Clean Coal Technologies

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ABSTRACT Coal is a primary fossil fuel and it is being used continuously as a main source for the production of electricity. It is a heterogeneous fuel, which contains carbon, hydrogen, sulfur, oxygen, nitrogen, moisture, and ash. Coal on combustion releases several pollutants such as CO$_2$, SO$_x$, NO$_x$, H$_2$S, and fly ash into the environment leading to global warming. Exposure of these gases to the atmosphere directly affects human health by causing lung and heart diseases. Therefore, it is crucial to develop efficient technologies for the production of clean energy from coal. Currently, research and developments are more focused toward clean coal technologies for commercialization. This chapter deals with the recent developments of coal technologies for a sustainable and clean energy recovery from the existing coal resources. It provides an overview of several clean coal technologies such as precombustion-, postcombustion-, and oxy-fuel combustion-based carbon capture and storage; coal beneficiation; NO$_x$ and SO$_x$ removal technologies; chemical looping combustion technologies; coaled methane; underground coal gasification; supercritical and ultra-supercritical boiler-based IGCC technologies; and coal to liquid fuels and hydrogen. Integration of a mixture of these clean coal technologies in the existing power-generating systems is necessary to achieve a minimal energy penalty for carbon capture and storage. Therefore, the chapter also briefly discusses the feasibility of potential hybrid systems on clean coal combustion for clean energy recovery.

2.1 Introduction

Fossil fuels possess a vital role in the energy sector for the production of electricity. These fuels are present in three states such as coal (solid), petroleum crude (liquid), and natural gas (gas). The utilization of these fuels leads to the production of greenhouse gases such as CO$_2$, CH$_4$, and NO$_x$ which results in global warming. Therefore, research and development is essential toward the growth of clean fuel technologies. Of all the fossil fuels, coal satisfies 69% of the electricity demand of India (Ambedkar et al. 2011). Coal contains carbon, nitrogen, sulfur, and traces of mercury and other inorganic pollutants. On combustion of coal, these components are oxidized into CO$_2$, NO$_x$, SO$_x$, and inorganic oxides. Flue gas contains these global warming pollutants and contaminates the atmospheric air. Flue gas from coal combustion affects the life span of flora and fauna. Hence, the development of clean coal technologies is essential for the safe environment.

Figure 2.1a and b shows the state-wise distribution of crude petroleum and natural gas in India, respectively (Energy statistics of India, 2014). It is estimated that 758.27 million tons of crude petroleum sources are found in India. The total quantity of natural gas resources of India is estimated as 1254 billion m$^3$ (Energy statistics of India, 2014). India also produces electricity using renewable resources. Figure 2.1c shows the percentage-wise distribution of electric power production from renewable energy. It is
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evaluated that 94,125 MW (Energy statistics of India, 2014) of electricity are generated through wind, biomass, wastes, and so on.

Figure 2.2a shows the total quantity of electricity production using conventional energy sources of India (Energy statistics of India, 2014). Majorly, 8,172,225 GWh of electricity is generated from thermal power plants and 48,000 GWh of energy is produced from nonutility sources. Figure 2.2b shows the year-wise energy intensity of India (Energy statistics of India, 2014). It is estimated that an increasing trend of energy intensity of India is observed from 2005–2006 to 2012–2013. An estimate of 5.1% of energy deficit was calculated for the year 2014–2015. In order to reduce the energy scarcity, unconventional energy technologies such as underground coal gasification (UCG), coalbed methane (CBM), and enhanced oil recovery (EOR), should be commercialized in India.
Coal is the primary fossil fuel in India. The major coal reserves of India are found in the states such as Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Andhra Pradesh, and Maharashtra. Bituminous/sub-bituminous coal and lignite reserves of India are estimated to be about 301.05 and 43.22 billion tons, respectively (Ministry of Coal, Annual Report 2013–2014). The state-wise bituminous/sub-bituminous coal resources of India are shown in Figure 2.3.

Coal production of India was estimated as 565.77 million tons during the year 2013–2014, which is 1.68% higher than the utilization during 2012–2013 (Ministry of Coal, Annual Report 2013–2014). However, the production of lignite in India is decreased by 4.7% in the year 2013–2014. The Energy Statistics report of India (Ministry of Coal, Annual Report 2013–2014) shows that coal and lignite produce a significant amount of energy of about 73.48% of the total energy production through primary fuel sources. Crude petroleum and natural gas produce 11.81% and 10.18% of the total energy, respectively. The quantity of raw coal and lignite utilization in various industries of India is listed in Table 2.1 (Ministry of Coal, Annual Report 2013–2014). Figure 2.4 shows the percentage-wise distribution of coal and lignite utilization in Indian Industries. It was found that 74.7% of raw coal and 83.09% of lignite were utilized for the production of electricity, and the rest amount of coal and lignite was used in other industries.

