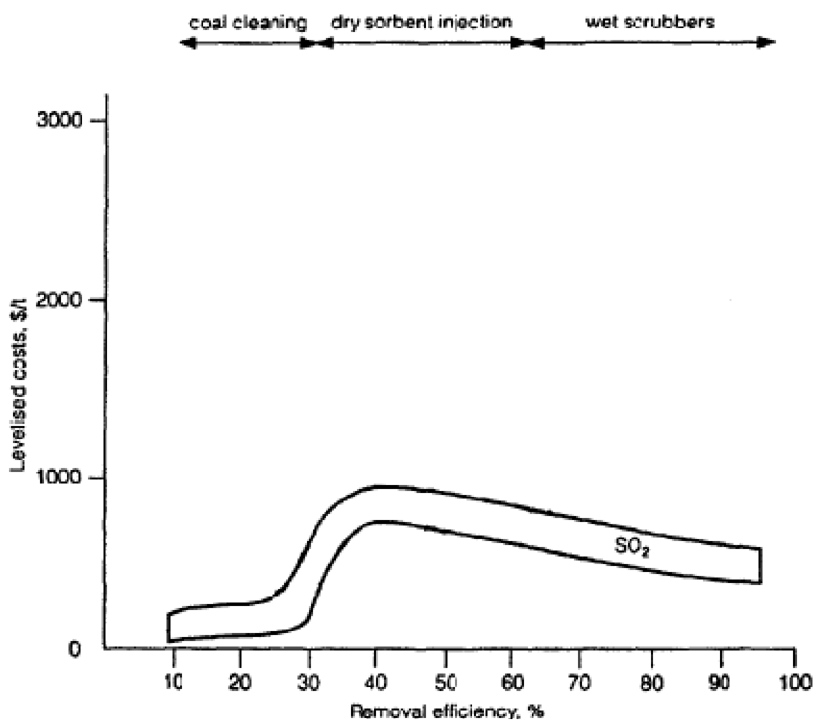


Figure 3.13 Levelized costs in US \$/ton of SO_2 separated for different technologies

Source: International Energy Agency

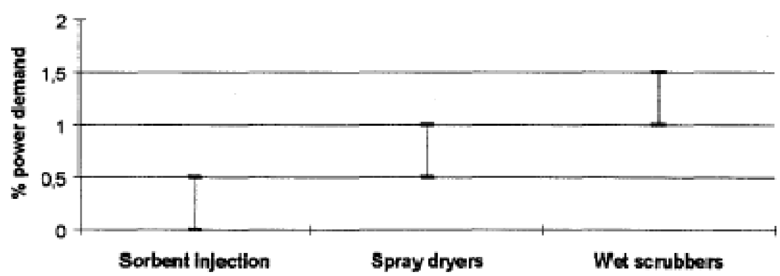


Figure 3.14 Parasitic Power demand for different SO_2 removal methods

Source: World Bank Technical paper no 387, 1997

3.9.1 Sorbent Injection Process

" For PC boilers, injection of a sorbent is a simple technology for SO_2 removal. This chapter deals with three categories of sorbent injection processes: furnace sorbent injection, duct sorbent injection, and hybrid sorbent injection. The processes are illustrated in figure 3.15. In the first two processes, the sorbent is injected directly into the boiler furnace or duct. Hybrid sorbent injection is a combination of furnace and duct sorbent injection, as injection of sorbent into the furnace is followed by either:

- downstream sorbent injection into the duct;
- reactivation of the sorbent by humidification in a reactor; or
- separation of unreacted sorbent removed along with ash from the ESP followed by reactivation and recycling of the unreacted sorbent.

The SO_2 removal efficiency is highly dependent on the sorbent to sulfur ratio (Ca/S molar ratio). An increased sorbent to sulfur ratio improves the SO_2 removal. However, at higher sorbent ratios the sorbent utilization, i.e. the fraction of reacted sorbent, decreases. This leads to increased sorbent consumption and higher operating costs. In some cases, it may not be economically justifiable with a large increase in sorbent consumption, to achieve only a small improvement in SO_2 removal.

After the Ca/S ratio, the single most important factor affecting sorbent injection efficiency is the approach-to-adiabatic-saturation temperature. The SO_2 removal increases with decreased approach temperature. The efficiency can also be raised by reactivating excess sorbent through humidification of the flue gas, by recycling unreacted sorbent, and by the use of additives. These tests indicate that these methods can raise the removal efficiency to 90-95%. Humidification also serves another purpose as it improves the ESP performance.

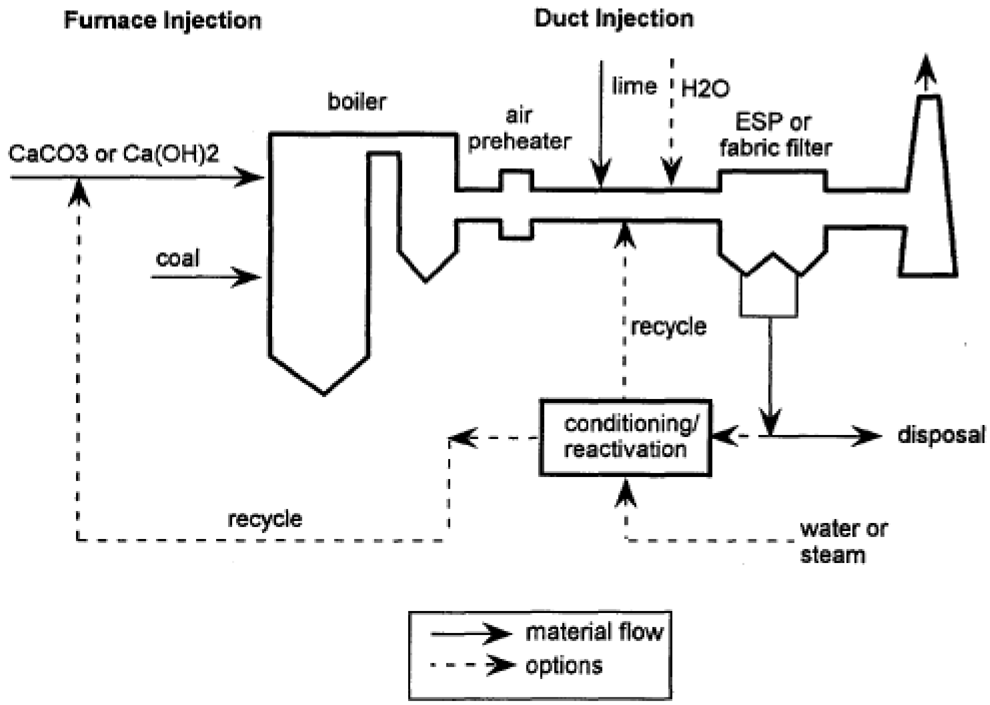


Figure 3.15 Sorbent injection systems

Source: World Bank Technical Paper no 387, 1997

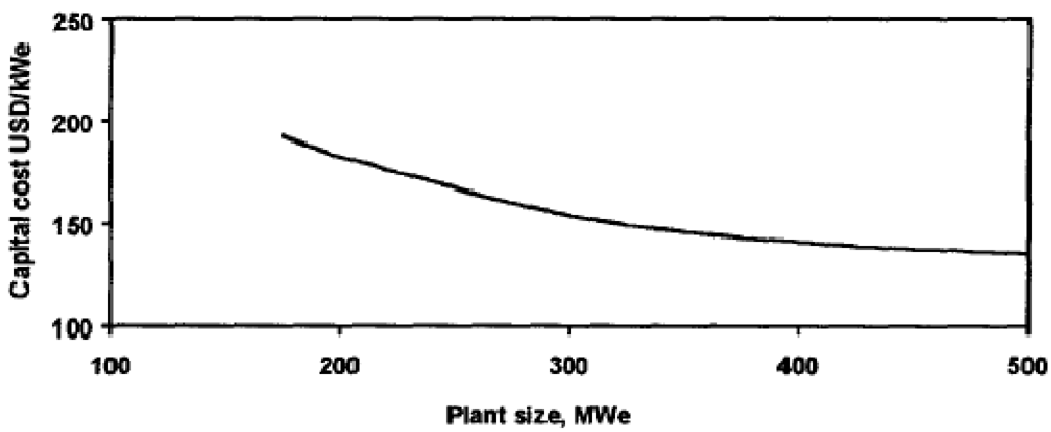


Figure 3.16 Investment for a wet FGD plant depending on plant size

Source: International Energy Agency, retrieved from WB Technical paper no 387,1997.

With some processes, even higher efficiencies up to 95% can be achieved. The SO_2 removal efficiency is highly dependent on the sorbent to sulfur ratio (Ca/S molar ratio). An increased sorbent to sulfur ratio improves the SO_2 removal. However, at higher sorbent ratios the sorbent utilization, i.e. the fraction of reacted sorbent, decreases. This leads to increased sorbent consumption and higher operating costs. In some cases, it may not be economically justifiable with a large increase in sorbent consumption, to achieve only a small improvement in SO_2 removal"(Karin Oskarson et. al).

3.9.2 Spray dry scrubbers

"Spray dry scrubbers were developed as a cheaper alternative to wet scrubbers in the early to mid- 1970s. Presently, they have a market share of about 10 %, but the demand has fallen recently due to difficulties with utilization of the by-product. The by-product, which consists of a mixture of unreacted lime, fly ash, and calcium sulfite/sulfate, must be disposed of.

Dry scrubbers have lower capital costs than wet scrubbers because there is no need for waste sludge handling and processing, and because cheaper material can be used in the absorber etc. The spray dryer absorber, which operates at 10-20°C above dew point of the flue gas, can be constructed of carbon steel; whereas wet scrubbers operate below the dew point and therefore require rubber lining or stainless steel. But the drawback of spray dry scrubbers is the four to five times higher cost for lime sorbent compared to the limestone used in wet scrubbers. This is why spray dry scrubbers are used mostly in small boilers burning low to medium sulfur coals, i.e. less than 2.5% sulfur, and for large plants in peak load operation. For the same reasons, the system is suitable for retrofit on plants with a limited remaining lifetime. Due to their low capital requirements, spray dryers are suitable for developing countries. However, a significant percentage of the capital requirements, at least during the first 3 to 7 years of technology deployment will be in foreign exchange. Demonstration may be needed for high ash Indian coals and high sulfur coals generally. An important feature of spray dry scrubbers compared with wet scrubbers is that no waste water is produced. Therefore, they are suitable for sites where there is no space for waste water handling. Because they normally are more compact than wet systems, they are also advantageous in retrofit applications where there are often space constraints. The process has a high efficiency for SO_3 and HCl removal, which makes it suitable for plants with such requirements. A critical aspect of spray dry scrubbers is the increase in waste production. The effect on precipitator performance and ash handling cannot be neglected. In retrofit installations, modifications to the existing ESP may be required" "(Karin Oskarson et. al).

3.9.3 Wet Scrubbers/Wet Flue Gas Desulfurization

"Wet scrubbers or wet flue gas desulfurization have 85% of the market for processes capable of removing SO_2 from flue gases in thermal power plants. Wet scrubbers include a large number of processes based on gas/liquid reactions which occur when the sorbent is sprayed over the flue gas in an absorber. The sulfur oxides in the flue gas react with the sorbent and form a wet by-product. The wet lime/limestone process is the single most popular wet scrubber process having a market share of 70%. In most industrialized countries wet scrubbing is a well-established process for removing SO_2.

Wet scrubbing is the technology of choice for new and retrofit applications that require more than 80-90% SO_2 removal. The investment is higher than for sorbent injection systems and spray dry scrubbers, but due to the lower sorbent demand they are more cost-effective than sorbent injection systems and spray dry scrubbers for coals with high sulfur content and for large boilers. The drawback relative to sorbent injection is that wet FGD systems require a larger surface area. There is a lot of chemistry involved in a wet scrubbing process. Chemical engineers, chemical laboratories and revised O&M procedures will be needed in order to achieve a properly functioning plant with both minimal emissions and material corrosion.

Generally, investment costs have gone down over the years due to simplification of the design and improvements in the FGD process. Therefore, advanced wet limestone FGD processes can often be more cost effective than conventional wet scrubbers. The influence of plant size on the investment cost is shown in Figure 3.16. The capital cost per kw installed decreases with increased plant size up to around 300-400 MW where the curve flattens. The retrofit cost is approximately 30% higher than the cost of installing a scrubber on a new plant.

The investment cost for the FGD plant does not depend as much on the sulfur content of the coal as on boiler size. The boiler size and the flue gas flow determine the scrubber size. The only parts of the total process that depend on the sulfur content are the sorbent and waste product handling equipment. To maintain the same emission level when the sulfur amount in the coal increases from 1 to 2%, the investment cost increases approximately 10%.

Wet scrubbers are the most widely used FGD technology for SO_2 control throughout the world. Calcium, sodium- and ammonium-based sorbents have been used in a slurry mixture, which is injected into a specially designed vessel to react with the SO_2 in the flue gas. The preferred sorbent in operating wet scrubbers is limestone followed by lime. These are favoured because of their availability and relative low cost. The overall chemical reaction, which occurs with a limestone or lime sorbent, can be expressed in a simple form as:

$$SO_2 + CaCO_3 = CaSO_3 + CO_2$$

In practice, air in the flue gas causes some oxidation and the final reaction product is a wet mixture of calcium sulphate and calcium sulphite (sludge). A forced oxidation step, in situ or ex situ (in the scrubber or in a separate reaction chamber) involving the injection of air produces the saleable by-product, gypsum, by the following reaction:

$$SO_2 + CaCO_3 + \frac{1}{2} O_2 + 2H_2O = CaSO_4.2H_2O + CO_2$$

Waste water treatment is required in wet scrubbing systems. Commercial wet scrubbing systems are available in many variations and proprietary designs. Systems currently in operation include:

- lime/limestone/sludge wet scrubbers;
- lime/limestone/gypsum wet scrubbers;
- wet lime, fly ash scrubbers; and
- other (including seawater, ammonia, caustic soda, sodium carbonate, potassium and magnesium hydroxide) wet scrubbers.

Wet scrubbers can achieve removal efficiencies as high as 99%. Wet scrubbers producing gypsum will overtake all other FGD technologies, especially with the increased cost of land filling in Europe and the introduction of increasingly stricter regulations regarding by-product disposal”(Karin Oskarson et. al).

3.10 NOx Emission Control Technologies

“The first step in any NOx, emission reduction strategy is to optimize plant operation. Operational changes should be made prior to implementation of any NOx reduction technology or installation of additional equipment. For example, low excess air and boiler fine tuning can be regarded as methods of reducing NOx formation significantly at little or no extra cost. Both methods are easy to implement and require no boiler modifications. Minimizing excess air may also lead to increased boiler efficiency. As every boiler is more or less unique, each must be tested to find the optimum level of excess air at which the boiler can be operated without risking corrosion or high rates of unburned coal.

Upgrading or replacing coal pulverizers to maintain coal fineness, and balancing fuel and air flows to the various burners to create a staged combustion are other low cost routes to the reduction of NOx emissions. The staged combustion is accomplished by withdrawing a portion of the total air required to achieve complete combustion from the early stage of combustion in order to create a combustion zone with lack of oxygen, which oppresses the NOx formation. The air is added-in at a later burner stage to ensure complete combustion. The NOx emission reductions which can be achieved by these methods may not be sufficient to reach the required emission level, but they are extremely cost-effective. These methods can also be combined with other low-cost modifications. Optimizing operational performance should not only involve individual component elements. The entire fuel preparation and furnace system must be optimized if NOx formation is to be effectively minimized. A reliable system for continuous monitoring of O_2 and NOx concentrations in the flue gas can assist in defining the optimum operational parameters. After optimizing plant operation, in-furnace NOx reducing equipment should be applied on PC boilers. In-furnace NOx reducing equipment involves modification of the combustion process, e.g. low NOx burners (LNB), OFA, flue gas recirculation and gas or coal reburning.

After this type of in-furnace NOx control has been implemented, post-combustion measures must be installed to reduce NOx emissions further. Post-combustion NOx. removal equipment includes: selective non catalytic reduction, selective catalytic reduction, and combined SO_2/NOx removal. Such methods are the only available options for reduction of NOx emissions from fluidized bed boilers, however, uncontrolled NOx emissions tend to be quite low from fluidized bed boilers.

Figure 3.17 shows estimated levelized costs per kwh of electricity produced for various removal efficiencies. The figure shows that combustion modifications such as LNB and OFA give the lowest increase in production cost but they can only reduce the emissions up to 60%o. SCR is the most efficient way to reduce NOx emissions, but it is also the most expensive technology. Combustion modifications require a lower capital cost than SCR, and they have very low, if any, O&M costs. The variable O&M cost for SCR represents up to 50% of the total levelized cost" (Karin Oskarson et. al).

3.10.1 Low NOx Combustion Technologies

"Low NOx combustion modifications include LNB, OFA, flue gas recirculation and gas or coal reburning. These measures can be implemented on PC boilers to reduce NOx emissions. In low NOx burners, air staging is achieved within the flame to prevent NOx formation. Today, almost all boiler and burner manufacturers supply low NOx burners, and they are routinely installed in new boilers. OFA is a type of air staging in which a portion, typically 10-30%, of the combustion air is withdrawn from the combustion zone. This stream of air is added through special OFA ports situated higher up in the furnace to complete combustion. Reburning is another name for fuel staging. A portion of fuel is injected in a second combustion zone, the reburning zone, situated over the primary combustion zone in the furnace. The reburning fuel can be a portion of the primary coal fuel or another type of fuel such as natural gas or oil.

