# Recent approaches in $CO_2$ fixation research in India and future perspectives towards zero emission coal based power generation

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*With an ultimate goal of stabilization of greenhouse gases in the atmosphere, new scientific approaches are being researched worldwide leading to a shift in the policies from low carbon and no carbon energy sources to fossil fuel sources with capture of carbon and its storage or permanent fixation. The carbon capture and storage is no doubt a progressive approach to limit $CO_2$ concentration in the atmosphere. In India, $CO_2$ fixation research has been initiated on novel amine based, multiphased absorbents and innovative adsorptive materials in different R&D laboratories. New possibilities exist in biofixation of $CO_2$ from the flue gases through microbial and microalgal processes. There is need to intensify R&D efforts further for development of cost-effective regenerative adsorbents and processes. It is also important that advanced coal combustion technologies are investigated keeping in view the properties of coal and the concept of zero emission plants. Emerging trends in advanced coal combustion processes and challenges in R&D towards zero emission coal based power generation are enumerated.*

**Keywords:** Climate change, coal combustion, $CO_2$ fixation, energy, zero emission.

IN the 19th century, mankind entered into a new geological era which includes the last 200 years. 'We are not in Holocene, but in Anthropocene era because it is we who determine the climate', said Paul J. Crutzen, 1995 Nobel laureate, in his lecture delivered at the Indian National Science Academy during February 2007. Different approaches towards reengineering of the atmosphere have been proposed. A simulation experiment of injection of sulphate aerosols in the stratosphere shows that releasing one million terragram sulphur per year at 25 km altitude in the tropical belt (10°N to 10°S) would be sufficient to cancel the effects of global warming caused by doubling of $CO_2$ in the atmosphere[1]. These and other geological and ecological 'solutions' in the wake of increasing greenhouse gas emissions and their accumulation with adverse consequences on the climate in the 21st century; and how scientific priorities can change have become the focus of discussions in many forums across the world. The Royal Society, UK has undertaken a scientific feasibility of geoengineering of climate with a goal to diminish radiative forcing by as much as 1 $W/m^2$. (Problems in geoengineering schemes are also discussed in a recent article in *Current Science*, 2009, **96**, 41–48).

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Visibly, the year 2007 became the seminal year on climate change due to the following global actions:

- The Fourth Assessment Report of UN Intergovernmental Panel on Climate Change (IPCC) released in February 2007 stated 'warming of climate system is univocal'.
- The IPCC report further documented evidence of global average temperature increase by about 0.74°C in the last 100 years (1996–2005) resulting from observed changes in the atmospheric composition of carbon dioxide, methane and nitrous oxide concentrations.
- *An Inconvenient Truth* about the perils of global warming won the Oscar Academy Award for best documentary film.
- 2007 Nobel Peace Prize was awarded jointly to R. K. Pachauri, Chairman, IPCC and Al Gore, US Vice President, giving a big boost to the international campaign for actions against global warming and climate change.

## Energy and climate change outlook

Coal based energy generation remains the main source of electricity worldwide. For developing economies like India it has potential to provide energy access to all. In 2007, world production of coal and lignite became 6.4 Bt.

Table 1 gives a glimpse of coal production and its share in the total energy in major coal-producing countries from different parts of the world[2]. Clearly, energy from coal is one of the options to overcome energy shortages in the foreseeable future.

While considering various energy technology options, we are concerned with the rise in $CO_2$ emissions from coal combustion. Nature captures $CO_2$ from the atmosphere by way of photosynthetic reaction, in which plants and photosynthetic algae or bacteria use energy from sunlight to combine carbon dioxide ($CO_2$) from the atmosphere with water ($H_2O$) in the soil to form carbohydrates in presence of chlorophyll, as follows:

$$6CO_2 + 6H_2O \xrightarrow{\text{Sunlight}} \underset{\text{Glucose}}{C_6H_{12}O_6} + 6O_2, \quad (1)$$

The anthropogenic increase in $CO_2$ levels mainly from fossil fuel combustion is however, affecting the carbon balance and is giving rise to global warming concerns. The measured radiative forcing which results from increase in $CO_2$ and other greenhouse gases (1.6 $W/m^2$) is clearly much higher than that resulting from solar intensity (0.12 $W/m^2$).