Further, it is estimated that 37% of coal resources of India are located at a higher depth of 300 m (Khadse et al. 2007). Indian coal has high ash content, and therefore, it is low calorific. Conventional mining is an uneconomical process for the extraction of deep mine coals. Thus, suitable coal extraction technologies need to be developed for the energy sustainability of India.

Consumption of huge reserves of coal for electricity production results in a massive production of global warming gases. In order to achieve a minimal pollutant environment, it is necessary to implement clean coal technologies in the existing power plants. Coal can be considered as a clean fuel, only if the final flue gas CO$_2$ is captured and stored underground without emitting it into the environment. CO$_2$ capture can be achieved using pre-, post-, and oxy-fuel combustion technologies. The conversion of carbon energy into hydrogen energy before combustion is referred to as precombustion CO$_2$ capture. This technology includes coal gasification (production of CO and H$_2$) and water–gas shift.
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FIGURE 2.3
India’s state-wise bituminous/sub-bituminous coal field. BT, billion tons. (From Energy Statistics of India, Central statistics office, Ministry of statistics and programme implementation Government of India, New Delhi, 2014. With permission.)
reactions (conversion of CO into H₂). It also includes coal beneficiation, which removes sulfur and ash content prior to combustion. Precombustion cleaning technology increases the thermal efficiency of power plants. The capture of CO₂, NOₓ, and SOₓ from the flue gas is known postcombustion cleaning technology. Combustion of coal using pure oxygen produces a highly concentrated CO₂ stream, which is known as oxy-fuel combustion technology. Implementing these technologies leads to a reduction in the net thermal efficiency of the power plant. However, loss of thermal efficiency due to CCS can be compensated by integrating suitably with integrated gasification combined cycle (IGCC) technologies, supercritical and ultra-supercritical boiler technologies, and integrated gasification fuel cell (IGFC) technologies, and so on. Also, unmineable coal resources can be exploited using unconventional technologies such as CBM and UCG. These clean coal technologies are explained in the Section 2.6.

2.2 Coal Beneficiation

Precombustion fuel cleaning technology is the best option to avoid ash and sulfur handling problems during coal combustion. High ash and high sulfur coal require precombustion washing treatment for the production of clean fuel. As Indian coal contains high ash content, fly ash emissions and ash disposal are the major problems during
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power production. Indian coal contains 30%–40% of ash, which undergoes chemical and physical transformation on combustion, and a part of the fine ash is carried away with the flue gas. The fly ash needs to be captured using electrostatic precipitators or using other filtration techniques from the flue gas before it is exposed to the atmosphere. The residual bottom ash content of the boiler creates a disposal problem in thermal power plant stations.

In addition, Indian coal contains a significant amount of sulfur, especially from the northeastern region of the country. High sulfur coal leads to SO$_x$ production on combustion. Release of SO$_x$ into the atmosphere causes respiratory health issues and environmental impacts. Therefore, removal of ash and sulfur content of coal prior to combustion would result in clean energy and environment. Application of clean technologies in the precombustion stage reduces the complexity of operation and undesired side reactions. Conventional techniques for coal beneficiation are flotation, gravity settling, and acid treatment for the separation of ash and sulfur. However, these technologies consume a huge energy penalty for the separation of combustible and noncombustible matter. High carbon recovery from the noncombustible matter of low-rank coal cannot be achieved by the conventional method of flotation with normal oil collectors.

Ultrasound-enhanced beneficiation is a new technology for the separation of ash and sulfur from the mined coal (Ambedkar et al. 2011). Ultrasound enhances the separation of noncombustible matter and sulfur from coal through the acoustic streaming and cavitation process with a frequency above the human audible range. Ultrasonic treatment causes the formation and collapsing of bubbles, which produces high pressure and temperature differences resulting in turbulence and further removal of surface coatings of coal. Ultrasonic treatment can increase the hydrophobicity of coal and the hydrophilicity of sulfur during the coal flotation process. This technology is still at the research level and requires efforts for commercialization and to make economically feasible.