Low NOx burner technologies are very suitable for developing countries due to their low investment cost compared to other more efficient techniques. By adjusting air distribution and swirling flow intensity in the burner according to properties of the coal fired, we are assured that NOx emission can be brought down to under 100 ppm with bituminous coal presently used in thermal power station and the unused carbon concentration in the ash can be kept between 1.5-2.5% [107] New boilers should be equipped with low NOx burners and OFA. The use of low NOx burners and the installation of OFA will hardly affect the cost of new boilers. If a new boiler is not equipped with OFA, the boiler should still be designed for future installation of OFA. Different low NOx combustion measures can be used in combination to reduce NOx emissions. LNB, for example, are commonly used in combination with OFA. These methods are also suitable to use in combination with other NOx control technologies. Reburning is an attractive option where natural gas is available at the power plant site and required NOx emissions are below 800 mg/Nm^3. Reburning gives a NOx reduction in the same range as SNCR but gives no ammonia slip. LNB are not easily used on wet bottom boilers because the temperature in the furnace changes, which may cause problems with slag drainage. For such boilers, natural gas reburning may be the only available NOx control technology.

Due to their low capital cost, low NOx combustion measures are suitable for retrofit of old boilers with a limited remaining lifetime. However, in retrofit applications these techniques may lead to unwanted changes in the boiler operation. Combustion efficiency can decrease due to a higher level of unburned carbon in the fly ash, and due to change in temperature profile in heat exchanging parts. Also, LNB with a higher pressure drop and flue gas recirculation consume more power for the flue gas fans, which reduces the plant efficiency. Operating with low excess air, LNB and OFA create zones with reducing atmosphere, which may cause corrosion on the boiler tubes. Furthermore, there are often physical limitations for installation of low NOx combustion measures on existing boilers, e.g. limited space around the furnace and duct, and limited area in the furnace for installation of OFA ports or burners for the reburning fuel.

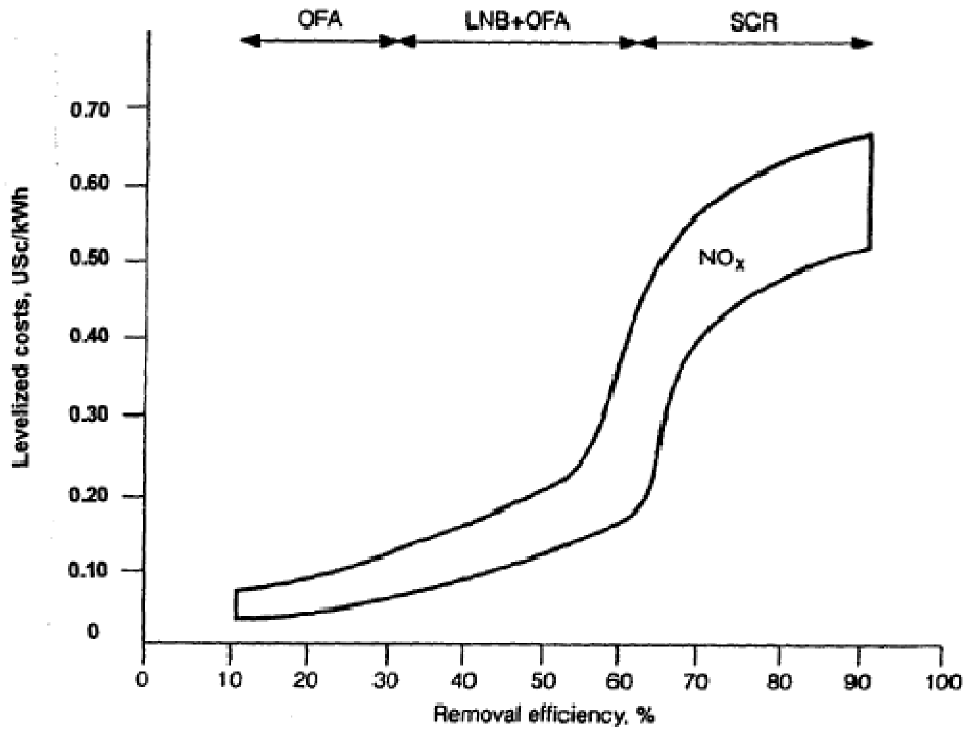


Figure 3.17 Levelized costs in UScents/kwh electricity for different NOx reduction Technologies.

Source: Takeshita, Mitsusu. 1995. Air Pollution Control Costs for Coal-fired Power Stations. IEA Coal Research, IEAPER/17. International Energy Agency. London, UK.

Table 3.4 NOx reduction efficiency for various technologies

Measure	NOx reduction %
Low excess air	15-25
Flue gas recirculation	15-20
OFA	12-25
LNB	30-55
LNB + OFA	30-55
Natural gas reburning	45-60

Source: Takeshita, et. al 1995.

Reduction efficiency is physically achieved by different combustion modifications are listed in Table 3.4. The efficiency achieved when retrofitting an existing plant is generally lower than that of a new plant because of plant specific limitations. Low excess air and flue gas recirculation achieve NOx reduction levels only upto around 20% as stand alone measures, but the techniques are often used in combination with other primary measures such as OFA or reburning to achieve higher removal efficiencies" (Karin Oskarson et. al).

3.10.2 Selective Catalytic Reduction (SCR)

"These systems use ammonia to reduce oxides of nitrogen (NOx) to harmless nitrogen and water. SCR uses a catalyst to speed the reaction at lower temperatures. SCR technology achieves 80-90% NOx reduction. In the SCR process, the NOx in the flue gas is reduced by the addition of ammonia in the presence of a catalyst. The SCR reactor can be placed in three different locations:

- high dust - at the outlet of the economizer before the ESP;
- low dust - after the ESP before the air pre heater; or
- tail end - after the particulate filter and the FGD system.

SCR is suitable for use in developing countries when combustion modifications are not sufficient to meet the emission limits. It is suitable for coal-fired power plants when the required NOx emission limits are less than 100 ppm, and 80 to 90% NOx reduction is required, for example in power plants located in heavily populated areas. Technology demonstration and some adaptation may be required in the case of possible use with high sulfur and high ash coal types. Installation of a high dust SCR system in an existing boiler requires extensive modification of the boiler back pass. Lack of available space for retrofitting is often a constraint.

In SCR systems, ammonia vapour is used as the reducing agent and is injected into the flue gas stream, passing over a catalyst. NOx emission reductions over 80-90% are achieved. The optimum temperature is usually between 300°C and 400°C. This is normally the flue gas temperature at the economiser outlet. There are three typical layout arrangements of SCR systems applied to coal-fired power stations. High dust position is the most widely used SCR configuration, especially with dry bottom boilers, because it does not require particulate emissions control prior to the denitrification process. Low dust positioning has the advantage of less catalyst degradation caused by fly ash erosion, but requires a more costly hot-side ESP. Tail end position SCR has been used primarily with wet bottom boilers with ash recirculation to avoid catalyst degradation caused by arsenic poisoning. The configuration is also favoured with retrofit installations (due to SCR space requirements) between the economizer outlet and ESP.

The catalysts can have different compositions: based on titanium oxide, zeolite, iron oxide or activated carbon. Most catalysts in use in coal-fired plants consist of vanadium (active catalyst) and titanium (used to disperse and support the vanadium) mixture. However, the final catalyst composition can consist of many active metals and support materials to meet specific requirements in each SCR installation"(Karin Oskarson et. al).

"SCR technology has been used commercially in Japan since 1980 and in Germany since 1986 on power stations burning mainly low sulphur coal and in some cases medium sulphur coal. There are now about 15 GW of coal-fired SCR capacity in Japan and nearly 30 GW in Germany, out of a total of about 53 GW worldwide. During the 1990s SCR demonstration and full-scale systems have been installed in US coal-fired power plants burning high sulphur coal. Their commercial use has followed the introduction of stringent limits to regulate NOx emissions in each country". [108]

3.11 Particulate Emission Control Technologies

"There are two main types of particulate emission control technology: fabric or baghouse filters and ESPs. Fabric filter technology is the most widely used particulate control device in industry, but ESPs is by far the most commonly used technology in power plants worldwide. Both technologies are capable of meeting very low emission limits. The choice of particulate control technology depends upon several site-specific conditions such as ash and fuel characteristics, environmental requirements and operational factors. The influence of an outlet emission limit and fly ash resistivity on the choice of particulate collector is illustrated in Figure 3.18. The figure shows the capital cost for different types filters per kw of electricity installed as a function of the particulate emission limit. The figure shows that ESPs require a lower capital cost than baghouse filters for particulate emission limits higher than 30 mg/m^3 when firing coals with low fly ash resistivity. For coals with high fly ash resistivity, baghouse filters are more economical. Pulse jet baghouse filters have lower capital cost when stringent emission limits are required.

Looking at the levelized cost gives a somewhat different picture. ESPs have a lower O&M cost than fabric filters because they have a lower pressure drop over the filter, and because fabric filters require an annual cost for bag replacement. The pulse-jet baghouse filters have the highest O&M cost of the three filter types. Figure 3.19 shows the levelized cost for the three filter types per kwh of electricity produced depending on the particulate emission limit. The figure shows that ESPs are competitive for low resistivity coals at the whole range of emission limits. They are also competitive for coals with medium to high fly ash resistivity at less stringent emission limits. When firing coals with high fly ash resistivity, baghouse filters gives a smaller increase in production cost.

Another important aspect in the selection of particulate control equipment is the power consumption of the process. Despite the power consumption required by the ESPs in order to create the electric field, ESPs normally have a significantly lower total power consumption than fabric filters. This is because ESPs have a lower pressure drop than fabric filters, approximately 0.2-0.3 kPa versus 1-2 kPa, resulting in lower power consumption by the flue gas fans. The total power consumption of ESPs is approximately 60-70% of that of baghouses" (Karin Oskarson et. al).

3.11.1 Electrostatic Precipitators

"The electrostatic precipitator is the single most used emission control equipment in thermal power plants. The principle of operation is based on the creation of an electrostatic field. Emitted particulates are charged when they pass through the electrostatic field and are attracted to the electrodes, where they are collected. ESPs have a lower pressure drop than fabric filters and can operate at higher temperatures. They are relatively insensitive to disturbance.

Electrostatic precipitators are competitive for medium and high sulfur coals with low to medium ash resistivity (<1,012 Ohm-cm). For these coals, they are suitable for particulate removal efficiencies up to above 99.5%. They have lower capital and levelized costs in this area than baghouse filters. They are also cost-effective for low sulfur coals and coals with a high fly ash resistivity when lower emissions are required. Due to their robust design, ESPs can normally endure tough conditions. This is an attractive characteristic when firing coals with a high ash content and with an erosive ash such as Indian coals. In cases where more than 99.5% collection efficiency is required, especially for low sulfur, high resistivity coals, reverse air or pulse-jet fabric filters are normally more cost-effective than ESPs. A number of options exist to enhance the performance of ESPs, especially suitable in developing countries. Replacing existing ESP systems with new ones when environmental regulations become stricter will require a considerable capital investment. Therefore, improvements of existing ESPs may present a cost-effective option. When some clean coal technologies are used (specifically spray dryers, sorbent injection, and fluidized bed combustion) improvements of ESPs may be needed.

Electrostatic precipitators are the most widely used particulate emissions control technology in coal fired power plant. Particulate/dust laden flue gases are passed horizontally between charged collecting plates – the particles are attracted to the plates, where they accumulate and are removed. ESPs can remove over 99% of particulate emissions. Cold side (dry) ESP is located after the air pre heater and operates in a temperature range of 130-180°C. The cold side ESP, with fixed/rigid electrodes, makes up a large portion of the current market although ESP with moving electrodes are becoming more widely used. Hot side (dry) ESP, used mainly in the USA and Japan, is located before the air pre heater where the operating temperature range is 300-450°C. A 1990 study showed 150 hot side ESP were built in the USA between 1935 and 1990. In wet ESP, a liquid film is maintained on the collection plates using spray nozzles. The process eliminates the need for rapping as the liquid film removes any deposited fly ash

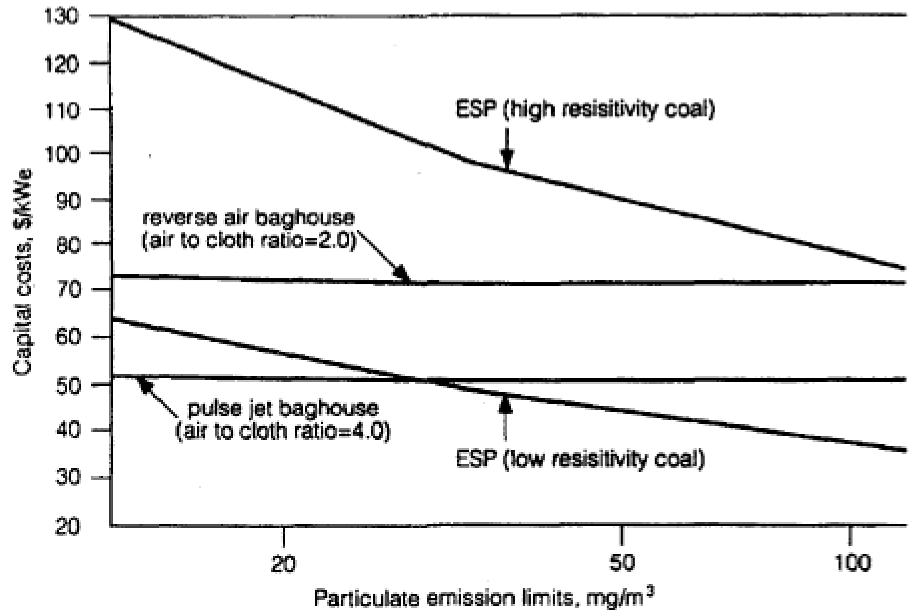


Figure 3.18 Capital Cost per kw Electricity Installed for ESPs and Baghouse filter

Source: Sloat, D.G., R.P. Gaikwad, and R.L. Chang. 1993. "The Potential of Pulse-Jet Baghouses for Utility Boiler Part 3

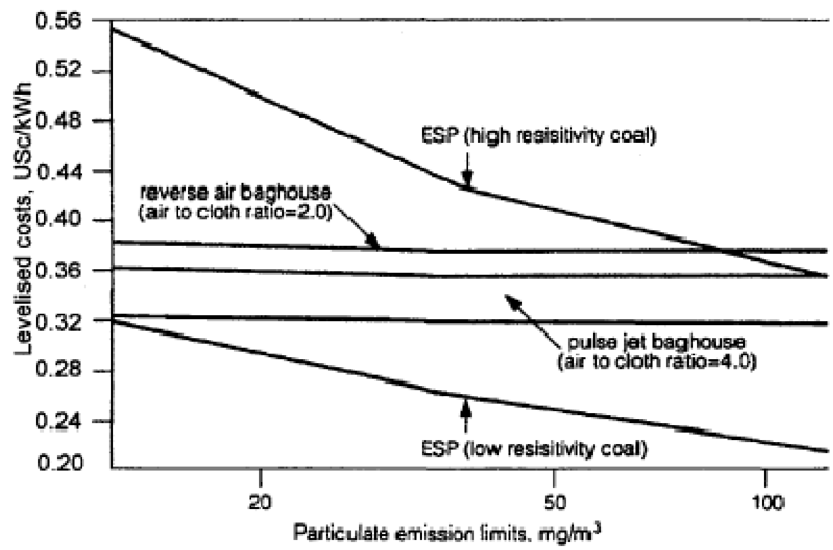


Figure 3.19. Levelized Cost per kwh of Electricity Produced for ESPs and Baghouse Filters

Source: Sloat et al.

particles. Thus, problems with re-entrainment, fly ash resistivity and capture of fine particles become obsolete. However, wet ESP require saturation of the flue gas stream with water, generate waste water and sludge and operate at low temperatures" (Karin Oskarson et. al).

"It is possible to size an ESP to meet almost any outlet emission level. For example, at some utility plants subject to very strict environmental regulations, ESPs are used to limit emissions to below 30 mg/Nm^3 (even below 10 mg/Nm^3 in some cases). Section 3.1.3.1 identifies precipitator sizes that will achieve 200 mg/Nm^3 and below 50 mg/Nm^3 . In each case, the performance estimate indicates that the actual outlet emission level will be only about half the specified limit when all the electrical fields are operating at the estimated power levels. However, if one electrical field malfunctions due to an electrical short or a hopper that becomes too full, the emissions will increase to a level that is close to the indicated limit".[109]

3.11.2 Fabric Filter (Baghouse)

"For a long time fabric or baghouse filters have been the most widely used particulate control device in industry. Their application potential has been increased by the introduction of new materials capable of withstanding highest temperatures. They are popularly used in thermal power plants, especially in the United States. A feature of baghouses is their relative insensitivity to gas stream fluctuations and to changes in inlet dust loading. In fact, outlet emission becomes almost independent of inlet particulate concentration. Another advantage is that they can enhance SO_2 capture in combination with upstream sorbent injection and dry scrubbing systems.