The carbon capture and storage (CCS) technology is therefore suggested as one of the options to meet the global emission stabilization targets while meeting national energy needs[3]. It involves capture of $CO_2$ in the atmosphere and its permanent fixation away from the atmosphere. If the power plants and the storage sites are not close to each other, it will involve transport of $CO_2$ in liquid form over longer distances. In this context, International Energy Agency has identified five areas in CCS R&D[4] as follows:

1. Clean coal technologies – technologies such as super critical coal combustion, integrated gasification combined cycle (IGCC), increase efficiency and reduce $CO_2$ emission per kWh of electricity generated.
2. Post combustion capture – chemical absorption, adsorption and membranes separation techniques are under development for post combustion $CO_2$ capture from the flue gas of coal based power plants.
3. Pre-combustion capture – pre-combustion capture or decarburization of coal by its conversion into synthetic gas (syngas) and then converting carbon monoxide into $CO_2$ and hydrogen in a shift reactor, is a step towards hydrogen economy.
4. Oxyfuelling – oxy-coal combustion involves coal combustion in the presence of pure oxygen, resulting in concentrated flow of $CO_2$ in the flue gas.
5. $CO_2$ capture in manufacturing industry – energy intensive industry contributes 22% of world's energy and the process related $CO_2$ emissions therefore needs ways to mitigate them.

**Table 1.** Coal production and its share in total electricity for selected countries

| Country | Coal production in 2006 (Mt) | Share of coal in electricity generated in 2007 (%) |
|---|---|---|
| PR China | 2380.0 | 81 |
| USA | 1053.6 | 49 |
| India | 447.3 | 68 |
| Australia | 373.2 | 76 |
| Russia | 309.8 | 70 |
| South Africa | 256.9 | 94 |
| Germany | 197.2 | 49 |
| Poland | 156.1 | 93 |

Source: Data from World Coal Institute.

## India's response to climate change

Current energy situation in India is dominated by the use of coal in power generation as well as industrial production. The total electricity installed capacity was 138 giga watts (GW) in 2007. Share of different fuels in total electricity generation[5] is shown in Figure 1 *a*, and the regional distribution of installed capacity in Figure 1 *b*. With the projected growth rate of economy at 8–9% per annum, India is facing formidable challenges in meeting its energy demands, which should be at par with the economic activity.

As non-Annex I country, India has accepted the Kyoto Protocol though no commitment is required to reach any specific targets. Per capita emissions in India are low, about one tonne per annum as against world average of four tonne. The projected growth in the use of fossil fuels in 2031–32 (the installed capacity approaching 800 GW (ref. 6) – Integrated Energy Policy of India 2006) indicates that the coal requirement for 2031–32 may grow up to 2.0 Bt per annum with anticipated rise in emissions. India's policy for sustainable development, by way of promoting energy efficiency and the use of renewable energy, changing the fuel mix to cleaner sources, energy pricing, pollution abatement and forestation may result in a relatively low carbon energy path. Nonetheless, these early policies have formed the stepping stones for more goal-oriented National Action Plan on Climate Change, which has identified measures to be taken in eight core areas to maintain high economic growth with the commitment that at no point of time India's per capita greenhouse gas emission would exceed that of developed countries at present. The approach to policy with regard to CCS technology is that technology should be developed and tested in industrialized countries first and only then can it be implemented in developing countries.

Obviously, India cannot afford excessive cost of electricity due to application of CCS to thermal power generation and hence will not permit any embargo. Energy conservation has been in India's portfolio of development

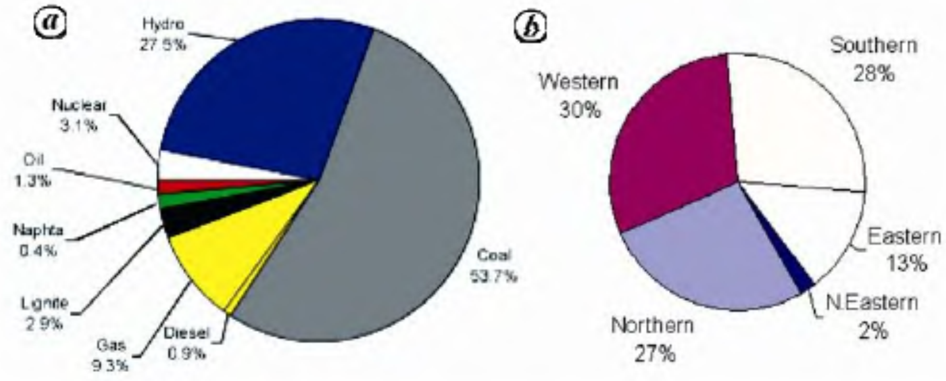


**Figure 1.** ***a***, Share of different fuels in total electricity generation; ***b***, Regional distribution of installed capacity (source: ref. 5).

since the 1970s. Several new initiatives in power sector are in place to enhance efficiency of future power plants as well as the existing ones. Research in carbon capture has also been initiated in the academic and industry sectors.