2.3 Coal Gasification

Coal gasification occurs in a gasifier, which converts solid coal into a gaseous mixture (syngas) having a good calorific value. The gas mixture is termed as syngas, which majorly consists of CO, H$_2$, CH$_4$, CO$_2$, and trace quantities of uncracked higher hydrocarbons.

\[
C + H_2O \rightarrow CO + H_2 \quad (2.1)
\]

\[
C + CO_2 \rightarrow 2CO \quad (2.2)
\]

\[
C + 2H_2 \rightarrow CH_4 \quad (2.3)
\]

The above reactions are gasification reactions, which occur between solid carbon and gasifying agents such as steam and CO$_2$. Conventional gasification is performed with the supply of a controlled amount of oxidant and a gasifying medium to the gasifier along with the feed. Advanced gasification technologies are molten gasification, plasma gasification, co-combustion, and so on, and these technologies are under development for commercialization.
2.3.1 Conventional Coal Gasification

In the conventional gasification process, coal is converted into syngas using moving bed, fluidized bed, and entrained bed gasifiers (Kivisaari et al. 2004). The choice of gasifiers is based on the nature of feed. As entrained bed gasifiers are operated at a high temperature with a higher feed velocity (less residence time), all types of feed can be processed. However, the size reduction of feed is an additional cost of the gasifier. In moving bed gasifiers, the size reduction of feed is not required, but the generated product gas is enriched with high tar. It is due to the noncracking of volatile matter, as it does not pass through the combustion zone in the gasifier. In fluidized bed gasifiers, the operating temperature of the reactor is maintained less than the ash melting point in order to sustain the fluidized condition of the bed. Therefore, high-ash Indian coals are suitably processed in the fluidized bed gasifiers.

Table 2.2 shows the comparison of the working conditions of the gasifiers (Smith and Klosek 2001). As fixed bed and entrained bed gasifiers are operating under the elevated temperature, low-ash coals are recommended due to ash slagging problems. High-ash coal can be gasified in fluidized bed gasifiers as they operate below the ash fusion temperature. Because of the low operating temperature of the fluidized bed gasifier, high reactivity coal is preferred for high conversion efficiency. Pure oxygen gas is preferred in fixed bed and entrained bed gasifiers in order to operate at high temperature.

2.3.2 Molten and Plasma Gasification

The waste heat of the slag from blast furnace is recovered by means of the molten gasification process. Li et al. (2015) performed thermogravimetric studies on the interaction of coal

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameters</th>
<th>Moving Bed Gasifier</th>
<th>Fluidized Bed Gasifier</th>
<th>Entrained Bed Gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operating temperature (K)</td>
<td>1500–1800 (in the combustion zone)</td>
<td>1173–1323</td>
<td>1473–1873</td>
</tr>
<tr>
<td>2</td>
<td>Pressure (MPa)</td>
<td>2.8</td>
<td>2.5</td>
<td>2.5–4</td>
</tr>
<tr>
<td>3</td>
<td>Particle size</td>
<td>5–80 mm</td>
<td>0.5–5 mm</td>
<td>&lt;500 μm</td>
</tr>
<tr>
<td>4</td>
<td>Tar content</td>
<td>High</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>5</td>
<td>Cold gas efficiency (%)</td>
<td>88</td>
<td>70–85</td>
<td>74–81</td>
</tr>
<tr>
<td>6</td>
<td>Reaction zones</td>
<td>Distinct zones such as pyrolysis, combustion, and gasification</td>
<td>No distinct zones</td>
<td>No distinct zones</td>
</tr>
<tr>
<td>7</td>
<td>Slag formation</td>
<td>Yes</td>
<td>No</td>
<td>Yes (need refractory line coating)</td>
</tr>
<tr>
<td>8</td>
<td>Reaction time (s)</td>
<td>15–60 min (high-pressure operation), in the order of hours (atmospheric pressure operation)</td>
<td>10–100</td>
<td>On the order of seconds</td>
</tr>
<tr>
<td>9</td>
<td>Coal reactivity</td>
<td>All range of coal reactivity is suitable under slagging operation</td>
<td>High-reactivity coal is essential as it operates at a low temperature</td>
<td>All ranges of coal reactivity are suitable</td>
</tr>
</tbody>
</table>

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with the blast furnace slag with CO\textsubscript{2} as a gasifying medium. It was found that the molten slag obtained as a waste from the blast furnace acts as a heat source as well as a catalyst for carbon gasification reaction. Plasma gasification is one of the recent technologies for the efficient conversion of coal into syngas. Coal is ionized into gases using an electric arc, which is energized by the electric current at an elevated temperature. Organic matter of coal is broken into elemental gases such as H\textsubscript{2} and CO. Inorganic substances are melted and removed as a slag at the bottom of gasifier (Janajreh et al. 2013).