Baghouse filters are normally more cost effective than ESPs when firing low-sulfur or high fly ash resistivity coals, and when more than 99.5 % collection efficiency is required. Pulse-jet fabric filters are a newer type of baghouse filter which has a lower capital and levelized cost than the more widely used reverse air fabric filters. Baghouse technologies can be used in combination with sulfur removal technologies such as sorbent injection and dry scrubbing systems. In installations downstream spray dryers or sorbent injection systems, fabric filters can enhance SO_2 capture because chemical reactions between particulates and gases can also occur in the filter system. The filters collect unused reagent from the process and absorb more SO_2. Pulse-jet fabric filters are being applied with increasing frequency at utilities equipped with spray dryer systems. SO_2 removal performance may be enhanced by 25% with a baghouse in combination with the spray dryer. Bag house filters are not commonly used in developing countries as the current emission limits favor ESPs. With the advance of more stringent emission limits, bag house filters may be further introduced in the power sector"(Karin Oskarson et. al).

3.12 Selection of Clean Coal Technologies for Power Plants

Installation of CCTs in power plants increases the power tarrif depending upon the technology installed. Generally more environment friendly CCTs are expensive than lesser friendly ones. A number of factors are considered for selection of CCTs while designing power plants. These include type of coal, maturity/availability of technology, efficiency, environmental regulations, installation/maintenance cost, construction time required etc. A trade off between all the factors is reached to select the technology best suited for the plant. In fact every region/country has its own requirements/legislations and hence CCTs are adopted and installed accordingly. "The choice of electricity generation technologies not only directly affects the amount of CO_2 emission from the power sector, but also indirectly affects the economy-wide CO_2 emission. It is because electricity is the basic requirement of economic sectors and final consumptions within the economy" [110].

3.12.1 Other Research/Studies

Studies have already been carried out world over to set up the criteria for selection of CCTs. Each one of them differs from the other, generally depending upon the region for which they are being applied and the type of coal to be used as feedstock. A few of them with a short description are given below:

3.12.1.1 Technology Assessment of Clean Coal Technologies for China

The study was carried out under Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP). Analysis is based upon the report prepared for the World Bank by Electric Power Research Institute (EPRI) of the US, under a contract to The Electric Power Development Corp (EPDC) and Tokyo Electric Power Co (TEPCO) of Japan.. World Bank staff led the overall project team supervising this study.

The study focuses on the cleaner and more efficient use of coal in power sector and provides an insightful analysis of the long-term opportunities CCT presents for sustainable development of China. Coal is China's chief energy source, accounting for 74% of primary energy consumption. Given the nation's abundant coal reserves and emphasis on development using indigenous resources, coal will remain the dominant fuel well into the 21st century. Environmentally acceptable economic growth is closely linked with further improvements in the overall efficiency of energy use. Both of these goals will require a continued increase in the use of coal to produce electricity, along with a more deliberate and rapid transition from direct coal combustion to the use of electricity and other cleaner coal-based fuel sources, especially for cooking, space heating, and industrial furnaces. The opportunity for environmental improvement in conjunction with economic growth lies in the wise adoption of clean coal technologies (CCT) for both the electric power and non-power sectors. The report presents CCT options for the power sector that can help China achieve these twin goals. The CCT options are:

- Air pollution controls for SO_2, NOx and particulates; and
- Advanced electricity generation technologies-supercritical pulverized-coal boilers, atmospheric and pressurized fluidized-bed combustors, and integrated gasification combined cycle plants.

The report emphasizes the replacement of old technologies with the advanced ones. These changes are vital because about 60% of coal production is currently consumed by these inefficient technologies, which emit their pollutants at low heights where they have greater direct impact on people's health.

This technology assessment report synthesizes the experience and extensive in-house information collected over the years by the study team. The study team supplemented its information base by visits to China to

- inspect several technology demonstrations; and
- discuss the readiness of Chinese boiler and turbine manufacturers to supply advanced generation processes.

The report describes each CCT with particular reference to conditions in China (boiler types, fuels used etc.), discusses its commercial readiness and applicability to China, presents its environmental performance and any impacts on the power plant, and then provides estimated costs for applications in China. The report compares same SO_2, NOx and particulate emissions control technologies for coal fired power plants which are being studied in our research work. It gives cost comparison for operational plants in China with different technology combinations. It also states the environmental performance of different technologies in the units being followed in Pakistan and is applied in our research work. Published in 2001, the report provides updated information viz a viz maturity of technologies and their cost effectiveness.

3.12.1.2 CCTs for Developing Countries

The report is World Bank's Technical paper No. 286 and forms part of the Energy series. It was compiled by E. Stratos Tavoulareas and Jean-Pierre Charpentie.

This report on clean coal technologies (CCTs) examines their performance, costs, and suitability for use by developing countries. The paper reviews in detail for each technology key elements including basic technological features, performance levels, commercial availability, costs of operation, time required for construction, suitability for developing countries, and issues affecting deployment. CCTs fall into three basic categories reflecting their relation to the combustion stage:

- Pre combustion technologies mainly involve the initial cleaning of coal by crushing and separating out pollution-generating impurities;
- In situ technologies involve altering the design and operating conditions of coal furnaces in a way that chemically or physically reduces emissions of SO_2 and NOx;
- Post combustion technologies also remove SO_2 and NOx, through the use of catalysts and other methods and may also scrub the gases produced by

combustion and pass them through filters and precipitators to remove particulate matter; and

- In addition, an emerging fourth category of CCTs is: advanced coal utilization technologies. These in effect supersede the traditional stages of burning pulverized coal by using coal in integrated energy conversion processes.

The report concentrates on commercially available technologies that are currently suitable and affordable for developing countries. But it also reviews more advanced demonstration-stage technologies in anticipation of both increased regulatory requirements and a drop in the costs of such technologies that would make them both necessary and practical for developing countries sometime in the near future. Commercially available technologies reviewed are as follows:

- Pre combustion*:* physical coal cleaning; in situ*:* low-NOx combustion, advanced pulverized coal combustion, and power plant rehabilitation;
- Post combustion: wet and dry flue-gas desulfurization, advanced electrostatic precipitation, and bagfilters; and
- Advanced coal utilization*:* atmospheric fluidized-bed combustion.

Demonstration-stage technologies reviewed are as follows:

- Pre combustion: advanced cleaning methods;
- In situ*:* sorbent injection;
- Post combustion: duct injection, selective catalytic and non catalytic reduction, combined SO_2/ NOx reduction, and hotgas cleanup; and
- Advanced coal utilization: pressurized fluidized-bed combustion, integrated gasification combined-cycle combustion.

Given the wide use of coal in some developing countries, the paper is especially concerned to assist policy makers in choosing and justifying the use of appropriate and cost-effective CCTs. The report thus concludes with three brief chapters. The first of these discusses the relationship between environmental regulations and choice of technology; the next provides an initial screening method for evaluating relevant technologies; and the last presents conclusions and recommendations on technology choices and some notes on World bank strategy for promoting dissemination of CCTs.

The report compares same CCTs which are being covered under WBFTTSM and provides a procedure for selection of CCTs in power sector for the developing countries. Additionally, it lists down the manufacturers/distributors of CCTs world over which is helpful to find out the information about the latest technologies . The same can be used each time while applying WBFTTSM. It also compares environmental standards for coal fired power plants followed in different countries of the world.

3.12.1.3 Coal Fired Power Technologies: Coal Fired Power Options on the Brink of Climate Policies

The study provides an overview of coal-fired power generation options. The deployment of coal power plants largely depends on their competitiveness compared to gas-fired power, nuclear power, etc. There are roughly four types of coal-fired power plants based on the combustion technology used. This report estimates that most coal-fired power plants to be built within the next decades will be either pulverized coal power plants based on the simple Rankine cycle (steam cycle), or Integrated Gasification Combined Cycle (IGCC) power plants and forecasts their costs and efficiencies uptil 2050. This study addresses the technological, economical and environmental perspectives of pulverized coal(supercritical and ultra supercritical), ACFB, PFBC and IGCC power plants. Attention is also paid to options for further reduction of SO_2 and NOx emissions at pulverized coal power plants.It analyzes the ultra supercritical technology which can also be incorporated in WBFTTSM at later stage. But details of SO_2, NOx and particulate emission control technologies are not included. The study do cover the options of CO_2 capture at pulverized coal and IGCC plants and shows their resemblances and differences.

3.12.1.4 A Planner's Guide for Selecting Clean-Coal Technologies for Power Plants

This report is World Bank's technical report no. 387 published first in November 1997.It was compiled by Karin Oskarsson Anders, Berglund Rolf Delingn,Ulrika Snellman, Ulle Stenback and Jack J. Fritz .

This report has been prepared as a technology selection guide for the use of power system planners and engineers to facilitate the selection of cost-effective, environmentally friendly technologies for coal-based power generation in countries grappling with impending power and capital shortages in the face of stricter environmental regulations. The report focuses on plants greater than 100 MW in India and China. This guide aims to help understanding power and associated pollution control technologies, their cost and performance.

It compares different combustion methods, SO_2, NOx, particulates emission control technologies and By product & Waste handling respectively. The procedure outlined for selecting environmentally friendly technologies requires evaluation and optimization of several technical, environmental and economic factors, including quality of coal, requirements on waste product, yearly operating time and operating lifetime of the plant. The same has been carried out for both new and retrofit of old power plants. The study also takes into account the socio-economic impact of the use of CCTs. It also describes low cost refurbishment options that can be carried out to increase efficiency, increase availability, reduce operating and maintenance costs etc. in an existing power plant.

3.12.2 Reasons for Using FTTSM as a Model for Selection of CCTs

FTTSM provides following advantages over others given in the earlier part of this chapter

- It provides a logical framework for selection of CCTs provided by the World Bank ,being one of the biggest donors to Pakistan;
- It focuses the power plants in China and India. China is the likely investor in the future coal fired power plants of Pakistan;

- It provides more in depth analysis covering most of the technical, economic and environmental aspects of the CCTs;
- It covers the aspect of waste disposal and by-product utilization wherever applicable; and
- It can help select CCTs for new plants and refurbishment of old power plants.

3.13 Emissions from Coal Fired Power Plants

Because of the growing concern over climate change, the understanding of GHG emission characteristics of power generation technologies from an environmental perspective is becoming increasingly important. Energy analyses of electricity generation systems have been extensively conducted worldwide over the past two decades. Previous LCA studies of electricity generation options have contributed to the understanding of the technologies available and their relative environmental impacts. Lave and Freeburg [111] found that coal posed significant environmental risks, not only from direct combustion but also from mining and transport. The authors stated that oil and natural gas have much smaller environmental effects than coal. It is recognized that lignite and peat are usually more polluting than bituminous coal. According to the IPCC, the amount of CO_2 released from 1 MJ of lignite is 101 g, while that released from 1 MJ of bituminous coal is below 96 g [112]. On the other hand, 1 MJ of natural gas produces only 56 g of CO_2. As a result, half of the UK CO_2 emissions from power plants in 2005 were attributed to coal power plants even though they only constituted 33% of the electricity generation capacity [113]. Methane emissions from coal mining make a significant contribution to total Life Cycle Emissions from the coal fuel cycle. The ExternE report [114] concluded that methane emissions accounted for around 63% of the global warming damages from coal mines and that impacts from the transportation of coal and limestone were relatively small. The report also stated that significantly higher levels of environmental damages (due to SO_2, NOx and particulates) are produced by conventional PC (pulverized coal) power plants. The level of damages from IGCC (integrated gasification combined cycle) and CHP (combined heat and power) plants are lower, reflecting their higher efficiencies.

Spath et al. [115] analyzed the life cycle impacts of hypothetical US coal fired power plants. The authors stated that most of the SO_2 and NOx come from the power plant, while mining was the main source of methane. Accounting for the three major GHGs (CO_2, CH_4, and N_2O), the authors calculated total Life Cycle Emissions of 1042 g CO_2-e/kWh and concluded that power plant operation represented the largest source of these emissions (95% or 991 g CO_2-e/kWh) with the majority of that coming from combustion while smaller amounts were from the production and transport of limestone. In a recent study, Hondo [116] calculated that total emissions from Japanese coal fired power plants are 975 g CO_2-e/kWh with 90.9% coming from direct combustion.

IGCC life cycle emissions are 15% less than those from PC power plants. Furthermore, upon investigating the influence of power plant parameters on life cycle emissions, it was determined that, while the effect of changing the load factor is negligible, increasing efficiency from 35% to 38% can reduce emissions by 7.6% [117].

3.14 Emissions Standards for Coal Fired Power Plants

3.14.1 World Bank Requirements

The proposed guidelines from the World Bank apply to fossil fuel-based thermal power plants or units of 50 MW or larger. In these guidelines, primary attention is focused on emissions of particulates less than 10 microns in size, on sulfur dioxide and on nitrogen oxides.

3.14.1.1 Air Pollution

The levels set in the guidelines on air pollution can be achieved by adopting a variety of low-cost options or technologies, including the use of clean fuel. In general, the following measures should be seen as the minimum that need to be taken:

- Dust control capable of 98-99% removal efficiency, such as fabric filters or electrostatic precipitators should always be installed;
- Low NOx burners combined with other combustion modifications should be standard practice;
- The range of options for control of SO_2 is greater depending largely on the sulfur content in each specific fuel:

- Below 1% sulfur, no control measures are required;
- Between 1 and 3% sulfur, coal cleaning and sorbent injection or fluidized bed combustion may be adequate; and
- Above 3% sulfur, flue-gas desulfurisation or other clean coal technologies should be considered.

The limit values set shown in Table 3.5 represent a basic minimum standard; more stringent emission requirements will be appropriate if the environmental assessment (EA) indicates that the benefits of additional pollution controls, as reflected by ambient exposure levels and by other indicators of environmental damage, outweigh the additional costs. All emission requirements should be achieved for at least 95% of plant operation time, averaged over monthly periods. Though metals are not listed in the emission requirements below, they should be addressed in the EA when burning some types of coal or heavy fuel oil which may contain cadmium, mercury etc.

3.14.1.2 Ambient Air

The World Bank also states that, in the long-term, countries should ensure that ambient exposure to particulates, NOx and SO_2 exceed the WHO recommended guidelines. These recommendations are summarized in Table 3.6. However, in the interim, countries should set ambient standards which take into account benefits to human health of reducing exposure to particulates, NOx, and SO_2; concentration levels achievable by pollution prevention and control measures, and costs involved in meeting the standards. For the purpose of carrying out EAs, countries should establish a trigger value for ambient exposure to particulates. This trigger value is not an ambient air quality standard, but is simply a threshold which, if it is exceeded in the area affected by the project, will mean that a regional and/or sectoral EA should be carried out. The trigger value may be equal to or lower than the country's ambient standard for particulates, nitrogen oxides and sulfur dioxide, respectively.

3.14.2 Environmental Regulations: WB vs Pakistan

GOP Ministry of Environment, Local Government and Rural Development Extraordinary gazette notification dated 8 August 2000 lays down the environmental

Table 3.5 World Bank's Max Emission Limits for coal-fired Thermal power Plants(1996)

Pollutants	Removal Efficiency(%)	Concentration(mg/m^3)	Specific Emission Levels(Tons/Day/MW)
Particles	99	50	-
NOx	40	750(6% excess O2- assumes 350 Nm^3/GJ)	-
SO_2	-	2000	0.20

Source: World Bank. 1996. "Proposed Guidelines for New Fossil Fuel-based Plants." Pollution Prevention and Abatement Handbook - Part III Thermal Power Plants.

Table 3.6 WHO Recommendations for Ambient Air Quality

Pollutant	Max Emission Increment 24 Hr Mean Value(mg/m^3)	Max Emission Increment Annual Average(mg/m^3)
SO_2	100-500	10-50
NOx	500	100
Particulates	100-150	-

Source: World Health Organization. 1987. Air Quality Guidelines for Europe. Regional Publications, European Series No. 23.

Table 3.7 Emission Limits: WB vs Pakistan

Emission	World Bank	Pakistan
SO_2 (mg/m^3)	2000	1700
NOx(mg/m^3)	750	1200
Particulates(mg/m^3)	50	500

Source: World Bank 1996 and NEQS Pakistan 2000 standards for industrial gaseous emissions which covers the coal fired power plants. Amongst all, comparison of the emission limits for coal fired power plants with those set by World Bank is given in the table 3.7.

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CHAPTER 4

Analysis, Discussion and Results

4.1 Framework for Selection of Clean Coal Technologies for Power Plants in Pakistan using World Bank Guidelines

The research suggests a framework for selection of CCTs for power plants in Pakistan. It consists of two parts.

- Comparison of CCTs; and
- Enhanced WBFTTSM

These are discussed below.

4.2 Comparison of CCTs

On the basis of the technologies presented in different studies a comparative matrix has been prepared. Technologies(X axis) and their relative matrices have been summarized in the form of tables 4.1-4.6, covering different parameters. These tables have been included to handle large amount of information which is required while selecting CCTs. This information is used while using enhanced WBFTTSM. A short description of each of these tables is given below:

4.2.1 Comparison of Combustion Technologies

Table 4.1 and 4.2 lists down the technical, environmental and economic parameters which can help a designer select suitable combustion technology while designing the power plants. It summarizes all the aspects of a technology and makes it easier to make a choice. Suitability, state of technology, plant size, fuel flexibility, efficiency and the waste disposal are the parameters of combustion technologies which fulfils the overall requirements of a project. Suitability gives the overall picture of the technology. State of technology means how mature is the technology. A power plant consists of more than one unit to avoid complete breakdown in case of shutdown due to fault or maintenance. The increasing environmental pollution by coal fired power plants makes the environmental performance of the technology an important factor to be considered while selecting CCTs.