Short-term opportunities and challenges for CCS in fossil fuel sector using advanced clean coal technologies as bridging option to energy security necessitating research in CCS were discussed[7]. Because climate change is a global issue and is posing danger to the existence of mankind, it requires policy and technological actions by all nations. In India, efforts towards clean coal technology development began more than two decades ago. In the Department of Science & Technology, New Delhi, studies have been carried out on pre-combustion and combustion clean coal technologies. When India joined the carbon sequestration leadership forum, a programme of Department of Energy, USA as founder member in 2003 and later became Vice-Chair to its Technical Group, it provided ample opportunity to focus on the challenge of carbon fixation research for sustaining the use of coal for our energy security[8]. A national programme on $CO_2$ sequestration research was initiated from the inter-sectoral perspectives of basic and applied research with participation from universities and R&D laboratories across the country. In this paper the highlights of CCS research and need for revisiting advance coal combustion technologies to enable efficient ways of carbon management are described.

### *$CO_2$ baseline data of Indian power sector*

The Central Electricity Authority devises the generation norms for energy produced from different sources. India has 176 thermal power plants of capacity ranging from 200 to 500 MW. About 40% of them are more than 20 years old and will be phased out in the next 20 years. Most coal-based power generation installations with capacity up to 500 MW are based on pulverized fired units, which some use gas turbines. A few circulating fluidized bed boilers for high sulphur lignite are also being operated. Emission factor from a power plant is computed from generation, fuel consumption and fuel quality data, using the following equation:

$$\text{EF (kgCO}_2\text{/MWh)} = \text{HR(kcal/MWh)} \times \text{FE (kgCO}_2\text{/kg fuel)/CV(kcal/kgfuel)}, \quad (2)$$

where EF is emission factor; HR is heat rate; FE is fuel efficiency and CV is calorific value.

Taking into account the present coal-based power generation in the country, the average $CO_2$ emission factor for electricity generation has been computed as 0.846t/MWh[9]. The regionwise baseline emission factors from the power plant data for the year 2006–07 are shown in Table 2.

## Highlights of CCS research in India

$CO_2$ sequestration for carbon capture and storage is in essence a scientific and technological approach to mitigate carbon dioxide in the atmosphere. Scientific Departments have made a beginning through invited research on $CO_2$ sequestration and support to multi-disciplinary scientific projects in basic and applied areas[10]. Research on $CO_2$ separation from the flue gas of a power plant, post-combustion capture, terrestrial sequestration, geological sequestration, enhanced hydrocarbon recovery, biofixation and industrial uses has been started. Novel ways to convert $CO_2$ into fuel through genetically designed

**Table 2.** Regionwise weighted average emission factor in $tCO_2$/MWh

| Region | Share in installed capacity (%) | Average emission factor |
|---|---|---|
| North | 36.8 | 0.74 |
| East | 41.7 | 1.00 |
| South | 38.3 | 0.72 |
| West | 18.0 | 0.86 |
| North-east | 2.5 | 0.40 |

Average emission factor is the average emission of all power generating systems in the grid, weighted by net generation. (Source: ref. 9).

microorganisms are being pursued. In this context, the following areas of research are getting highlighted.

- $CO_2$ separation and capture processes.
- Biofixation through microorganisms for fuel generation.
- Sequestration in terrestrial ecosystem.
- Underground fixation in minerals, rocks and gas hydrates.

International vis-à-vis national trends in these areas of research are discussed here.

### *Carbon separation and capture processes*

$CO_2$ capture technology as end-of-pipe solution to power generation is based on chemical absorption, membrane separation, physical adsorption and cryogenic separation methods. Chemical absorption process requires the use of chemical solvents. Monoethanolamine (MEA), diethanolamine (DEA), mixed amines and tertiary amines have been investigated. Physical processes are based on cryogenic cooling or solid adsorbents. Solvents with low binding energy such as polyethylene glycol dimethyl ether (Selexol) and propylene carbonate, etc. are also being studied. Notwithstanding regenerative capability of the solvent, the energy penalty and additional equipment requirements for circulating large volumes of liquid absorbents add significantly to the cost and limit applications of the process.