2.3.3 Co-Combustion and Gasification

Co-combustion is a suitable clean technology for energy recovery from seasonal fuels (biomass) along with fossil fuels such as coal. Biomass is one of the renewable energy sources, and the energy production from such sources reduces the emission of CO\textsubscript{2}. The biomass can be renewed in a short span of life with the absorption of atmospheric CO\textsubscript{2}. Co-combustion of biomass with coal consumes less fossil fuels and thus reduces the level of global warming. There are several advantages of co-combustion. It is not only advantageous in terms of carbon reduction but also beneficial for the sustainability of flame front during combustion. Biomass contains high volatile matter and less carbon and ash content. The liberation of these gaseous components sustains the combustion front and enhances the gasification efficiency. However, the preliminary treatments such as feed storage, drying, and size reduction are the additional cost of the process.

2.4 Carbon Capture and Storage

Thermal power plants majorly produce CO\textsubscript{2} via electricity production. The emission of the carbon gases to the atmosphere leads to global warming. Capture and storage of CO\textsubscript{2} in a suitable reservoir under the earth and sea is the solution to maintain a clean environment. Flue gas contains the major portion of N\textsubscript{2}, CO\textsubscript{2}, and other trace gases in the conventional combustion process. The carbon capture method includes postcombustion, precombustion, and oxy-fuel combustion methods. In the postcombustion capture technology, the final flue gas contains a mixture of CO\textsubscript{2} and N\textsubscript{2}, which can be separated by the amine absorption technique. Absorption of CO\textsubscript{2} from flue gas stream and regeneration of amine solution are the energy consumption steps in the postcombustion capture technology. The disadvantage of the technology is the handling of huge volume of gas for the gas treatment process. The precombustion technology includes gasification, high- and low-temperature water–gas shift technology, and pressure swing adsorption of CO\textsubscript{2} from raw gas. The sequential setup of reactors in the precombustion process consumes energy, which reduces the efficiency of the process. In the oxy-fuel combustion technology, the air separation unit (ASU) consumes the major portion of the energy for the separation of oxygen.

Pure stream of CO\textsubscript{2} from the carbon capture process can be stored in two ways such as geological and oceanic storage (Metz et al. 2005). Geological storage includes gas reservoir, oil reservoir, saline aquifers, and unexploited deep coal seams. EOR is an established technology for recovering the residual oil, which is left in the reservoirs after the primary oil recovery process using CO\textsubscript{2} stream. CO\textsubscript{2} can also be stored in saline aquifers in dissolved form. The dissolved CO\textsubscript{2} reacts with mineral contents of the surrounding rock
strata and converted into solid carbonaceous material. Enhanced CBM (ECBM) technology uses CO₂ gas for replacing the leftover adsorbed methane gas from coal seam. As India contains 37% of coal reserves, which are found at a depth greater than 300 m, the storage of CO₂ in these unexploited seams is one of the potential options for the reduction of pollutants.

The formation of CO₂ lake and the dissolution of CO₂ on the sea are termed as oceanic storage. High-density liquid CO₂ settles and forms CO₂ lake on the seafloor. Absorption of CO₂ occurs naturally in seawater. As CO₂ dissolves in water, the concentration of CO₂ in air is found in equilibrium with seawater. An increase of CO₂ content in atmospheric air leads to absorption of the gas in seawater. Therefore, storing a large amount of CO₂ in the deep seawater can reduce the pollutants for several decades. Due to the acidity nature of CO₂, the pH of seawater may be low and this can be neutralized by the alkali mineral matter of the sea.