After the overall or general parameters, technical parameters like load range, load change rate, start up time, availability and maintenance period are considered for evaluation. MCR is the maximum continuous rating. A minimum load has to kept all the time for safety and long life of the plant. Similarly the load is applied on the plant in two modes i.e rapid and normal. ACFB technology has a better load change rate than others. On the other hand PCC gives a better start up time than others. Availability is the time for which the plant is operating in a year. The plant has to be closed for maintenance, overhaul or unforeseen repairs.

Construction period for PFBC and IGCC is 42 and 48 months respectively which is more than others. Complexity includes both the technical parameters and the operation. The rapid growth of electric power consumption worldwide calls for planning and building of cost-efficient power plants. Therefore cost effective technologies must be selected for power plants. It consists of two portions i.e capital or investment cost and operation and maintenance cost(Fixed and variable). Investment cost is the initial cost for installation. Fixed O&M includes the salaries of the employees whereas variable O&M comprises of cost of repair, maintenance and overhaul.

Available combustion technologies include conventional PC-fired units, with subcritical steam data and, hence, moderate efficiencies and supercritical PC units with higher efficiencies. Pulverized coal-fired technology is the most widely used coal combustion technology for boiler sizes up to 1000 MW. Atmospheric circulating fluidized bed combustion (ACFB) is a relatively mature technology which will likely contribute to new coal-fired units.

There are also comparatively new coal combustion technologies i.e. pressurized fluidized bed combustion (PFBC) and integrated gasification combined cycle (IGCC). In order to be cost-effective, new plants should have high efficiencies, high availability, low emissions, and produce a by-product that can be utilized, avoiding the need for disposal. The use of washed coal is a first cost-efficient step towards increased plant efficiency and availability, reduced investment and O&M costs. The use of washed coal with low ash content also reduces the amount of solid waste disposal at the plant.

A major concern today is the inefficient use of coal in the power industry due to low plant efficiencies (33 to 36%). Older power plants might have efficiencies as low as 25%. Higher plant efficiencies will reduce the emissions of SO_2, NOx and particulates and the waste production per Mwh. In addition to these advantages, coal consumption is reduced per Mwh produced.

Internationally the current trend in base load PC-fired power plants is to build large, supercritical plants with efficiencies around 45%, which could be the high efficiency technology alternative. Pulverized coal-fired units cannot meet moderate emission standards without pollution control equipment. Since reducing emissions from a PC unit is not without cost, other technologies have been developed. The ACFB technology has a low-cost advantage of a wide fuel flexibility and low emissions of both NOx. and SO_2. Sulfur is captured directly in the boiler bed and NOx formation is low due to the low combustion temperature. The drawback of today's ACFB technology is that its waste of mixed ash and desulfurization products is difficult to utilize. An ACFB plant also emits significant amounts of N_2O which has a potential for global warming. The efficiency is relatively low due to the use of subcritical steam parameters. Currently subcritical ACFB boilers are commercial in sizes up to approximately 320 MW. Developmental work is underway on larger size units, with possibilities for waste utilization and even increasing steam parameters. Market prices are difficult to predict, but a cost comparison between a PC plant equipped with wet FGD and an ACFB plant usually shows a lower investment cost for the ACFB plant. Offering high efficiencies and low emissions, PFBC and IGCC are technologies under development with lesser number of plants in the world. Further improvement is needed before they reach commercial status. Improving efficiency in existing power plants must be considered as an important, achievable first step to increased, cost-effective power generation.

4.2.2 Comparison of SO_2 Emission Control Technologies

Table 4.3 and 4.4 compares three technologies i.e sorbent injection, spray dry scrubbers and wet FGD. It lists down a few additional parameters than table 4.1 and 4.2, like power consumption, sorbent and the area requirements. Efficiency is gaged in terms of SO_2 removal capacity of the technology. Power consumption requirements also differ from one another. Also each technology uses different sorbents for SO_2 removal. Area requirement is critical because dimensions of the boiler, flue gas path have to be designed accordingly.

Sorbent injection provides the low cost method for SO_2 removal efficiency, but it consumes a large amount of sorbent that has to be disposed off after use. It is suitable for low to medium sulfur coal due to medium SO_2 removal efficiency. But when more stringent environmental regulations are followed, wet FGD is the ideal choice. Although it has high investment cost but lowest cost per ton of SO_2 removed due to highest efficiency. Because of the same reason, it is particularly suitable for high sulfur coal. The solid waste is the commercial grade gypsum which can be utilized and gives FGD an added advantage over the others. Moreover it is available for all boiler sizes. Its only disadvantage is more power consumption.

4.2.3 Comparison of NOx Emission Control Technologies

Table 4.5 gives a comparison of NOx emission control technologies. Twelve technical, environmental and economic parameters have been tabulated to help a power plant designer select suitable technology. They can be broadly categorized into in-situ and post combustion technologies. Low NOx combustion, are the in situ low cost and SNCR/SCR, are the post combustion high cost technologies

NOx emissions are significant when high grade coal is used in power plants. It is because they require above 1000 deg C temperature for combustion at which there are high NOx emissions. Lignite requires less temperature for combustion and therefore the NOx emissions are well within limits and low cost NOx combustion techniques are sufficient. That is one of the reasons that lignite is suitable for power production.

The high cost techniques, SNCR and SCR, are installed when anthracite or bituminous coal are used in power plants. However with stricter environmental regulations in future high cost technologies may be required.

4.2.4 Comparison of Particulate Emission Control Technologies

Table 4.6 provides a comparison of particulate emission control technologies. There are two main types of particulate emission control technologies: fabric filters (baghouse filters) and ESPs. Fabric filter technology is the most widely used particulate control device in industry, but ESPs is by far the most commonly used technology in power plants worldwide. Both technologies are capable of meeting very low emission limits. The choice of particulate control technology depends upon ash and fuel characteristics, environmental requirements and operational factors. ESPs require a lower capital cost than baghouse filters for particulate emission limits higher than 30 mg/Nm^3 when firing coals with low fly ash resistivity. For coals with high fly ash resistivity, baghouse filters are more economical. Pulse jet baghouse filters have lower capital cost when stringent emission limits are required.

ESPs have a lower O&M cost than fabric filters because fabric filters require an annual cost for bag replacement. The pulse-jet baghouse filters have the highest O&M cost of the three filter types. Another important aspect in the selection of particulate control equipment is the power consumption of the process. Despite the power consumption required by the ESPs in order to create the electric field, ESPs normally have a significantly lower total power consumption than fabric filters. The total power consumption of ESPs is approximately 60-70% of that of baghouses.

Baghouse filters are normally more cost effective than ESPs when firing low-sulfur or high fly ash resistivity coals, and when more than 99.5% collection efficiency is required. Pulse-jet fabric filters are a newer type of baghouse filter which has a lower capital and levelized cost than the more widely used reverse air fabric filters. Baghouse technologies can be used in combination with sulfur removal technologies such as sorbent injection and dry scrubbing systems. In installations downstream spray dryers or sorbent injection systems, fabric filters can enhance SO_2 capture. Pulse-jet fabric filters are being used with spray dryer systems. SO_2 removal performance may be enhanced by 25% with a baghouse in combination with the spray dryer. Baghouse filters are not commonly used in developing countries as the current emission limits favor ESPs. With the advance of more stringent emission limits, baghouse filters may be further introduced in the power sector.

4.3 Enhanced WBFTTSM

The selection of technology for a coal-fired power plant is a complex task. It involves the evaluation and optimization of a large number of technical, environmental and economic considerations. This model is part of the Planner's guide which can be used to help select environment friendly technologies for coal fired power plants. It is simply called the Fast Track Model. The model gives a working procedure for the technology selection phase of a pre feasibility study.

4.3.1 Original WBFTTSM.

WBFTTSM in its original shape has following shortcomings

- It is very sketchy and cannot be used easily;
- It jumps to the result of each step without explaining the procedure;
- It has not been explained diagrammatically;
- It was published in 1997 and therefore contains old data related to CCTs which has changed over a period of time;
- The parameters of CCTs are spread over a large text;
- It cannot be used by one expert. It handles technical, environmental and economic parameters related to CCTs To understand and use all three type of parameters experts from all the three fields are required. E.g Tarrif calculation is performed by NEPRA in Pakistan and involves a lengthy and cumbersome calculation. It covers 10 pages of this document to calculate the tarrif for different combination of technologies; and
- It does not contain the emissions calculation.

4.3.2 Improvements Made in WBFTTSM

WBFTTSM has been made user friendly and suitable for use in power plants in Pakistan. Following additions have been made in the model

- Overview of model Figure 4.2;
- Data for screening of technologies Table 4.9;
- Specimen table for Screening of technologies Table 4.10;
- Updation of data contained in Table 4.9;
- Tarrif calculation explained while using the model for Thar coal power plant;

By making these improvements in the model it can now be used by one person easily.

4.3.3 Enhancement of WBFTTSM

WBFTTSM was provided as a guideline by World Bank for China and India in its technical paper no 397, 1997. The environmental legislations were not that strict as today. Moreover Kyoto protocol had not come into effect. Therefore one step has been added to the model as step 5 which calculates the amount of annual emissions from the power plant. The same can serve as a guide for the ministry of environment GOP to keep a record of the emissions at national level and amend the emission standards accordingly.

The model explained and used subsequently is improved and enhanced shape of WBFTTSM.

4.3.4 Salient Features

- Fast Track Model enables the user to recommend the most suitable technology combination for a power plant, taking into account aspects such as environmental impact and costs. A planner gets following information and figures
  - Possible power plant concepts;
  - Investment cost;
  - Electricity production cost;
  - Flue gas cleaning cost;
  - Cost/ton SO_2 removed;
  - Cost/ton NOx removed; and
  - Per year CO_2, SO_2, NOx and particulate emissions from power plant.

The Fast Track Model is meant to be used early in the project during the pre feasibility phase, when the first technology selections are made. During the pre feasibility phase, alternative power plant concepts are studied to find the most suitable technology combination for each specific project. In the feasibility phase, concepts that proved successful in the pre feasibility study are examined in detail;

- The Fast Track Model only deals with the technology selection part of the pre feasibility study based on technical, environmental and some economic requirements. Some of these also have an effect on technology selection;
- Technology areas covered by the Fast Track Model, shown in figure 4.1 are
    - Coal quality;
    - Combustion technologies;
    - Emission control technologies for SO_2, NOx and particulates; and
    - By-products and waste handling,
- CCTs installed at pre combustion, combustion and post combustion stages of a coal fired power plant, covered by FTTSM are listed in the table 4.7.

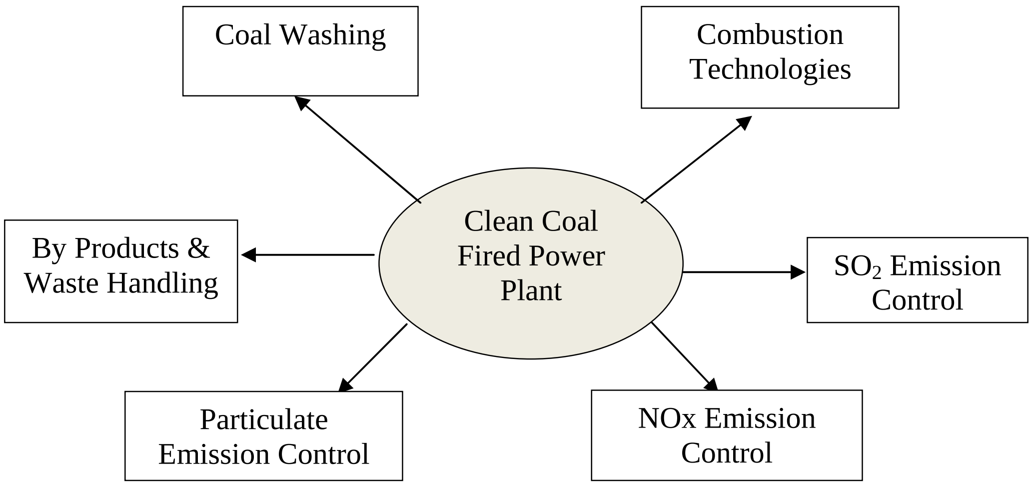


Figure 4.1. Technology Areas Covered by the Fast Track Model

Table 4.7. CCTs Covered by WBFTTSM

	Pre combustion	Combustion	Post combustion
Combustion Tech		• PC subcritical • PC supercritical • ACFB • PFBC • IGCC	
SO_2 control tech	Coal washing	• Sorbent injection • Combined SO_2/NOx control	• Spray dry scrubbers • Wet scrubbers
NOx control tech		• Low NOx burners • OFA • Low NOx+OFA • Flue gas recirculation	SNCR SCR
Particulate control technology	Coal washing		• ESP • Baghouse filter

4.3.5 Structure of the Model

The Enhanced Fast Track Model is built up by five logical steps. Each step has a clearly defined scope and result. An overview of the CCT selection framework including enhanced model is given in Fig 4.2 showing the scope and results of each step. This step design provides a tool which will enable the user to handle the large amount of information that have to be considered in power plant projects.

4.3.5.1 Step 1: Project Definition

The aim of Step 1 is to document non-changeable project data. Use of the project definition data by all members of the project group is vital. It ensures that everyone in the project group uses the same input data and works towards the same goal. A well-defined project forms the basis for all related work and provides the foundation for progress. Project definition data that need to be settled are:

- Type of project whether a green field power plant or retrofit of an existing power plant;
- Type and amount of products produced at the plant;
- Objectives of a retrofit; and
- Pre requisites.

The work procedure for project definition is illustrated in figure 4.3.