Solid adsorbents have better promise as they reduce regeneration and recirculation costs and increase binding capacity for $CO_2$. The adsorption of $CO_2$ gas by use of molecular sieves (zeolites) is based on significant intermolecular forces between gases and surfaces of certain solid materials[11]. Both pressure swing adsorption (PSA) and temperature swing adsorption (TSA) have been attempted, however the efficacy of the process depends on the plant parameters with variation in temperature in one case and pressure in other. Novel approaches, materials, and molecules for the abatement of carbon dioxide ($CO_2$) at the pre-combustion stage of gasification-based power generation point sources include membranes that consist of $CO_2$-philic ionic liquids encapsulated into a polymeric substrate for better permeability and selectivity[12].

Through industry support, research in India has been initiated on novel amine based, multiphased absorbents and adsorptive materials as well as processes in different R&D laboratories[13,14]. These R&D efforts are aimed at development of cost-effective regenerative adsorbents and membrane materials. To develop highly efficient carbon based composite materials as solid adsorbents for $CO_2$ capture, studies on carbon dioxide adsorption over Ca/Al hydrotalcite and Mg/Al hydrotalcite have been reported in the temperature range of 40 to 800°C, at different pressures and molar ratios[15]. Design of a 0.5 tpd $CO_2$ absorption pilot plant leading to its conversion into hydrogen and methane has been developed and demonstrated at Rajiv Gandhi Green Energy Technology Centre, Bhopal[16]. Research has also begun on high temperature $CO_2$ removal (IGCC conditions) technique using lithium silicates for pre-combustion capture and on exploratory investigation of gas hydrates as future $CO_2$ absorbers in marine environment. Modelling and simulation studies for producing diethyl ether as fuel are underway.

### *Biofixation through microorganisms for fuel generation*

Algae farming with $CO_2$ is probably the most cost-effective technology today. Application of the flue-gas treatment using algal bioprocesses for the absorption of $CO_2$ is a growing field of research. Triangular air-lift bioreactors[17] have been designed as most suited for algal growth and from the first series of experimental data obtained for two different algal species in a pilot-scale unit supplied with flue gases from a small power plant, removal efficiency of $CO_2$ ~80% has been reported. The ultimate objective of microalgae biofixation is to be able to operate on large-scale so as to convert a significant fraction of the $CO_2$ in flue gas to biofuels. Preliminary cost analysis suggests that microalgae biofixation from a 550 MW coal-fired power plant could cost-effectively sequester 25% of the $CO_2$ if the value recovered from the harvested algae was approximately \$100 (ref. 18). The research requirements are high $CO_2$ utilization efficiencies, very high algal productivities and considerable scale-up of such systems.

In this context, design of a solar bioreactor using computational fluid dynamics and selection of appropriate microorganism has been targeted in the National Institute of Technology, Trichy[19]. Sequestrating capacity assessment from batch scale studies on $CO_2$ capture to bury the microorganism (preferably algae–bacterial symbiotic system operating under high pH condition) has begun. In this case, scaling up can be done much more easily than algae production, which requires thousands of acres of space to soak up the $CO_2$ from one coal plant. Another approach is biofixation through effluent treatment of steel industry at Vishakhapatnam for producing medicinally useful products. Development of an algal-based sequestration system integrated with a biohydrogen production is another option. Laboratory scale sequential bioreactor for $CO_2$ sequestration with screening of barophilic algae/bacteria with simultaneous precipitation of bicarbonates formed is being investigated.

### *Sequestration in terrestrial ecosystem*

Terrestrial biosphere is estimated to sequester large amount of carbon dioxide and is thought to be one of the most cost-effective means of reducing atmospheric levels of $CO_2$. Terrestrial storage would result in aforestation and can also enhance crop productivity. Advance crop species and cultivation practice could be designed to increase the uptake of $CO_2$ by terrestrial as well as coastal ecosystems through enhanced photosynthetic rate. Research on determination of sequestration pattern in maize–mycorrhizal system in laboratory and field testing to assess $CO_2$ distribution in innoculated and un-innoculated soils has been proposed. Mechanics of $CO_2$ sequestration after revegetation by tree species (monotypic and mixed species) in coal mined-out areas and to varying depths of the mine spoils is another promising research topic. An extended R&D approach aiming at development of improved techniques for sequestration by using the least forest area through modelling and simulation studies is desirable.