The level of CO₂ emission in India was estimated as 1610 million tons in 2007 (United Nations Statistics Division, 2007). CO₂ storage in unmineable coal beds of India is one of the potential sources of geological infrastructure. About 37% of Indian coal reserves is found too deep and it cannot be exploited economically by the conventional mining process. These coal seams are appropriate for long-term storage. Holloway et al. (2008) discussed the CO₂ storage potential of India and its subcontinent. It is theoretically assessed that 345 million tons of CO₂ can be stored in deep coal seams. However, it is pointed out that no single coal seam is available with CO₂ storage capacity, which is higher than 100 million tons. Also the CO₂ storage technology on coal seams is under demonstration phase. East Bokaro in Jharia, Barakar, and Raniganj coal fields contain 3.2, 6.7, and 0.97 billion tons of coal, respectively, at a depth below 1200 m. These deep coal seams are the potential options for CO₂ storage. The total estimated CO₂ storage capacity of coal between 300–600 m and 600–1200 m is 249 and 84 million tons of CO₂, respectively. However, the resource of coal for storage is insignificant compared to the level of CO₂ emission. Also the development of CO₂-ECBM technology is one of the feasible ways for the sequestration of CO₂. This technology is planned to initiate in Gondwana coal fields by the Directorate General of Hydrocarbons, India (Parikh 2010).

The geologic storage of CO₂ is also feasible in the Deccan Traps of India, which is extended from the region of Rajahmundry to the Gulf of Bengal (Parikh 2010). The basalt rock provides a cap for CO₂ storage and is stable for long-term storage. Sedimentary basins are capable of storing CO₂. Parikh (2010) estimated that 1,390,200 km² onshore and 394,500 km² offshore sedimentary basins are found in India. Further, in deep waters, 1,350,000 km² resource basins are evaluated and a grand total of 3,134,700 km² area of sedimentary basins is estimated. The sedimentary basins are porous in nature and can store CO₂.

Saline aquifer is one of the potential sources for CO₂ storage in shallow offshore areas of Gujarat, Rajasthan, Assam, Mizoram, and Cachar. It is recommended that the storage potential of CO₂ in saline aquifers and oil and gas fields should be evaluated and quantified field-wise (Holloway et al. 2008). The storage capacity of the oil fields in India is estimated as 1–1.1 Gt of CO₂ and that of the gas fields is evaluated as 2.7–3.5 Gt of CO₂. Particularly, the capacity of Mumbai oil basin reserves is estimated as 469 million tons of CO₂ (Holloway et al. 2008).

Many government organizations, public sector units, and private sector units of India are involving in the CCS research and development for commercialization (Parikh 2010). A rough estimate of CO₂ storage capacity of India is available in the literature, and a consistent storage capacity needs to be assessed for reliable data (Viebahn et al. 2014).
2.4.1 Precombustion Technique

This technique involves three stages. First, coal is processed to separate the ash and sulfur content using the coal beneficiation technique. Second, carbon-enriched coal is converted into hydrogen gas before the end use. This can be carried out by steam and CO\(_2\) gasification of coal. After the conversion of solid fuel into syngas, it is further reformed into hydrogen through water–gas shift reaction (2.4):

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2
\]  

Finally, CO\(_2\) can be separated by the membrane separation technique or through the conventional amine absorption process. Hence, the final gas contains pure hydrogen and can be utilized as a clean fuel.

2.4.2 Postcombustion Technique

In this technique, coal is combusted directly without any pretreatment. If coal is combusted using air as oxidant, N\(_2\)- and CO\(_2\)-rich content flue gas is generated. Sulfur present in the coal is combusted into SO\(_x\). The flue gas can be treated for the separation of CO\(_2\) and SO\(_x\). Amine absorption method is a conventional CO\(_2\) separation technique. However, the postcombustion technique is expensive compared to other techniques.

2.5 Clean Combustion Techniques

Several modification technologies of combustion of fuel favor the efficient capture of CO\(_2\) and reduce the formation of pollutants. These technologies are explained in Sections 2.5.1 through 2.5.5.