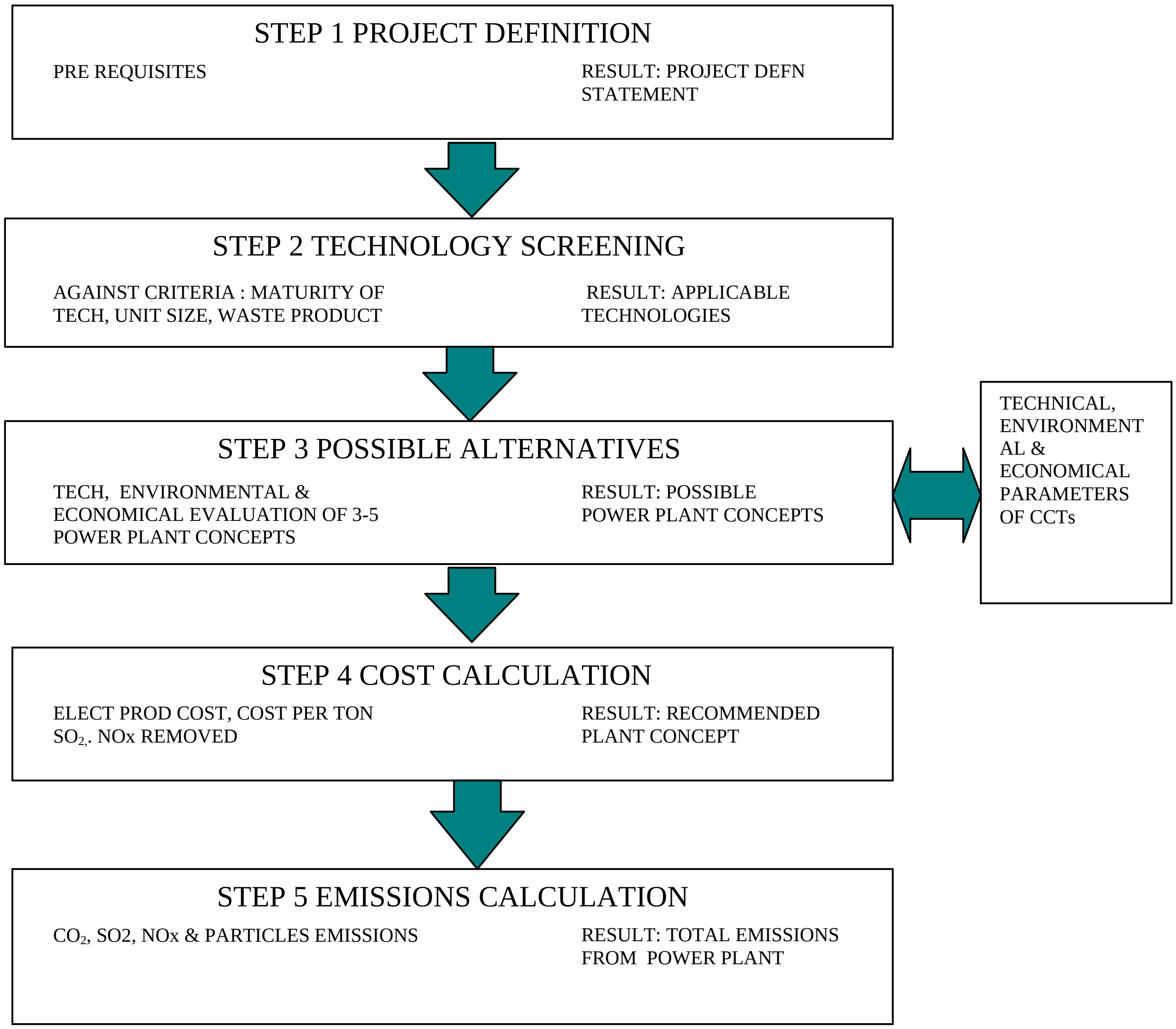


Figure 4.2. Framework for Selection of CCTs

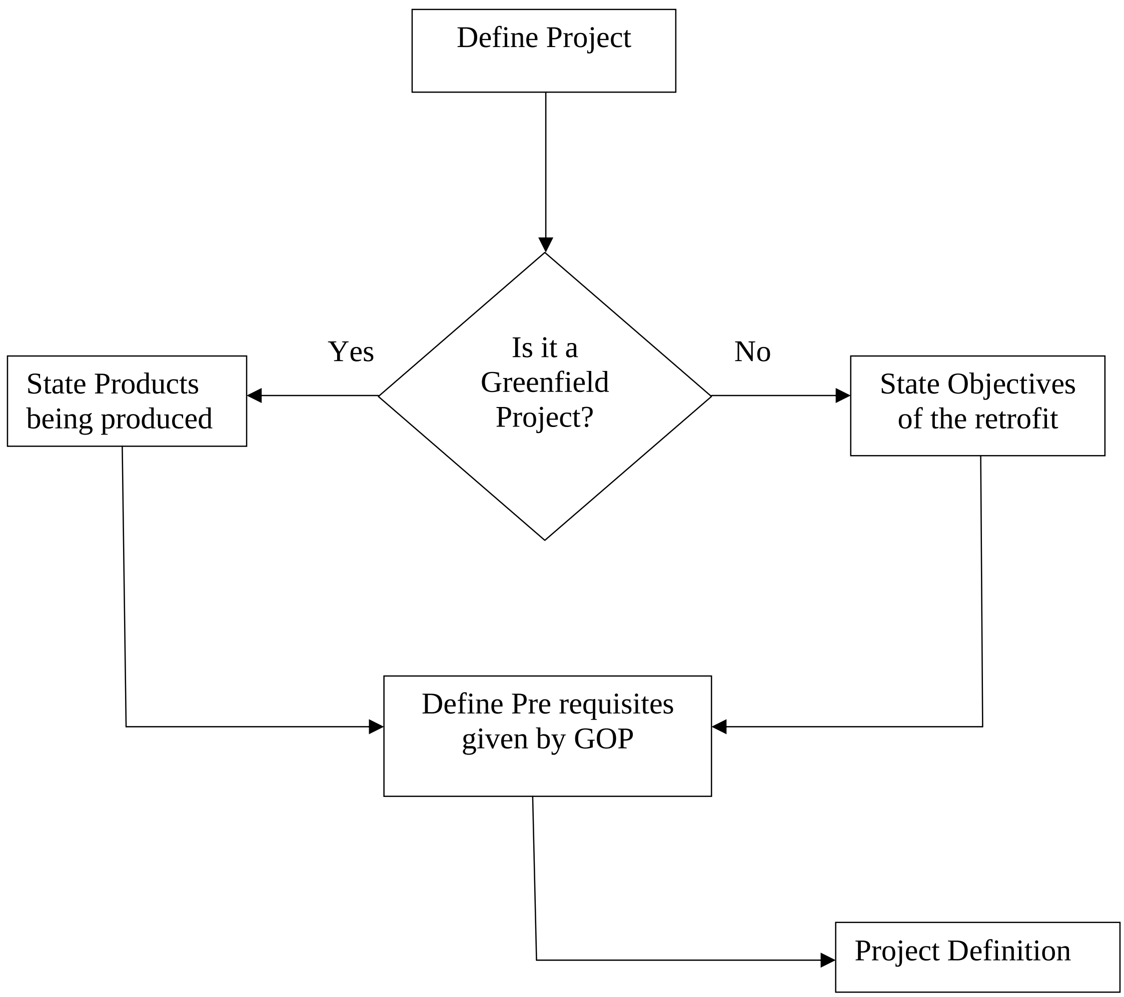


Figure 4.3. Project Definition - Flow Diagram

The project definition starts by answering simple questions.

- Is it a green field plant or a retrofit?
- What are the main objectives and needs?

For a green field power plant, type of products that are going to be produced are defined, it includes

- Electricity;
- Steam;
- Oxygen, nitrogen etc; and
- District heating.

For a retrofit project the objectives of the retrofit are defined, For example

- Reduce operating and Maintenance cost;
- Increase plant efficiency;
- Increase efficiency;
- Increase availability;
- Reduce environmental impact;
- Increase unit lifetime; and
- Increase electricity production.

After defining the type of project, the prerequisites listed in Tables 1-4 of appendix A are stated to make the frames and objectives of the project more clear. Some of these prerequisites will be used to evaluate different plant concepts technically, environmentally and economically in step 3. The prerequisites are divided into four categories: general, economic, environmental and operational.

4.3.5.2 Step 2: Technology screening

The technology screening procedure is illustrated by a flow chart in Figure 4.4.

Screening is done to quickly find which technologies do or do not meet overall requirements. Those that do not can be quickly eliminated. The applicable technologies which meet the overall project requirements will be used in Step 3, when the alternative power plant concepts are stated**.**

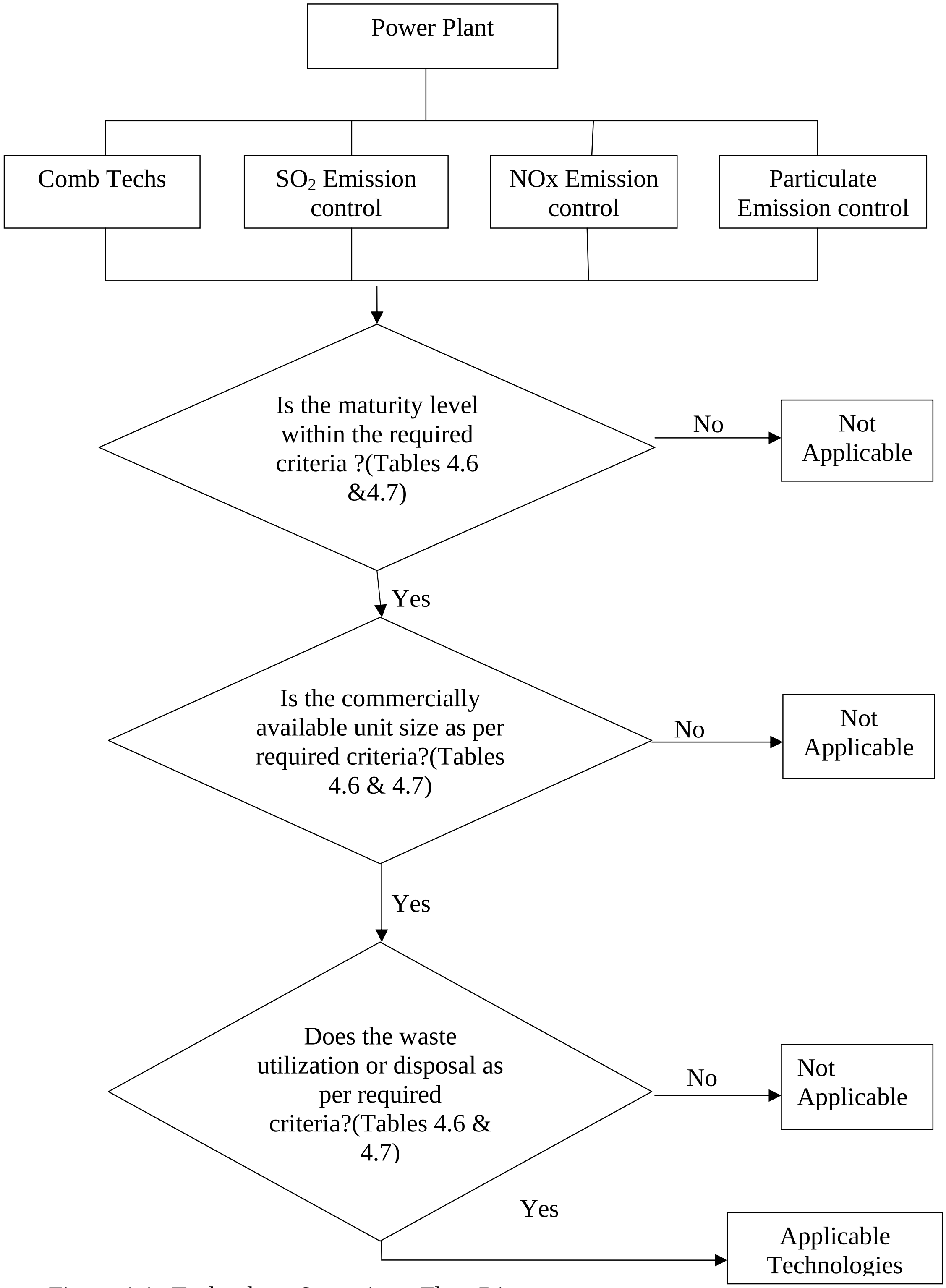


Figure 4.4. Technology Screening - Flow Diagram

The screening is carried out for four of the technology areas:

- Combustion technologies;
- SO_2 emission control technologies;
- NOx emission control technologies; and
- Particulate emission control technologies.

Screening is carried out against three criteria. The screening criteria can be used for all projects, but the requirements on the criteria are project specific. Requirements can be chosen from the ones given in Table 4.8.

- Required maturity of technology is set by the type of project. When the project is commercial and the requirements of availability are high, the requirements on maturity of technology can be high. In a development project, the requirements on maturity of technology can be lower;
- Maximum number of units accepted or plant size were also determined in step 1 and are used when screening each technology area against number of units required e.g the commercially available sizes for PC supercritical technology are above 1000 MW and let the required plant size is 370 MW. Therefore the PC supercritical technology is applicable to the power plant; and
- By-product/waste-related requirements. It has to be decided as per the existing policy of the state or local government. In Pakistan there is no specific waste disposal policy for the coal fired power plants. Different Combustion and flue gas cleaning technologies produce different types of solid byproducts/ waste.

Screening should be made against the requirements on the waste product defined in Step 1. Should it be possible to use the by-product, for example in the building industry, or should it just be disposed off?

Screening Criteria	Choice of requirements	Choice of requirements	Choice of requirements

Maturity of technology	>10 commercial reference plants worldwide	<10 commercial reference plants in China >10 commercial reference plants worldwide	<10 commercial reference plants worldwide
Req no of units	Total plant size 1-2 units	Total plant size is 3-4 units	Total plant size is >4 units
Waste product	Possible to use without processing	Possible to use after processing	Disposal

Table 4.8 Choice of Requirements on Screening Criteria

The screening criteria can be applied for each technology and compared with the data and information given in the the table 4.9. The screening criteria and choice of requirements can be compared with the help of specimen table 4.10.Result column of the same gives the applicable technologies which meet the overall requirements of the project, in terms of required maturity of technology, number of units accepted and the requirements for the by-product/waste. These technologies will be used for stating possible power plant concepts in Step 3.

Tables 4.9 and 4.10 are not contained in original WBFTTSM and have been included in the model to summarize the large amount of information and make its application easier.

Table 4.9.Data for Screening of Technologies

S-No	Category	Technology	Maturity level (High/Low)	Maximum Commercialized Unit size (MW)	Solid Waste product Disposal

1	Combustion	PC Subcritical	High	1300	Possible to use without processing
		PC Supercritical	High	1300	-do-
		ACFB	High	320	Not possible to use
		PFBC	Low	340	Needs disposal
		IGCC	Low	350	Possible to use
2	SO_2 emission control	Sorbent injection	High	All sizes	Not possible to use
		Spray dry scrubbers	High	All sizes	-do-
		Wet FGD	High	All sizes	Possible to use
		Combined SO_2/NOx control	Low	-	Possible to use
3	NOx emission control	Low NOx burners	High	All sizes	None
		Low NOx +OFA	High	All sizes	None
		Reburning	High	All sizes	None
4	Particulate emission control	ESP	High	All sizes	None
		Baghouse filter	High	All sizes	None

Table 4.10.Specimen Table for Screening of Technologies

S-No	Technology	Level of maturity H= High L= Low		Max unit size MW A= All sizes		Waste Requirements P= Possible to use D=Needs Disposal		Result A= Applicable NA= Not Applicable
		Aval	Reqd	Aval	Reqd	Aval	Reqd	
1	Sub critical	H	H	1300	370	P	P/D	A
2	Super critical	H	H	1300	370	P	P/D	A
3	ACFB	H	H	320	370	D	P/D	NA

4.3.5.3 Step 3: Possible Alternatives

Now applicable technologies from Step 2 can be combined to form possible power plant concepts i.e alternatives. The alternatives represent technical solutions for the whole power plant. Figure 4.5 shows the different parts of Step 3.

4.3.5.3.1 Coal quality

As shown in Figure 4.5, the first question to deal with is which quality of coal should be purchased since coal quality has a major effect on the economics of power plant operation. The available coal quality is defined in the general prerequisites (Table 1 appendix B) and now it is found: Which is the best coal to use considering both environmental and economic impacts? The details helping to make this decision are given in Tables 4.1-4.6.

4.3.5.3.2 Stating the Possible Alternatives

After deciding which coal quality should be purchased, a number of alternatives regarding the power plant configuration can be stated by following the steps given below

- Use the result from the technology screening i.e Step 2 to further eliminate unsuitable technologies;
- Use information in tables 4.1-4.6 especially the columns "Suitability" and "Fuel flexibility" to find which technologies are suitable for the selected coal quality;
- State a number of alternatives that represent technical solutions for the whole power plant, starting from the one following less stringent to most stringent environmental regulations;
- Use cost data and other technical information given in tables 4.1-4.6 to find the technologies that are most likely to be successful for the project. Alternatives should always include at least one configuration which complies with each of the following:
    - National or local requirements (NEQS Pakistan);
    - World Bank environmental guidelines; and
    - More stringent environmental requirements.

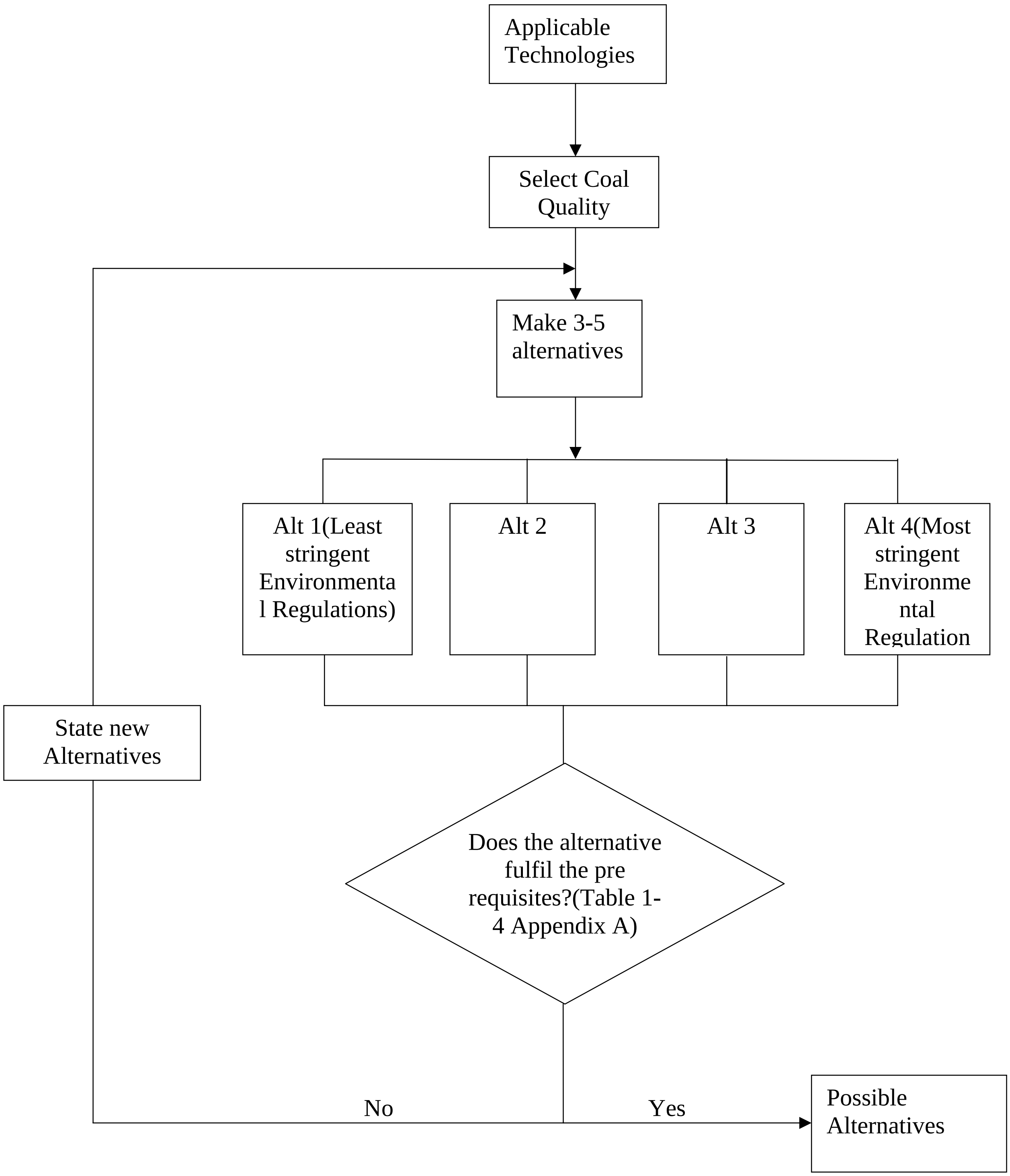


Figure 4.5 Logical Sequencing and Developing Project Specific Power Plant Alternatives

4.3.5.3.3 Evaluation of Alternatives

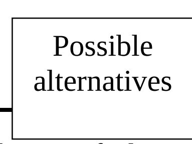
Now the alternatives need to be evaluated. The results of the technical evaluation are alternatives that correspond with the prerequisites. Then the alternatives are compared with the prerequisites stated in step1 for compliance. Most of the economic evaluation is done in the final Step 4. Step 3 results in possible power plant alternatives that meet the main prerequisites. If there is no alternative which complies with the prerequisites, then new alternatives are stated, and the requirements of the prerequisites are loosened. If the later is necessary, the Fast Track Model steps must be reapplied from the beginning.