With a view to quantify the impact of defined changes in land use on carbon sequestration in different soils to assist in the policy studies to optimize resources in the selected spots are underway. Studies to quantify carbon sequestration potential in the selected soils and natural forests[20] in different regions for better carbon management are reported. Profiling of Glomalin in mycorrhizal symbiosis is proposed to predict carbon sequestration in non-mycorrhizal systems using ELISA methods.

### *Underground fixation in minerals, rocks, oceans and gas hydrates*

During the processes of underground storage, $CO_2$ reacts with the host rocks leading to the formation of secondary carbonate minerals – resulting in the phenomenon of mineral trapping. In basaltic rocks the inter-layered sedimentary sequences and denser low-permeability basalts overlying the sequential basalt flow can act as effective caps enabling mineralization reactions to take place. Natural sequestration of dissolved $CO_2$ can be readily observed in the field by the formation of secondary magnesium carbonate (magnesite) veins of varied thickness in the Mg-rich basalts of the Deccan Volcanic Province (Figure 2). Involving a combination of field geological investigations, petrological and mineralogical studies, geochemical analysis, physical property measurements and simulation studies on mineral trapping using the naturally occurring Deccan basalt samples[21] have begun. Detailed laboratory studies to investigate $CO_2$ sequestration in certain selected regions of the Deccan Volcanic Province have shown growth of secondary carbonates on the surface upon reaction with $CO_2$ in supercritical conditions[22]. Future studies are planned to quantify $CO_2$ sequestration capability to prove its suitability for long-term storage.

Preliminary study of deep underground saline aquifers and other suitable sinks for possible carbon dioxide sequestration has been carried out[23]. Study of metamorphic hydrothermal fluids flow and its influence on $CO_2$ contents, with an emphasis on development of $CO_2$ clatharate formation on the lab scale in different media consisting of carbonates, silicates, gas hydrates, etc. has also been started. Recent experiments are reported in southwest Atlantic sector of the Southern Ocean jointly by Alfred Wegener Institute, Germany and National Institute of Oceanography, India as LOHAFEX (LOHA–iron, FEX–fertilization experiment) to experimentally test efficacy of iron fertilization in Southern Ocean for $CO_2$ sequestration.

## Novel concepts in $CO_2$ fixation

This is not all. How fast the greenhouse gases will be eaten away by the genomes or how the molecular manufacturing capabilities in nanotechnology would find a solution to this global crisis? These challenges are opening new vistas in research. New scientific discoveries are expected to emerge in the next decade. $CO_2$ reduction metallurgy for energy intensive industry is being projected[24]. It is becoming possible to air capture $CO_2$ from the atmosphere. Development of microbes or extramophile genes and enzymatic structures, which have affinity to $CO_2$ would provide means of cost-effective capture of $CO_2$ from the atmosphere and its conversion into useful biochemicals. Subsurface technologies of $CO_2$ fixation in porous rocks and microbial hydrogen generation from fossil fuels at low depths with subsurface coupled fuel cells to handle very low concentrations have been proposed as cost-feasible options[25].