2.5.1 Oxy-Fuel Combustion Technique

In the oxy-fuel combustion technology, coal is combusted using pure oxygen as the oxidant. As a consequence, the generated flue gas contains a pure stream of CO\(_2\) and H\(_2\)O. Further, CO\(_2\) can be separated on condensation of steam and further removal of SO\(_x\). In this technology, the adiabatic flame temperature of fuel in a boiler or a combustor is high and should be maintained within the operating limit. Steam-moderated oxy-fuel combustion (SMOC) and CO\(_2\)-moderated oxy-fuel combustion (CMOC) are the proposed techniques for moderating the flame temperature in the oxy-fuel combustion environment (Seepana and Jayanti 2010, 2012). The addition of steam or CO\(_2\) or the recycling of CO\(_2\)-enriched flue gas to the combustor controls the adiabatic flame temperature. Hence, the flue gas contains CO\(_2\)-enriched gas and can be stored without any further treatment. As the oxy-fuel combustor operates at a high temperature, fuel NO\(_x\) may be formed as a pollutant in the flue gas. Oxy-fuel combustion is a matured technology at a pilot-scale level and reduces the cost of CCS compared to pre- and postcombustion CS technologies. The separation of oxygen from air using an ASU is major energy consumption factor in oxy-combustion technique. Several methods such as membrane technology, pressure swing adsorption technique, and cryogenic distillation method, are available for the separation of oxygen from air.
Table 2.3 shows the comparison of different air separation techniques (Smith and Klosek 2001). Adsorption, absorption, and polymeric membrane technologies are under the developing stage. Adsorption process contains multiple packed beds, which can be interchanged during regeneration operation. Adsorbents can be regenerated by pressure swing and temperature swing operations. Absorption technique is a chemical process that uses an absorbent for the separation of oxygen. This absorbent can be regenerated by a stripper operation. Except the polymer membrane technology, other technologies require the pretreatment process for the removal of moisture and CO₂ from atmospheric air. The development of suitable polymeric membranes is under way for high purity air separation. Cryogenic separation technique is a matured technology that produces liquid oxygen, liquid nitrogen, and liquid argon. This technology works on the principle of refrigeration cycle.

<table>
<thead>
<tr>
<th>ASU Process</th>
<th>Purity Limit (vol.%)</th>
<th>Separation Material</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorption</td>
<td>93–95</td>
<td>Zeolite (nitrogen adsorption), carbon molecular sieve (oxygen adsorption)</td>
<td>Pretreatment is required to remove CO₂ and moisture in air.</td>
</tr>
<tr>
<td>Absorption</td>
<td>99</td>
<td>Molten salt absorbs O₂</td>
<td>Pretreatment of air is required. Corrosion issues related to use of salt.</td>
</tr>
<tr>
<td>Polymeric membrane</td>
<td>~40</td>
<td>Polymeric material</td>
<td>Continuous process at near-ambient conditions; membrane tolerates the presence of CO₂ and moisture in air.</td>
</tr>
<tr>
<td>Cryogenic separation</td>
<td>99</td>
<td>Distillation column</td>
<td>Refrigeration cycle is required. Liquid nitrogen and liquid argon are also produced as by-products.</td>
</tr>
</tbody>
</table>


2.5.2 Combustion Technologies on NOₓ Reduction

NOₓ emissions in pulverized-coal boilers have an unfavorable impact on the environment. NOₓ reacts with water and other compounds and forms various acidic compounds, fine particles, and ozone. Ozone production at the ground level creates respiratory illness to the human beings. Excess oxidant in the pulverized boiler increases the carbon conversion as well as fuel NOₓ generation. A suitable design of the burner and fuel–oxygen contacting pattern of feed may reduce the NOₓ generation in the furnace. NOₓ is formed under different reaction conditions of the fuel and oxidant. It is classified as follows:

1. *Thermal NOₓ*: It occurs by the oxidation of N₂ and atmospheric oxygen at high temperature (>1500°C). The formation of thermal NOₓ depends on the temperature and residence time of reactants.

2. *Fuel NOₓ*: Nitrogen present in the coal is converted into NOₓ during combustion. It depends on coal composition and the extent of pyrolysis reaction.

3. *Prompt NOₓ*: This is due to the combination of CH portions (hydrocarbon fragments) of the fuel with nitrogen from air. HCN, H₂CN, and CN compounds are formed and they are easily oxidized further into NO.
The formation of NO$_x$ can be reduced by combustion modification techniques. Introducing the fuel and oxidant in a combustor at several stages can reduce the NO formation. The details of combustion modification techniques are explained in Sections 2.5.2.1 and 2.5.2.2.

2.5.2.1 Design of Furnace and Combustion System

A tangentially fired utility boiler gas burners at the corners and coal particles are injected into each burner (Diez et al. 2008). The flame front is produced at all the corners and focused toward the center of the boiler. The flame fronts meet at the center, and a well-mixed zone is established. High carbon conversion is achieved due to intense mixing of fuel and oxidant. This ensures a complete combustion and uniform heat distribution around the boiler. As the peak flame temperature is minimized, the formation of thermal NO$_x$ can be eliminated in the tangentially fired utility boiler.