4.3.5.4 Step 4: Cost Calculation

The aim of Step 4 is to make an economic evaluation of the alternatives that comply with the main prerequisites. In an economic evaluation, two parameters are usually important

- Investment (US$ millions) and
- Electricity production cost (US$/Mwh).

When evaluating different emission reduction technologies, a third parameter is equally important. This is the cost/ton emission removed: for example US$/ton sulfur removed and US$/ton NOx removed. An overview of the cost calculation recommendation step is given in Figure 4.6.



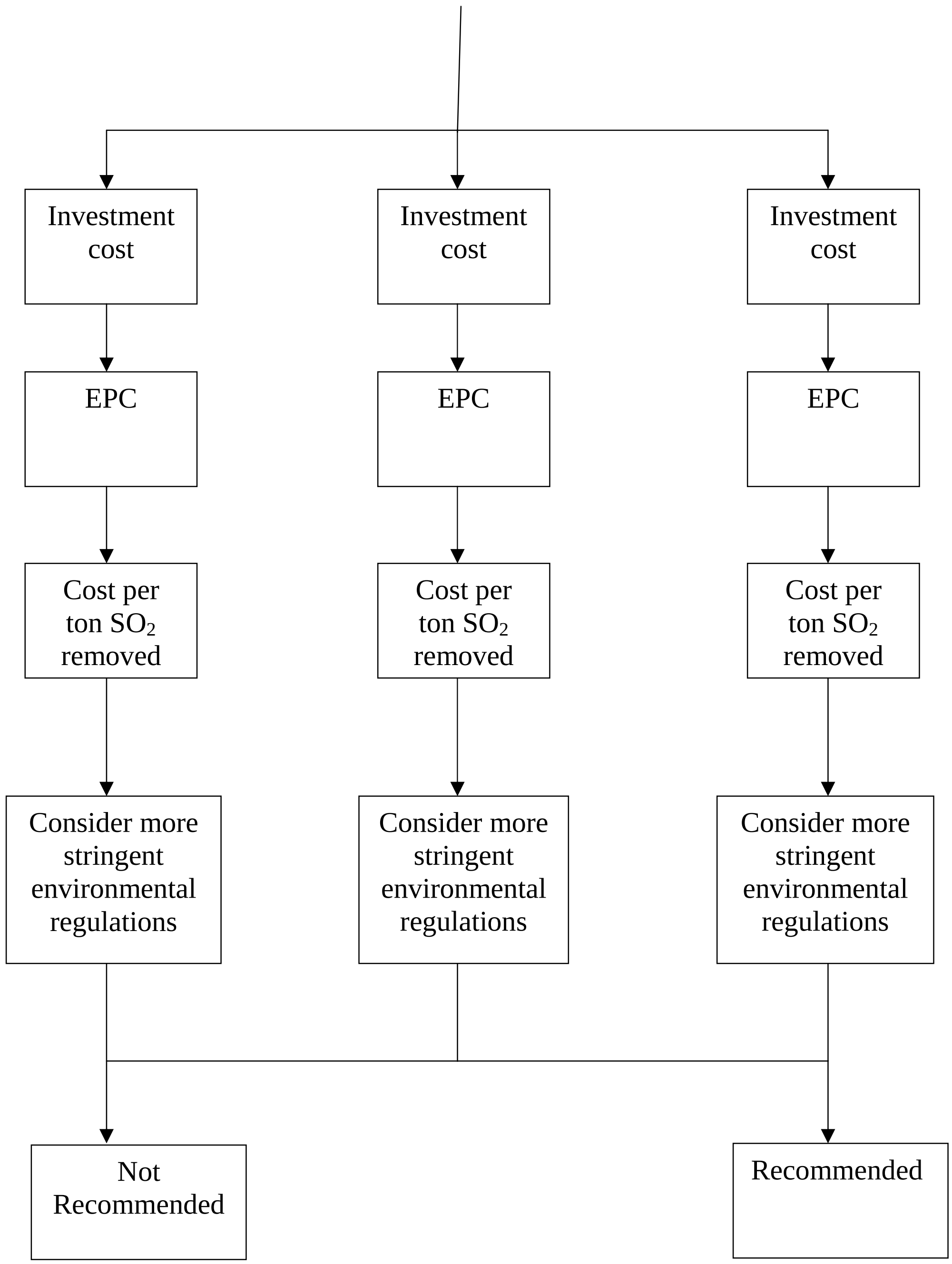


Figure 4.6 Cost Calculation Recommendation - Flow Diagram

4.3.5.4.1 Investment Cost

Key for calculation is that the investment cost per kw decreases with increase in plant size. The investment cost is a very important factor in the decision as to whether a project will be carried through. Total investment cost for the plant is sum of the investment costs for all the technologies used. It is calculated in Million US$. Data for estimating the investment for different technologies is found in tables 4.1-4.6. Specimen table for calculating the total investment cost is given as table 5 of appendix ‘A’.

4.3.5.4.2 Operation and Maintenance Costs

It consists of two portions, fixed and variable. Fixed O&M mainly consists of the employees salaries and is measured as US$/kw/year. Therefore it decreases with the size of the plant. Variable O&M includes the cost for lubricants, parts replacement and the repair cost. It is measured in UScents/kwh and generally increases with the size of the plant. O&M cost data for the different technologies can be found in tables 4.1-4.6. Table 6 at appendix ‘A’ is used to calculate the total O&M cost for the alternatives.

4.3.5.4.3 Electricity Production Cost

The electricity production cost (EPC) in US$/Mwh is the price of electricity that is needed to achieve the required profit and is calculated as

EPC= capital costs + variable operating costs + fixed operating costs + fuel costs.

Table 7 of appendix A lists data required for the calculation of electricity production cost. The availability factor for the combustion technology can be used as the availability factor for the whole plant. Efficiency data for whole power plants can be found under each combustion technology in table 4.2.

Next, the average yearly electricity production volume is calculated in Mwh by multiplying the plant capacity with the annual operation time. Use the required rate of return and the economic life time defined in step 1 to:

A. Calculate the sum of the net present values of the investment, O&M costs and fuel costs in US$;

B. Calculate the sum of the net present values of the amount of electricity produced during the economic lifetime of the plant in Mwh; and

C. Obtain required levelized electricity price by dividing A by B.

Net present value is the one which has to be paid in the first year of economic lifetime. To find out how big portion of the electricity production cost that derives from fixed O&M, variable O&M, fuel and capital costs, respectively: calculate the sum of the net present value of each individual item in US$. Divide each sum by B above to calculate respective cost in US$/Mwh.

The electricity production cost depends on economic assumptions that have to be stated for each project. Economic assumptions include rate of return, estimated inflation and economic lifetime. The production cost is just as important as the investment when deciding which process alternative to choose. The lower the production cost the better. Low variable costs are important when the plant has been built, since a plant with low variable costs can have a longer yearly operating time than one with high variable costs. Country specific taxes can also have a great impact on the electricity production cost but are not considered in this report.

4.3.5.4.4 Cost per Ton Emission Removed

To compare the cost-effectiveness of different emission reduction technologies, calculate the cost for each emission reduction technology/ton emission removed. For example, the cost of sulfur removal equipment/ton sulfur removed is derived by:

A. Calculate the sum of the net present values of the investment in SO_2 removal equipment and O&M costs related to SO_2 removal in US$;

B. Calculate the sum of the net present values of the yearly removed amounts of SO_2 from the plant in tons; and

C. Divide A by B to get the cost/ton sulfur removed.

4.3.5.5 Step 5 Emissions Calculation

In the final step all the major emissions i.e CO_2, SO_2, NOx and particulates are calculated for the power plant. This step has been added to calculate the annual emissions from the power plant and its contribution towards the national emissions. These are calculated by consulting tables 4.1-4.6.

4.3.6 Recommendation

The Enhanced Fast Track Model produces a range of alternatives, each presented with information on investment (US$ millions); electricity production cost (US cents/ kwh); flue gas cleaning cost (US$/ton SO_2 and NOx removed); emissions of SO_2, NOx, and particulates, and by-products and waste. The two alternatives that are best from an economic and environmental stand point should be recommended for further examination in a feasibility study.

Although the current state in Pakistan is more concerned about the power generation and does not stress upon the installation of flue gas cleaning equipment or the utilization of by-products. But the emergence of environmental problems will definitely change the opinion of the authorities regarding these questions. More stringent environmental requirements can be expected to be imposed in the near future. When selecting technologies, it is essential to plan to meet increasingly strict pollution control legislation. It should be possible to add pollution control equipment to a plant at some later stage and to have strategies available for the utilization of by-product. For example, space should always be set aside for the installation of additional equipment, such as wet FGD and SCR.

4.4 Use of Framework for selection of CCTs for 1110 MW Thar Coal Fired Power Plant

To achieve the objective of research, World Bank's FTTSM is used to the Mine mouth power plant to be fueled by Thar lignite coal. It is part of integrated mining and power plant project whose feasibility study was carried out by Rheinbraun Engineering and Wasser Gmbh(RWE) Germany in 2004.

4.4.1 Data Collection

The data has been obtained from the following sources

- "Pakistan Coal Power Generation Potential" of February 2008 by Private Power and Infrastructure Board report;

- “Bankable Feasibility Study for the Thar lignite mine, Province of Sindh, Pakistan September 2004” by Rheinbraun Engineering and Wasser Gmbh (RWE) Germany;
- “A Planners guide for selecting CCTs for Power plants”, World Bank technical paper no 387.
- National Environmental Quality standards of Pakistan(NEQS) by GOP Ministry of Environment, Local Government and Rural Development Extraordinary gazette notification dated 8 August 2000; and
- World Bank Emission standards for coal fired power plants.

The feasibility study mentioned above was prepared under a contract between GOP through Sind coal authority and RWE Germany for utilization of Thar coal for power generation. It was the desire of GOP to investigate the 1000MW power plant. This study was carried out for an integrated mining and power project with following salient features.

- Local lignite coal will be used as fuel for the power plant;
- The power plant will be installed at the mouth of the coal mine;
- Lignite available in Thar contains 47.8% of moisture which will be reduced to 12% through a drying plant resulting in more plant efficiency and less fuel consumption. The water obtained through drying will be used in the boilers after treatment; and
- A power plant with 1110MW gross capacity and 1000MW net capacity will be installed.10% of the gross capacity i.e 110MW will be consumed by the power plant itself and 1000MW will be available at the grid.

The report gives a detailed analysis of the mining portion of the project but just touches upon the power plant. It states that the design of power plant requires evaluation of a large number of parameters such as load flow patterns, power plants in the vicinity etc but a separate study has to be carried out for detailed analysis of the power plant. The possible technologies i.e PCC, IGCC, PFBC and FGD have only been explained and no comparison has been carried out. Also no criteria for selection of technologies for the power plant is stated therein. Therefore WBFTTSM is used for the selection of clean coal technologies for this power plant.

4.4.2 STEP 1 Project Definition

- The project presented below was initiated as a result of an increased demand for power and because new clean coal fired power plants have become necessary;
- To meet up with the demand for power, a new plant with an electric output of 1110 MW will be installed;
- The questions regarding which technologies to choose for this new plant are solved using the Fast Track Model;
- This is a coal fired plant located at Thar, province of Sindh Pakistan that will produce electricity only;
- The plant will have a base load function and use domestic lignite as fuel;
- It is a commercial project meaning that only mature technologies will be used and the demands on availability are high;
- Although the environmental requirements applicable for this project are not yet decided, solutions with low emissions meeting the World Bank/Pakistan environmental standards should be achieved to minimize the environmental impact of new power plant;
- Tables 4.11-4.14 summarize the pre requisites that are valid for this project. These pre requisites are specified by GOP to the firm carrying out the feasibility or by the designer of the power plant. Here most of them have been gathered from the RWE feasibility study

Table 4.11 General Pre requisites

Pre Requisite	Needed for TC
• Type of project	• Commercial
• Size of plant	• *1110 MW
• No of units	• 3
• Coal Type	• Lignite
• Distance from Domestic mine to power plant	• Mine mouth power plant
• Value & range of main characteristics	
➢ Ash content	➢ 5.2-8.92 %
➢ Sulfur content	➢ 0.92-2.50 %
➢ Heating value	➢ 20.04 MJ/Kg
➢ Moisture(Dry Lignite)	➢ 12%
• Date of commissioning	• 36 months after award of contract

*110 MW will be consumed by the plant and accessories. Only 1000 MW will be available at the grid.

Table 4.12 Economic Prerequisites

Pre Requisite WBFTTSM	Needed for TC
• Project economy	
➢ Rate of return	➢ 15%
➢ Economic Lifetime	➢ 30 years
• Financing Policy	• 75/25
• Purchasing policy	• 60:40
• Requirements on Domestic Manufacturing	• As much as possible should be manufactured locally

Table 4.13 Environmental Prerequisites

Pre Requisite WBFTTSM	Needed for TC (less than)
• SO_2	• 1700mg/Nm^3
• NOx	• 1200 mg/Nm^3
• Particulate	• 500 mg/Nm^3
• Other environmental policy	• Strive for low emissions

Table 4.14 Operational Prerequisites

Pre Requisites WBFTTSM	Needed for TC
• Operation time	• 7000 hr/yr
• Availability factor	• 80%
• Load change rate	• 4% per min(Normal)
• Minimum load	• 25-40%
• Efficiency	• 40%
• Coal consumption(Dry Lignite)	• 3.62 Million tons/annum

- Rate of Return (ROR), also known as return on investment (ROI), rate of profit or sometimes just return, is the ratio of money gained or lost (realized or unrealized) on investment cost of power plant. The amount of money gained or lost may be referred to as interest, profit/loss, gain/loss or net income/loss. The money invested is referred here as the capital or the investment cost. ROI is usually expressed as a percentage rather than a fraction;
- Economic Lifetime refers to the cost of the power plant distributed over its lifetime prescribed by the manufacturer. Each year the life of plant decreases and so is its cost;
- Financing Policy of 75/25 means that 75% of the total investment will be through loans and remaining 25% will be paid by the party installing the plant. The loans are acquired from the banks or international agencies like world bank, Asian development bank on the guarantee of the government;
- Purchasing Policy of 60/40 means that GOP is bound to purchase 60% of the electricity generated and remaining 40% is at the discretion of the contractor . The same is decided in the power purchase agreement(PPA);
- Operation Time is the number of hours for which the plant operates in a year. Availability factor of 80% means that plant is operating 80% of the time i.e 7000 out of 8760 hours. Rest of the time the plant is closed for maintenance, overhaul and repair work. All the units are shut down turn by turn for routine maintenance and overhaul so that power supply is not cut off completely;
- Load Change Rate is the rate at which the load is applied to the plant when it is powered on after shut off. Load is always applied gradually;
- Minimum Load. Power plant is never operated at no load for longer period. The prescribed minimum load has to be kept for safety and long life of the plant; and
- Rate of Return (ROR), also known as return on investment (ROI), rate of profit or sometimes just return, is the ratio of money gained or lost (realized or unrealized) on investment cost of power plant. The amount of money gained or lost may be referred to as interest, profit/loss, gain/loss, or net income/loss.

The money invested is referred here as the capital or the investment cost. ROI is usually expressed as a percentage rather than a fraction;

- Economic Lifetime refers to the cost of the power plant distributed over its lifetime prescribed by the manufacturer. Each year the life of plant decreases and so is its cost;
- Financing Policy of 75/25 means that 75% of the total investment will be through loans and remaining 25% will be paid by the party installing the plant. The loans are acquired from the banks or international agencies like world bank, Asian development bank on the guarantee of the government;and
- Purchasing Policy of 60/40 means that GOP is bound to purchase 60% of the electricity generated and remaining 40% is at the discretion of the contractor . The same is decided in the power purchase agreement(PPA).

The standards mentioned in table 4.13 for SO_2, NOx and particulates emission are the World Bank emission standards and environmental quality standards of Pakistan(whichever is more stricter) for coal fired plants and are mentioned in “The Gazette of Pakistan, extraordinary, Islamabad dated 10 August 2000 by ministry of environment, local government and rural development notification dated 8 August 2000. Under this notification Pakistan environmental protection agency(PEPA) has amended the previous regulations.