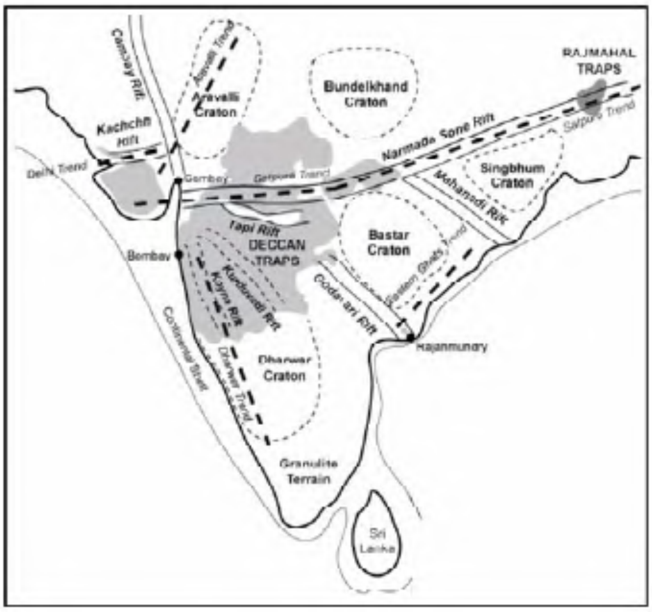


**Figure 2.** Geology map of Deccan Volcanic Province, India[21].

*Perspective in use of clean coal technology towards zero emission*

$CO_2$ fixation through clean coal technology offers significant potential in mitigation or reduction of emissions in the atmosphere. However, considerable R&D challenges exist in their adoption in India because of the high ash content. Clean coal technology options for CCS are grouped as (i) pre-combustion, (ii) combustion and (iii) post-combustion carbon capture. So far we have discussed research highlights in post-combustion carbon capture. The post-combustion carbon capture however, may not fully capture $CO_2$ from the flue gas even at its highest efficiency. The opportunities and challenges lie in pre-combustion and combustion options. Two frontier coal based CCS technologies in this context are described here.

*Pre-combustion $CO_2$ capture – IGCC technology:* In IGCC, coal is gasified in presence of oxygen/air under high pressure (30 bars) maintained above 1000°C. Syngas comprising mainly CO and $H_2$ is produced, which needs to be cooled and cleaned of impurities before it is burnt in the gas turbine. It has two main technologies: (i) coal gasifier system and (ii) combined cycle power generation cycle, having gas turbine and steam turbine for coal gas and steam respectively (Figure 3). The heat from the gasifier and the hot gases is recovered in the heat recovery steam generator and used in a steam turbine as a combined cycle. Mineral matter in the coal is separated as slag from the bottom of the gasifier. The process for gasifying coal is selected depending upon the coal properties. In a conventional coal based plant, $CO_2$ is captured from the outgoing flue gas, which comprises many other impurities. But in IGCC for $CO_2$ capture, the syngas produced in the gasifier is passed through a water shift reactor and converted into $CO_2$ and $H_2$. The $CO_2$ is then separated (present in high concentration) and can be fixed away from the atmosphere at the pre-combustion stage itself. The hydrogen is either combusted in a turbine or used in fuel cells directly for production of electricity.

The first IGCC plant of 250 MW capacity using coal came up in 1994 at Buggenum, The Netherlands. It used low ash coal and was based on shell gasification process. Later trials with coal having up to 14% ash content were made. In the past 14 years, 28 new plants of capacity up to 300 MW have been installed and a few others using coal or lignite and refinery residues are in the pipeline. Globally the progress in commercialization of IGCC has been slow. The plant size in future is expected to be of the order of 600 MW.

In India, early research trials in IGCC were carried out way back in 1989 at Bharat Heavy Electricals Ltd (BHEL) in a pilot scale plant of 6.2 MW capacity. Coal with up to 40% ash was tested at temperatures of 960°C and 1050°C at 0.8 MPa in a fluidized bed gasifier (Figure 4). Indigenous coal has also been tested for IGCC application at Gas Research Institute, USA. These studies form the basis for scale up and setting up of a demonstration power plant of 125 MW capacity[26]. No $CO_2$ capture is however planned.

*Coal combustion technology for $CO_2$ capture:* The coal combustion option of reduction of $CO_2$ emissions in the atmosphere are two-fold: (i) Use of technologies such as circulating fluidized bed combustion, supercritical pulverized and ultra supercritical coal combustion. They can raise the efficiency of generation, thereby reducing $CO_2$