The peak flame temperature can be reduced in a low-NO$_x$ burner system using several modifications such as fuel/air staging, overfire air, reburning, flue gas circulation, and low excess air. The combination of these techniques greatly reduces the NO$_x$ formation in the combustion system. The temperature-moderating agents such as steam, CO$_2$, or flue gas are injected along with the fuel for controlling the adiabatic flame temperature. Fuel/air staging is one of the modification techniques in which the fuel is burnt in an oxygen-deficient atmosphere at the early stage of combustion. However, the unburnt fuel is combusted by supplying the secondary oxidant at later stages through overfire air. Figure 2.5 shows the combustion modification technologies in a boiler working for the steam production.

In the primary combustion zone, low excess air is supplied for the combustion of coal (US DOE report 1999). Due to less flame temperature, the production of thermal NO$_x$ is minimized in this zone. There is an adjacent reburn zone, where the additional fuel is

![Schematic representation of combustion modification technologies in the boiler working for the steam production.](image-url)
injected to create an oxygen-deficient condition (fuel rich). In the reburn zone, the generated thermal NO\textsubscript{x} reacts with the CH portion of the injected fuel and reconverts NO\textsubscript{x} into N\textsubscript{2} gas. Therefore, it is called as the reduction zone. A burnout zone, which is next to the reduction zone, is supplied with secondary air for the complete combustion of unconverted fuel, and it is known as overfire air. In the burnout zone, the overfire air is injected with 20% of the total oxidant requirement (US DOE report 1999). A low quantity of thermal NO\textsubscript{x} is produced in the burnout zone. However, it is very small compared to the conventional combustion process.

\[
\text{NO}_x \text{ formation: } N + 0.5 O_2 \rightarrow NO
\]  

\[
\text{Reduction in the reburn zone:}
\]

\[
NO + CH \rightarrow NH
\]

\[
NH + NO \rightarrow N_2
\]

### 2.5.2.2 Inflame NO\textsubscript{x} Reduction Burner

In the inflame NO\textsubscript{x} reduction burner, the above-mentioned combustion modifications can be performed in the burner itself instead of carrying them to different stages of combustion. The contact pattern of oxidant and pulverized coal should be adjusted. Therefore, the design of coal nozzle tips and the tilting angle of the burner are crucial for designing the inflame low NO\textsubscript{x} burner. Figure 2.6 shows the schematic representation of an inflame NO\textsubscript{x} reduction burner.

Primary air is injected through the nozzle along with fuel in low excess quantity (Tsumura et al. 2003). The flame is classified into several zones. At the ignition point with low excess air, volatile matter is released and thermal NO\textsubscript{x} is formed. In the next zone, hydrocarbon free radicals (CH*, NH*) from the volatile matter are generated (free radical formation zone). These free radicals reduce thermal NO\textsubscript{x} into N\textsubscript{2} gas in the NO\textsubscript{x} reduction zone. The secondary air is supplied in the side ways of the flame, and it meets the

![Schematic diagram of the inflame NO\textsubscript{x} reduction burner.](image-url)
unconverted fuel in the oxidizing zone, where the fuel is completely burnt out. Hence, the modification of the contacting pattern of oxidant and coal reduces the thermal NO₂ in the flame itself instead of carrying it out to several stages of operation.

2.5.3 High-Temperature Air Combustion

High-temperature air combustion (HiTAC) is one of the promising techniques for NOₓ reduction. The thermal stability of the combustion flame and the high efficiency of the boiler can be achieved using the HiTAC process. Air combustion of fuel leads to the formation of thermal NOₓ due to the nonuniformity of thermal distribution in a boiler. Injection of cold air under the atmospheric condition into the boiler reduces the sustainability of the flame front. Further, it produces a high peak flame temperature, which leads to more NOₓ formation. This can be reduced using the HiTAC technology. Figure 2.7 shows the schematic diagram of the HiTAC process.

Air is preheated in the regenerative heat exchanger using a portion of recovered thermal energy of hot flue gases from the boiler (Zhang et al. 2007). Oxygen concentration in air is reduced by mixing it with hot flue gas from the combustor. The temperature of preheated air is maintained nearly to the auto-ignition temperature of fuel, and therefore, the fuel is burnt uniformly in the combustor with high flame stability. Due to the reduction of oxygen concentration, thermal NOₓ is minimized. Also due to uniform thermal distribution, high conversion of carbon is achieved, and therefore, the efficiency of the boiler is increased. Low-calorific fuels can be burnt easily. Hence, it is a feasible technology for utilizing high-ash Indian coals without the operation difficulty of flame instability.