4.4.3 STEP 2: Technology Screening

Technology screening is done using table 4.16 using one of the criterias given in Table 4.15. Screening criteria has been set, after consulting the coal expert at PPIB, keeping in view the following considerations

- Since this is a commercial project, the requirements on maturity of technology are high;
- In order to avoid the breakdown of the whole plant in case of fault or overhaul, the size of the plant shall be accommodated in three or four units; and

Table 4.15.Screening Criteria for Thar Coal Fired Power Plant

S-No	Technology Area	Maturity of technology	Required no of units	Waste product
1	Combustion	>10 Commercial reference plants worldwide	Total plant size: 3 units	Possible to use with/without processing
2	SO_2 Emission Control	>10 Commercial reference plants worldwide	–	Disposal or possible to use with/without processing
3	NOx Emission Control	>10 Commercial reference plants worldwide	–	–
4	Particulate Emission Control	>10 Commercial reference plants worldwide	–	–

Table 4.16. Screening of Technologies

S-No	Technology	Level of maturity H= High L= Low		Max unit size MW A= All sizes		Waste Requirements P= Possible to use D= Needs disposal		Result A= Applicable NA= Not Applicable
		Present	Reqd	Aval	Reqd	Present	Reqd	
1	Sub critical	H	H	1300	370	P	P/D	A
2	Super critical	H	H	1300	370	P	P/D	A
3	ACFB	H	H	320	370	D	P/D	NA
4	PFBC	L	H	340	370	D	P/D	NA
5	IGCC	H	H	320	370	P	P/D	A
6	Sorbent injection	H	H	A	370	D	P/D	A
7	Spray dry scrubbers	H	H	A	370	D	P/D	A
8	Wet FGD	H	H	A	370	P	P/D	A
9	Combined SO_2/NOx	L	H	A	370	D	P/D	NA
10	Low NOx burner	H	H	A	370	-	P/D	A
11	Low NOx burner+OFA	H	H	A	370	-	P/D	A
12	SNCR	H	H	A	370	-	P/D	A
13	SCR	H	H	A	370	-	P/D	A
14	ESP	H	H	A	370	-	P/D	A
15	Baghouse filter	H	H	A	370	-	P/D	A

Table 4.17. Applicable Technologies for a 1000-MW Power Plant in Thar Desert, Pakistan

Applicable combustion technologies	Applicable SO2 emission control technologies	Applicable NOx emission control technologies	Applicable particulate emission control technologies
• Sub critical PC boilers • Super critical PC boilers • IGCC	• Sorbent Injection • Spray dry scrubbers • Wet FGD	• Low NOx burners • OFA • SNCR • SCR	• ESP • Bag house filter

- Since there is no specific policy for the coal fired power plants waste disposal in Pakistan ,the waste products will be either disposed off or possible to use with /without processing.

4.4.3.1 Applicable Technologies

The screening criteria is applied for each technology and compared with the data and information given in the table 4.9 by using the specimen table 4.10. The screening results in step 2, table 4.17, gives the applicable technologies, which meet the overall requirements of the project (Table 4.11- 4.14). These technologies will be used for stating possible power plant concepts in Step 3.

4.4.4 STEP 3: Possible Alternatives

4.4.4.1 Coal Quality

In this case the available Thar coal is lignite. Lignite is known to be the best coal for power generation worldwide. It will have following advantages

- Lignite burns at low temperatures, there will be very less NOx emissions. There is no need to install NOx emission reduction technology;
- No NOx emission control technology means less investment cost and less power tarrif; and
- Less environmental pollution.

Therefore Lignite will be used as a fuel in the under study power plant. All NOx emission control technologies(Low NOx burners, OFA, SNCR and SCR) are eliminated at this step.

4.4.4.2 Stating the Possible Alternatives

- Lignite suits the sub critical and supercritical technologies;
- Sub critical and ACFB technologies are eliminated because they do not provide the required efficiency i.e 40%; and
- Comparing the information given in tables 4.1-4.6 , especially the columns of suitability and fuel flexibility we can state the possible combination of technologies for the power plant (Table 4.18), fulfilling the environmentally least to more stringent criterias.

4.4.4.3 Evaluation

The alternatives evaluated have to fulfil the prerequisites stated in Tables 4.11-4.14. Some of these prerequisites are gathered in Table 4.19 that shows how each alternative complies with the prerequisites. As shown in Table 4.19 the NOx emissions are very low. This is a result of using lignite as fuel. Lignite is burnt at temperatures below 1000 deg C as compared to anthracite (1200 deg C). As a result the NOx emissions are within allowable limits. Lignite starts melting at 1200 deg C and clinker formation starts in the boiler which can damage the boiler. There is a special safety in the lignite fired power plants which does not allow furnace temperature to exceed 1000 deg C. The same is being followed in the only coal fired power plant of Pakistan i.e 150 MW Lakra Power plant.

Table 4.18.Possible Alternatives configuration

Technology area	Alt 1	Alt 2	Alt 3	Alt 4
Combustion technology	Super critical PC	Super critical PC	Super critical PC	Super critical PC
SO_2 emission control	None	Sorbent injection	Spray dry scrubbers	FGD
NOx emission control	None	None	None	None
Particulate emission control	ESP	ESP	ESP	ESP

Table 4.19. Evaluation of diffrent alternatives against selected pre requisites

Pre requisites	Pre Requisite	Alt 1	Alt 2	Alt 3	Alt 4
SO_2(mg/Nm^3)	1700	2200	462	225	154
NOx(mg/Nm^3)	1200	500	500	500	500
Particulate(mg/Nm^3)	500	10-25	10-25	10-25	10-25
Solid waste	Disposal/Possible to utilize(D/P)	D	D	D	P

4.4.5 STEP 4. Cost Calculation

4.4.5.1 Investment Cost(I.C) Calculation

The investment costs per kw are given in tables 4.1-4.6. They are calculated for this specific power plant in table 4.20. The investment cost for all alternatives is calculated by adding the cost for the different technology areas (Table 4.21).

4.4.5.2 O&M Cost Calculation

O&M cost, both fixed(F) and variable(V), for different technologies can be found in tables 4.1-4.6. These O&M Costs are calculated in table 4.22 and further tabulated in Table 4.23.

4.4.5.3 Fuel Cost

3413 Btu produces 1kwh of electricity (standard followed by NEPRA)

whereas 1MJ = 948 Btu

Heating value (H.V) of Thar coal = 20.04 MJ/kg

= 20.04 x 948 Btu/kg = 18997.92 Btu/kg

It means that 1kg of coal can produce = 18997.92 Btu of heat

Therefoasare 1kg of coal can produce = 18997.92 / 3413 = 5.56 Kwh of electricity

or 1 ton of coal can produce 5.56 Mwh of electricity

Fuel cost = 40.47 US$ /ton (As per NEPRA),

Fuel cost = 40.47/5.56 = **7.3 US$/Mwh**

4.4.5.4 Savings in Fuel Consumption

Use of efficient combustion technology results in lesser fuel consumption. It is calculated for the under study power plant as follows:

Fuel consumption per year = 3.62 M tons per year

Electricity produced during the year = 7000 x 1110 = 7,770,000Mwh

With the use of PC super critical technology the efficiency is increased by minimum 4%. i.e 36 to 40%.

For 4% increase in efficiency the coal consumption is decreased from 500 kg/Mwh to 450 kg/Mwh.(Figure 3.5)

Reduction in coal consumption per Mwh = 500-450 = 50 kg/Mwh = 0.05 tons/Mwh

Table 4.20. Investment Cost Calculations

	Supercritical PC	Sorbent injection	Spray dry scrubbers	Wet FGD	ESP
I.C per kw (US$)	1050	100	110	160	50
I.C for 1110 MW (US$)	1110 x 1050 x 1000 = 1165 M	1110 x 75 x 1000 = 84.0 M	1110 x 110 x 1000 = 122.1 M	= 1110 x 160 x 1000 = 177.6 M	1110 x 50 x 1000 = 55.5 M

Table 4.21. Investment Cost for 1110 MW Thar Coal Power Plant

Technology Area	Investment(MUS $)			
	Alt 1	Alt 2	Alt 3	Alt 4
Combustion Technology*	1165	1165	1165	1165
SO_2 emission reduction	-	84	122.1	177.6
NOx emission reduction	-	-	-	-
Particulate emission reduction	55.5	55.5	55.5	55.5
Total investment	1220.5	1304.5	1342.6	1398.1

Note: (*) includes costs for complete power plant except flue gas cleaning equipment.

Table 4.22. Calculation of Fixed and Variable O&M Costs for Different Alternatives

	Supercritical PC	Sorbent injection	Spray dry scrubbers	Wet FGD	ESP
O&M (F) US$ per kw per year	27	6	9	12	12
O&M (F) for 1110 MW per year(US$)	27 x 1000 x 1110= 17.8M	6 x 1000 x 1110= 6.66M	9 x 1000 x 1110= 10.0M	12 x 1000 x 1110= 13.32M	12 x 1000 x 1110= 13.32M
O&M (V) UScents per kwh	0.2	0.3	0.3	0.15	0.15

Table 4.23. O&M Costs for Different Alternatives

Technology Area	O&M Costs Fixed (M US $/year) Variable(UScents/ kwh)			
	Alt 1	Alt 2	Alt 3	Alt 4
Combustion Technology*	17.8 0.2	17.8 0.2	17.8 0.2	17.8 0.2
SO_2 emission reduction	-	6.66 0.3	10 0.25	13.9 0.3
NOx emission reduction	-	-	-	-
Particulate emission reduction	- 0.3	- 0.3	- 0.3	- 0.3
Total O&M: Fixed Variable	17.80 0.5	24.46 0.8	27.80 0.75	31.70 0.8

Reduction in coal consumption per year = 0.05 x Electricity produced

= 0.05 x 7,770,000= 388,500 Tons= 0.39 M tons(approx)

4.4.5.5 EPC Cost Calculation

The economical presumptions that are necessary to calculate the electricity production cost were stated in tables 4.11-4.14. These economic presumptions and all other data necessary for the calculations are gathered in Table 4.24.

EPC = Capital cost + Fixed cost + Variable cost + Fuel cost

All these costs are converted into US$/MWh to get the EPC or power tarrif.

- Capital Costs

NPV is calculated by

NPV = (I.C/Economic life time) + (I.C x Rate of Return)

I.C(1/30 + 0.15) = I.C x 5.5/30 …………………(4.1)

Electricity produced per year = Size of plant x operating time…………………(4.2)

Calculation details are tabulated as table 4.25.

- O&M Costs

Fxed O&M (US$/Mwh) = Fixed O&M per year / No of MW / Operating hours

Variable O&M (US$/Mwh) = (Variable O&M in USCents/kwh) x 10

Calculation details are tabulated as table 4.26.

Table 4.24. Data for Calculating EPC for Different Alternatives

	Unit	Alt 1	Alt 2	Alt 3	Alt 4
Constr period	Months	36	36	36	36
Operating time	Hours/year	7000	7000	7000	7000
Availability	%	80	80	80	80
Coal price	US $/MWh	7.3	7.3	7.3	7.3
Electricity production	MW	1110	1110	1110	1110
Plant efficiency	%	40	40	40	40
Investment	MUS $	1220.5	1304.5	1342.6	1398.1
Fixed O&M	MUS $	17.8	24.46	27.80	31.70
Variable O&M	UScents/kwh	0.5	0.8	0.75	0.8
Rate of return	%	15	15	15	15
Economic Lifetime	Years	30	30	30	30

Table 4.25 Calculations of Capital Cost for EPC

	Alt 1	Alt 2	Alt 3	Alt 4
NPV(US$) =I.C x 5.5/30	1,220,500,000 x 5.5/30 = 223,758,333.3	1,304,500,000 x 5.5/30 = 239,158,333.3	1,342,600,000 x 5.5/30 = 246,143,333.3	1,398,100,000 x 5.5/30 = 246,143,333.3
Elect produced per year(MWh)	1110 x 7000 = 7,770,000	1110 x 7000 = 7,770,000	1110 x 7000 = 7,770,000	7,770,000
Capital cost(US$/Mwh)	223,758,333.3/7770000 = 28.8	239,158,333.3/7770000 = 30.8	246,143,333.3/7770000 = 31.7	246,143,333.3/7770000 = 33.0

Table 4.26. Calculation of O&M Costs for EPC

	Alt 1	Alt 2	Alt 3	Alt 4
Fixed O&M (US$/Mwh)	17,800,000/1110 x 7000 = 2.3	24,460,000/1110 x 7000 = 3.15	27,800,000/1110 x 7000 = 3.58	31,700,000/1110 x 7000 = 4.08
Variable O&M (US$/Mwh)	0.5 x 10 = 5.0	0.8 x 10 = 8.0	0.75 x 10 = 7.5	0.5 x 10 = 5.0

Table 4.27. Calculation of EPC/ Tarrif

	Alt 1	Alt 2	Alt 3	Alt 4
Capital	28.8	30.8	31.7	33.0
Fixed(O&M)	2.30	3.15	3.58	4.08
Variable (O&M)	5.0	8.0	7.5	8.0
Fuel cost	7.3	7.3	7.3	7.3
Project IRR(15%)	6.5	7.38	7.52	7.42
EPC/Tarrif (US $/MWh)	49.90	56.63	57.60	59.80

As shown in the table 4.27, alternative 4 results in the highest electricity production cost and alternative 1 the lowest. This is natural, since alternative 4 includes the most sophisticated emission control equipment. The figure shows that the electricity production cost varies between 49.9 US$/MWh and 59.8 US$/MWh depending on the extent of emission control equipment included.

4.4.5.6 Analysis of Calculated EPC

EPC connected to each alternative with contribution from capital, fixed and fuel costs are shown graphically in figure 4.7. Following is deducted

- EPC increases with the increase in the emission removal efficiency. Alt 1 with no sulfur removal equipment has the least tarrif whereas Alt 4 with wet FGD has the highest tarrif;
- The tarrif given by NEPRA for the same project is 7.8055 USCents/kwh which is more than calculated in chapter 3. This difference is due to the fact that the EPC given by NEPRA also includes the mining cost and the applicable taxes; and
- The tarrif announced by NEPRA for furnace oil is 16-18 USCents/kwh whereas for gas it is almost 8 USCents/kwh. Therefore coal still remains the cheapest among the fossil fuels. It will further be reduced once the mining is completed and the initial investment is recovered.

Inspite of the increase in cost due to clean coal technologies, tarrif for indigenous coal based power generation is lowest among fossil fuels in Pakistan.

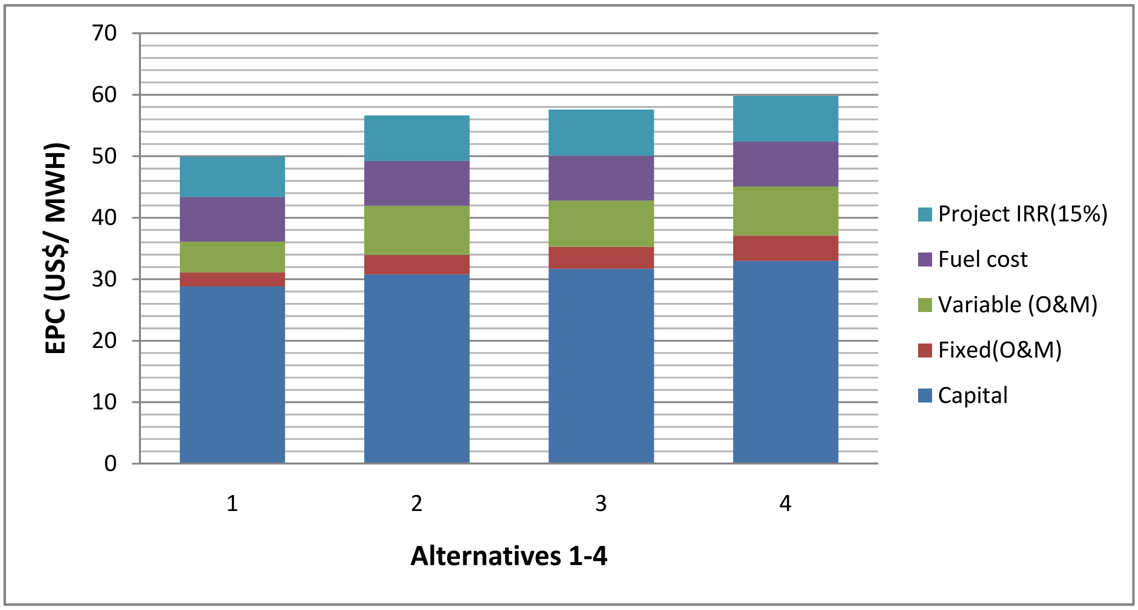


Figure 4.7 Electricity Production Cost for Different Alternatives

IRR= Internal rate of return

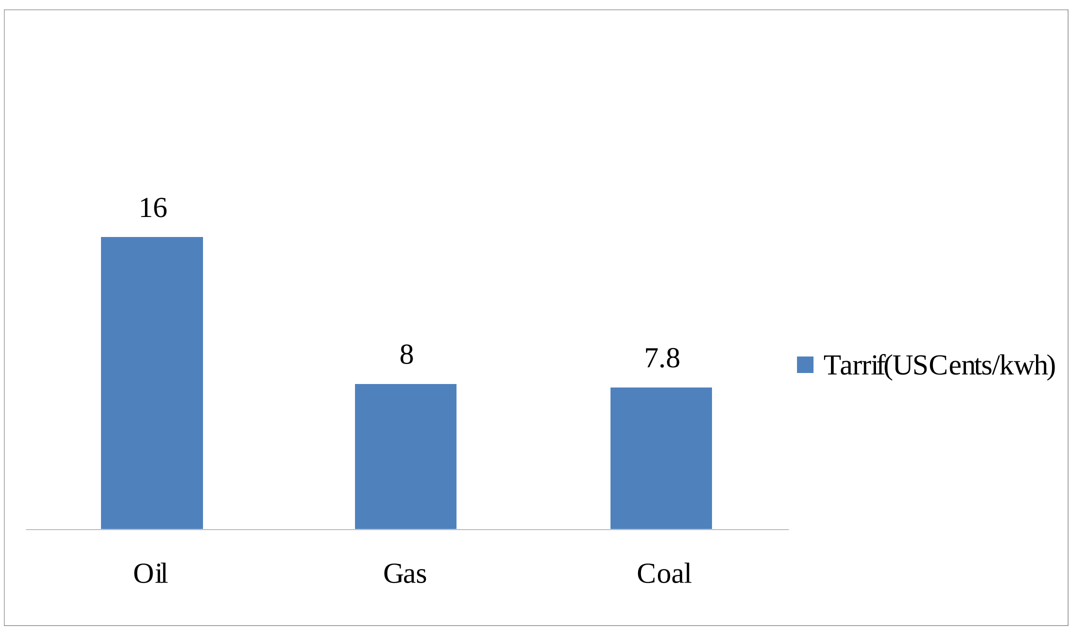


Figure 4.8 Comparison of Tarrifs by Fossil Fuels

4.4.5.7 Cost per Ton of SO_2 Removal

Annual consumption of coal = 3.62 M tons

Annual operating time = 7000 hrs

Consumption of coal per hour = 3,620,000 / 7000 = 517.4 tons

Sulphur content of coal(Average) = 1.5%

The emissions are calculated on the basis of sulphur contents of the coal.