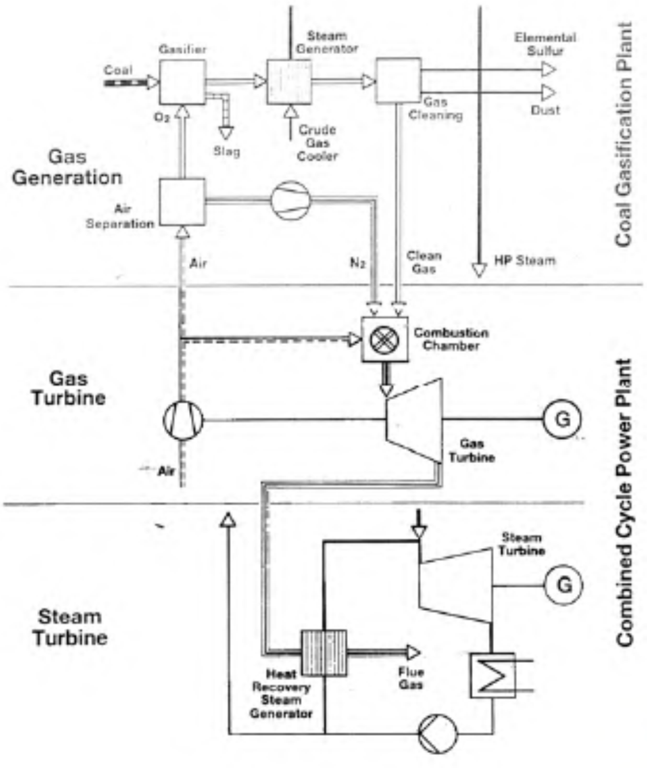


**Figure 3.** An IGCC plant schematic showing coal gasification system and combined cycle power plant. (Source: BHEL)

**Figure 4.** IGCC demonstration unit at BHEL, Trichy.

**Table 3.** A comparison of IGCC and oxyfuel technologies

| Parameter | IGCC | Oxy fuel combustion |
| --- | --- | --- |
| Current status in India | India has made a pioneering effort to demonstrate 6.2 MW IGCC with high ash coal in early 1990s. | Research initiated at Coal Research Center, BHEL in early 2000s. |
| Operational advantages | (i) Use of shift reactor for conversion of syn gas into $CO_2$ and $H_2$.<br>(ii) Hydrogen is produced as pollution free energy, which can be used in fuel cell directly. | (i) Use of high ash coal tends to have low slagging and fouling propensities, which reduce the quantity of ash retained within the boiler.<br>(ii) Up to 90% $CO_2$ in the flue gas makes it easier to separate from water in the flue gas. |
| Technical challenges | (i) IGCC has a molten ash removal system and needs instant flux additions to maintain it in molten form. When high ash coal is used, it would need higher level of flux because of higher fusion temperature and this would increase the operating costs and lower the efficiency of the plant[31].<br>(ii) Another challenge is minimization of energy use in $CO_2$ separation. | (i) In oxyfuel, use of 100% oxygen could produce temperatures that would damage the boiler components. To decrease the flame temperature it is desirable to dilute the oxidizing scheme, by recycling $CO_2$ into the boiler.<br>(ii) Another main challenge is that thermodynamics of oxyfuel combustion with coal is not fully understood. |
| Benefits | (i) Improvement in cycle efficiency<br>(ii) Less coal input<br>(iii) Drive towards hydrogen economy<br>(iv) Fuel cell stack development | (i) Reduced combustion product volume/mass<br>(ii) Increased condensable vapours<br>(iii) Increased radiant heat transfer<br>(iv) Advanced control and increased boiler efficiency. |
| Drawbacks | Heat losses in the slag are significantly higher, which may lead to lower availability of the plant. | High cost of air separation unit may lead to increase in electricity cost. |
| R&D needs | (i) Better refractory materials<br>(ii) Gas cooling systems and coal feeding to increase reliability and availability<br>(iii) Improved coal conversion technology<br>(iv) Hot dry gas clean-up<br>(v) $CO_2$ separation technologies for the gas coming out of the shift reactor | (i) Feasibility for understanding the design parameters and operation issues<br>(ii) Membrane development for oxygen separation plant, which is cost intensive at present<br>(iii) Better understanding of coal combustion processes including ignition, burnout and emissions<br>(iv) Re-circulation kinetics of $CO_2$ produced into boiler. |

emissions per kWh. (ii) Emerging technologies such as oxyfuel technology and chemical looping. In the oxyfuel technology, coal combustion takes place in the presence of 100% oxygen. Combustion in pure $O_2$ results in $CO_2$/$H_2O$ mixture in the flue gas with $CO_2$ content up to 90%. $CO_2$ can be sequestered without stripping from the gas stream. A further advantage of the technology revealed in pilot-scale tests is substantially reduced $NO_x$ emissions. For coal-fired combustion, the technology was suggested in the eighties; however, recent developments have led to renewed interest in the technology. Worldwide coal based oxyfuel combustion is in R&D and demonstration stage[27,28]. Theoretical studies combined with laboratory and pilot-scale studies (typically 30–100 MWe) have been announced or planned. There are no full-scale plants using oxyfuel combustion in operation yet.

Other promising development in coal combustion needing mention is chemical looping technology. It gives a fuel recycle option, while reducing the cost of oxygen separation. Chemical looping has two reactors; a fuel reactor, where a metal oxide is reduced by reaction with coal. Reduced metal oxide is circulated to an air reactor where it is oxidized and regenerated. Exit gases from fuel reactor contain $CO_2$ and $H_2$, pure $CO_2$ can be separated, whereas $H_2$ is combusted. Flue gas from air reactor contains $N_2$ and unreacted $O_2$ (ref. 29). Tested on laboratory scale, chemical looping in a circulating fluidized bed combustion process (which has already been tested on indigenous coal) appear to facilitate better $CO_2$ capture option as compared to IGCC. However this is an area needing further investigation.