SO_2 emission(without any emission control equipment) = 0.015 x 517.4 x 2

= 15.52 tons/hr

Here NPV is calculated by using equation 4.1

SO_2 emissions per annum(without any emission control equipment)

= 15.52 x 7000 = 108,640 tons

Calculation details are given in table 4.28.Alt 3 gives the lowest whereas Alt 4 gives the highest cost per tonne of SO_2 removed.

Table 4.28. Calculations Cost of SO_2 Removal

	Alt 1 No SO_2 equipment	Alt 2 Sorbent Injection	Alt 3 Spray Dry Scrubbers	Alt 4 Wet FGD
NPV Investment cost (US$)	-	(84/30 + 12.6) 1000,000 = 15.4M	(110/30 + 16.5) 1000,000= 20.17M	(177.6/30 + 26.64)1000,000 = 32.56M
NPV fixed O&M cost (US$)	-	24.46 M	27.8 M	31.7 M
NPV variable O&M cost (US$)	-	8 x 1110 x 7000 = 62.16 M	7.5 x 1110 x 7000 = 58.28 M	8 x 1110 x 7000 = 62.16 M
Total NPV(US$)	-	15.4 + 24.46 + 62.16 = 102M	20.17 + 27.8 + 58.28 = 106.25	32.56 + 31.7 + 62.16 = 126.42M
Tons of SO_2 removed per annum	-	(0.7 x 15.52) 7000 = 76048	(15.52 - 2.95) 7000 = 88,270	(15.52 - 1.46) 7000 = 98,420
Cost of SO_2 removed (US $/ton)	-	102,000,000 / 76048 = 1342	106,250,000 / 88,270 = 1204	126,420,000 / 98420 = 1285

4.4.5.8 Analysis Sulphur Removal Efficiency (SRE)

SRE for each alternative is calculated as follows and shown in figure 4.9

- Alt 1 No sulfur removal equipment

  SRE = 0 %
- Alt 2 Sorbent injection

  SRE = (76,048 / 108,640)100 = 70%
- Alt 3 Spray dry scrubbers

  SRE = (88,270 / 108,640)100 = 81%
- Alt 4 Wet FGD

  SRE = (98420 / 108,640)100 = 91%

SRE calculated for different technologies matches with the values contained in table 4.2.

4.4.5.9 Analysis Sulfur Removal Cost (SRC)

SRC for different alternatives is shown graphically in figure 4.10.

- EPC for Alt 3 is higher than Alt 2 whereas cost per ton of SO_2 removed for Alt 3 is less than Alt 2. This is because of the higher SO_2 removal efficiency for Alt 3;
- Similarly Alt 4 has the highest EPC but the SO_2 removal cost is lesser than Alt 2 due to the highest efficiency; and
- SRC may become the selection criteria for CCTs in future if more stringent environmental regulations are imposed in future.

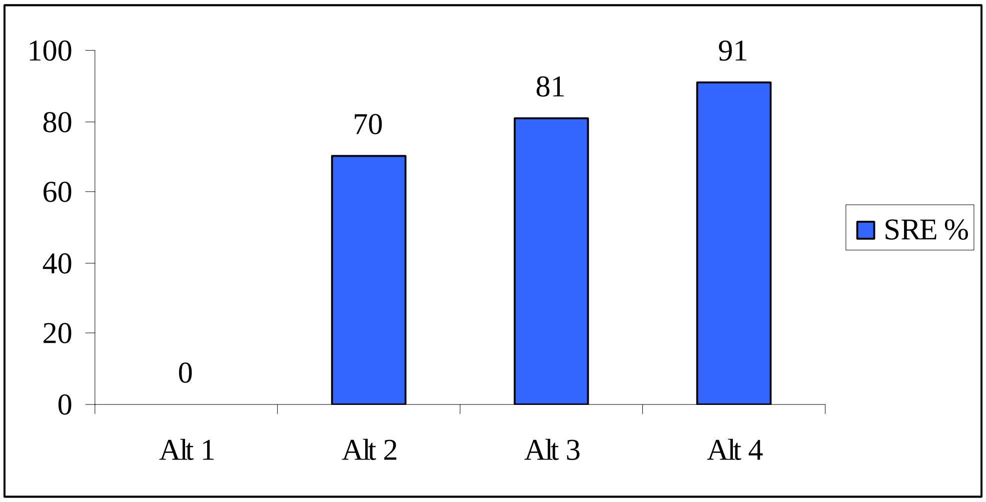


Figure 4.9 Comparison Sulfur Removal Efficiency

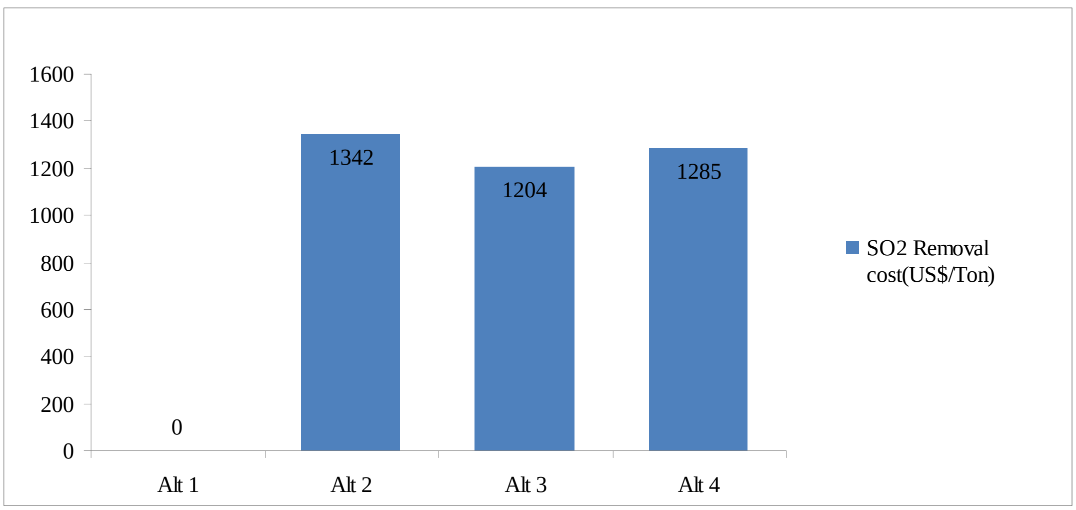


Figure 4.10 Comparison of SO_2 Removal Cost

4.4.6 STEP 5: Emissions From the Power Plant

- SO_2 emissions are already calculated in table 4.28
- Particulate emissions = 2.1 Tons / hr or 2.1 x 7000 = 14,700 Tons/ yr
- CO_2 emissions = 2.75 x 517.4 = 1423 Tons / hr

or 1423 x 7000 Tons /yr = 9.96 M Tons/yr

These emissions are given in table 4.29.

It can be seen that almost 98% of the emissions by weight are contributed by CO_2, whereas only 2% is shared by SO_2, NOx and particulates emission. It is because of the fact that emission control equipment is installed only for SO_2, NOx and particulates. The low cost methods available for CO_2 reduction are

- Coal washing; and
- Efficiency increase of the power plant.

CCS technology, which is under demonstration and R&D, is quite expensive, thus raising the EPC. It is hoped to be commercially available at an affordable cost around 2020.

Table 4.29 Emissions From the Power Plant

Type of emission	Alt 1	Alt 2	Alt 3	Alt 4
SO_2 (Tons/yr)	108,640	76,048	88,270	98,420
Particulates (Tons/yr)	14,700	14,700	14,700	14,700
CO_2 (M Tons/yr)	9.96	9.96	9.96	9.96

Table 4.30. Result of Environmental, Technical, and Economic Evaluation of 4x Alternatives

	Unit	Alt 1	Alt 2	Alt 3	Alt 4
Investment	M US$	1220.5	1304.5	1342.6	1398.1
Electricity production cost	USc/kwh	4.99	5.66	5.76	5.98
Cost of SO_2 removed	M US$/Ton	-	1342	1204	1285
SO_2 Emission	mg/Nm^3	1540	462	225	154
NOx Emission	mg/Nm^3	220	220	220	220
Particulate Emission	mg/Nm^3	10-25	10-25	10-25	10-25

4.4.7 Technology Recommendation

4.4.7.1 Result

The technical, economic and environmental evaluation of the resulting four alternatives are presented in Table 4.30.

4.4.7.2 Recommendations for Selection of Technologies

Keeping in view the results after the use of framework and the analysis carried out, following is recommended for the under study power plant

- Alt 1which is a plain plant without any emission control equipment except for an ESP, is eliminated due to higher emissions;
- Alt 4 with highest investment cost and SO_2 removal efficiency is eliminated due to higher costs; and
- Comparison of Alt 2 and 3 both contain SO_2 removal equipment. The difference is only the SO_2 removal efficiency. Alt 2 uses sorbent injection and Alt 3 uses spray dry scrubbers. Although investment cost for Alt 3 is higher but its calculated tarrif (EPC) is almost equal to Alt 2. Alt 3 has the lowest Cost/ton of SO_2 removal. Alt 3 is the likely choice. However detailed feasibility studies should be carried out for Alt 2 and 3.

4.4.7.3 Possibility to Comply with Future More Stringent Environmental Requirement

It is possible that the environmental requirements will become more stringent in the future. This means that if the plant will be built without spray dry scrubbers and wet FGD system, the layout of the plant should be such that their future installation is possible.

4.4.7.4 Deciding Technology

In case of under evaluation power plant, SO_2 emission control equipment will be the deciding factor for choice of alternative to be used.

CHAPTER 5

RECOMMENDATIONS AND CONCLUSIONS

5.1 Recommendations

During the research extensive literature review was carried out before arriving at the research question. Then WBFTTSM was improved and enhanced before applying it to Thar coal fired power plant for selection of CCTs. The results achieved recommended certain combination of CCTs for the power plant. These results were analyzed and important facts were found. During this process, certain deficiencies were observed and a need was felt to make some modifications in the model. The same are given in the form of recommendations below

- WBFTTSM in its original form covers 16 CCTs. It has the flexibility to incorporate more of emerging technologies as they mature e,g CCS technology;
- WBFTTSM covers four categories of emission control technologies i.e combustion technologies, SO_2, NOx and particulate emission control technologies. It does not cover the CCS technologies, since those are still in R&D and demo stage. Moreover CCS technologies are expensive and increase the EPC markedly. Therefore low cost methods for CO_2 reduction like efficiency increase, coal washing etc. must be applied as far as possible;
- The screening table 4.7 in step 2 of the model is used to eliminate the technologies that does not meet the overall requirements of the project. It must be updated before application of WBFTTSM by consulting the manufacturers/distributors;
- The combustion technology recommended by WBFTTSM for Thar coal fired power plant is PC supercritical which gives an efficiency in the range of 40-45 %, whereas efficiency pre requisite given by GOP is 40% which comes in the lower range of the respective technology. Therefore it is recommended that if PC supercritical technology is going to be used in such power plant , the efficiency requirement should be increased to the range of 42-45%;

- While analyzing the results, total emissions of the power plant per annum were calculated. The same was done to assess how much this plant contributes towards the CO_2 emissions at national level. It can be made part of the WBFTTSM and included in step 3 of the model. Whenever the model is applied total emissions from the plant per year and its contribution towards the total emissions should be calculated while designing the power plant;
- While analyzing the results, coal consumption per annum for the plant with the selected technology was calculated. The same should be calculated for each of the alternatives in step 3 of the model. It will enable the planner to evaluate the alternatives more comprehensively;
- During the visit to various institutes during research, it was found that no design standards exists for the coal fired power plants in Pakistan. The requirements given to the vendors/manufacturers are very general and limited ones. No stress is being laid on the selection of CCTs in the ongoing projects. This is due to the lack of expertise on the subject. Therefore it is recommended that a design standard should be specified by GOP for coal fired power plants in Pakistan which should include CCTs;
- During the course of research, it was found that no specific policy exists for the disposal of waste from coal fired power plants in Pakistan. It is very important as it defines a portion of the overall requirements of the project. Moreover it varies with each technology to be used and affects the economics of the project. Therefore it is recommended that some standards in this regard must be stated by ministry of environment for guidance of the power system planners;
- Selection of CCTs for power plants is a complex task. No definite criteria exists for the selection of CCTs in Pakistan. GOP is planning to increase coal fired power production from 150 to 19900MW by 2030;
- CCTs are continuously being researched in countries like USA and Japan. Due to the coal contribution to the environmental pollution and global warming, environmental friendly technologies with less emissions are being focused. No

such effort is being made in Pakistan. There is a requirement to research and keep a track of these technologies. It is recommended that a clean coal research institute for design and development of CCTs be established by GOP. An appropriate budget should be allocated for the purpose;

- Keeping in view that performance of CCTs is being improved continuously and new technologies introduced worldwide, the National Environmental Quality Standards (NEQS) for coal fired plants in Pakistan be revised at regular intervals for keeping up the pace with the developing world and controlling the environmental situation of the country;
- Courses on introduction of CCTs with special emphasis on power sector be introduced at undergraduate level of Power engineering and Energy management;
- Students at all levels should be encouraged and rewarded for the research on CCTs;
- Research at postgraduate level on different aspects of CCTs be encouraged and funded by GOP;
- Power system planners and the responsible government officials should be educated on the importance of introduction of CCTs in the power sector;
- “The penetration of cleaner and energy efficient technologies in small power systems such as the one in Sri Lanka has encountered many problems. This has caused major concerns among the policy makers, mainly in the context of the growing need to reduce harmful emissions in the electricity supply industry from the point of view of both local environmental pollution as well as the global warming concerns”[118]. Therefore Government of Pakistan also requires to devise a clear policy for penetration of CCTs domestically in the longer term.

5.2 Future Scope of Study

Keeping in view the substantial work being carried out on CCTs world over and the importance being attached to it, it is absolutely essential to carry out further research on the subject. Therefore following areas of studies are recommended to be researched

- Calculation of emissions from coal fired power plants under GOP's MTDF 2030 program;
- Prospects of using Thar coal for Coal to liquid technology;
- Prospects of using underground gasification technology in Pakistan;
- Prospects of using Thar coal for coal bed methane technology;
- In depth analysis of each CCT being used in the world today;
- Prospects of using advanced technologies like IGCC, PFBC, IGFC and CCS etc. in power plants; and
- Time line calculation for introduction of CCTs in Pakistan.

5.3 Conclusion

Coal will play a vital role in the energy sector of Pakistan in the 21st century. Coal provides the cheapest power tarrifs among the fossil fuels in Pakistan. Growing demand for power, widening energy supply demand gap and increased electricity tarrifs has made it necessary for GOP to explore the coal potential of the country as soon as possible. Pakistan's enormous coal power generation potential can help reduce the energy gap to a great extent. Pakistan in spite of 6th largest coal reserves has only one coal fired power plant i.e Lakra 150MW which amounts to 0.1% of the total installed capacity. The major drawbacks of coal use are the environment pollution, water pollution and disposal of waste. There is a requirement of using coal reserves in a wise manner. Use of Clean Coal Technologies in the power plants provides an effective method for utilization of these precious reserves. They not only reduce the coal consumption but also protects the environment against degradation. The addition of CCTs increases the power tarrif but is still lesser than other fossil fuels. Inspite of the utility and advantages of CCTs, nothing worthwhile has been done in this regard so far. There is very less awareness in our power system planners and government officials about the use of CCTs in the power plants. Moreover nothing worthwhile is being researched and demonstrated at academic and commercial level respectively. There is a need to create awareness on the subject at all levels and ensure implementation of CCTs in the power as well as non power sector. WBFTTSM compares different CCTs being used worldwide and provides an in depth analysis covering technical, environmental and economic parameters. WBFTTSM provides a guideline for the engineers and designers to help select cost effective and environment friendly CCTs for the power plants. It is especially useful for the developing countries like Pakistan who cannot afford high tarrifs and wants to protect environment at an affordable price. Its application to one of the proposed power plants fueled by Thar coal results in the recommendation of technology combination to be used in the said plant. It has the flexibility to absorb new technologies and give accurate results. Presently technology combination with low EPC is preferred over the higher ones. But with more stringent emission regulations in future cost of SO_2, NOx removed may become the deciding factor for selection of CCTs for power plants.

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