As regards to improved efficiency of power generation, India has made a beginning to install circulating fluidized bed combustion (CFBC) and supercritical pulverized coal firing units. Three supercritical coal pulverization units of 660 MW, in addition to seven ultra megapower projects, are under different stages of construction and planning. India also proposes establishment of an oxyfuel combustion test rig at BHEL, Trichy in R&D mode with the objective to study the suitability of the coal. Preliminary studies have been carried out on the effect of temperature zones along gas path on heat flux reduction.

## *A comparative study in the Indian context*

Clean coal technologies like IGCC and oxyfuel have potential to become CCS technology. A comparative study of these two technologies is made here in the Indian context. In IGCC, $CO_2$ is sequestered from the gaseous fuel (which is a mixture of $CO_2$, CO and $H_2$). In oxyfuel combustion, the flue gas is highly enriched by $CO_2$ (up to 90%) making it is easier to capture. For long, coal gasification has been considered the most efficient method to produce clean synthetic gas from coal as means of clean generation and efforts have been mounted. India has also joined FutureGen, world's first near zero emission coal gasification-based demonstration power plant of 275 MW capacity (proposed by Department of Energy, US and supported by Industry Alliance partners). To realize a demonstration size IGCC efforts have been mounted. However, the investment requirement is huge and it is yet to be operated successfully for high ash coals anywhere in the world.

On the other hand, oxyfuel combustion provides higher fuel flexibility in comparison to IGCC. Oxyfuel combustion is becoming the focus of high technology activity worldwide. According to an estimate, expected 40% lower commercial and less technical risk as compared to IGCC makes oxyfuel combustion a good choice, if oxygen production (used in combustion) becomes cost-effective. India is already on the path of installing super-critical coal combustion mega size plants. Sufficient experience exists in the Indian industry on atmospheric or circulating fluidized bed coal combustion processes and one needs to integrate these efforts towards oxyfuel to make it a business proposition[30].

A comparison of integrated coal gasification with combined cycle versus oxyfuel combustion (presuming similar generation efficiencies are achieved) in terms of operational and technical challenges, benefits and drawbacks as well as R&D needs is provided in Table 3. It can be seen that both technologies offer a number of R&D challenges and unresolved technical issues. Further research would be required to show a path towards zero emission technology.

## Conclusions

India is striving to meet basic energy demands of its people, which should be at par with emerging economic development. Use of coal resource is indispensable for achieving the goal of 'energy to all'. The $CO_2$ sequestration is an emerging option to reduce its concentrations in the atmosphere for a sustainable energy future. India has begun $CO_2$ fixation research in several R&D laboratories and universities through industry and government support. Some of the research areas in post-combustion $CO_2$ capture are: terrestrial sequestration, geological sequestration, bio-fixation and others. In clean coal technology, policies and programmes have been pursued for more than two decades. Notwithstanding the fact that these efforts are yet to result in a clean coal technology demonstration plant; technical and economic feasibility studies need to be carried out afresh keeping in view the properties of available coal. R&D challenges in two frontier technology options based on coal gasification and coal combustion have been identified. Suggestions for further research have been made.

Finally, it is recommended that a widespread network programme with accelerated adoption of clean coal technology as well as research on new techniques to separate and capture $CO_2$ is evolved for managing carbon by the energy industry.


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# MEETINGS/SYMPOSIA/SEMINARS

**National Virology Silver Jubilee Year Conference (VIROCON-2010)**

Date: 11–13 March 2010
Place: Tirupati

Theme: Recent trends in viral disease problems and management.

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**National Workshop on Techniques in Animal Cell Culture**

Date: 19–23 January 2010
Place: Madurai

Topics include: Lymphocyte culture and attached cell culture (passaging, staining and cryopreservation); Whole cell *in situ* hybridization using fluorescence tagged antisense RNA (expression of lineage specific mRNA using antisense probe); Fibroblast culture, subculturing and viability test (MTT); Rat tail collagen making and generating 3D collagen matrix and culturing animal cell culture on it. Rat/mice preimplantation embryo development *in vitro*.

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