2.5.4 Chemical Looping Combustion

In oxy-fuel combustion-based thermal power plants, pure oxygen is utilized for the combustion of fuel in order to produce CO₂-enriched flue gas for sequestration. This technology leads to a huge energy penalty in the ASU for the separation of oxygen from air. In the cryogenic technology, the compression cost of air leads to the consumption of huge energy in power plants. The ASU unit reduces 8%–10% (Prabu and Jayanti 2012a) of the net thermal efficiency of the power plant for oxygen separation. However, chemical looping combustion (CLC) is a clean fuel processing technology that processes fuel without an ASU unit (Sorgenfrei and Tsatsaronis 2014). It separates oxygen from air through metal oxide formation. The metal oxides such as NiO, Fe₂O₃, CuO etc. can be used for the combustion of fuel. As a result, 90%–98% of CO₂-enriched dry flue gas is obtained and can be sequestered without any further gas treatment (Prabu 2015). Therefore, it is an inherent clean coal technology for the implementation of CCS.
The CLC technology can process any form of fuels such as solid, gas, and liquid fuels. Solid fuels such as coal, biomass, and wastes can be combusted in the CLC process. They can be processed in a direct or an indirect operation in the CLC process. However, it has a complex reactor arrangement for the fuel combustion. The CLC unit has two major reactors such as air and fuel reactors. Figure 2.8 shows the schematic diagram of the CLC process.

Atmospheric air is circulated in the air reactor and metal particles are oxidized under the fluidized bed condition. The outlet stream of the air reactor is depleted in oxygen and enriched with nitrogen. In the reactor,

\[
\text{Metal (Me) + } \frac{1}{2} \text{O}_2(\text{air}) \rightarrow \text{MeO (metal oxides)}
\]  

The oxidized metal particles from air are circulated to the fuel reactor. In the fuel reactor, coal particles are burnt with metal oxides. For the combustion of solid fuel, a gasifying agent such as steam or \( \text{CO}_2 \) is supplied to the fuel reactor. First, coal is thermally decomposed into its constituents (Reaction [2.9]). Tar as a liquid product is further cracked into lower weight gas hydrocarbons. Carbon in coal is gasified by reacting with the supplied gasifying agents and converted into gaseous fuels such as \( \text{CO} \) and \( \text{H}_2 \). Second, the gaseous products formed as volatile matter (pyrolysis), tar gas (cracking), and carbon gas (gasification) are reacted with metal oxide particles and yield a \( \text{CO}_2 \)- and \( \text{H}_2\text{O} \)-enriched flue gas. The reactions that are taken place in the fuel reactor are as follows:

**Thermal decomposition of coal**

\[
\text{Coal} \rightarrow \text{volatile matter (CO, H}_2, \text{CH}_4, \text{CO}_2) + \text{char} + \text{moisture} + \text{ash} + \text{tar}
\]  

(2.9)

**Thermal cracking**

\[
\text{Tar} \rightarrow \text{lower hydrocarbons}
\]  

(2.10)

**In situ coal gasification**

\[
\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \\
\text{C} + \text{CO}_2 \rightarrow 2\text{CO}
\]  

(2.1)

(2.2)

**Metal oxide gas combustion**

\[
\text{MeO} + \text{CO} \rightarrow \text{CO}_2 + \text{Me}
\]  

(2.11)
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\[
\text{MeO} + H_2 \rightarrow H_2O + \text{Me} \quad (2.12)
\]

\[
\text{MeO} + CH_4 \rightarrow CO_2 + H_2O + \text{Me} \quad (2.13)
\]

The metal oxides are reduced to metals and it is recycled to the air reactor for oxidation after the separation of ash particles. Thermodynamics of metal to metal oxides and reduction of fuel are the major issues that should be considered for the metal selection criteria.

2.5.4.1 Metal and Metal Oxides

Ni, Fe\textsubscript{2}O\textsubscript{3}, Cu, Mn, and Mg are the metal particles that are considered in the CLC process. The melting point of these metal particles and ash is the major constraint that decides the upper limit of the operating temperature of the reactors. These metal particles are supported in an inert medium such as Al\textsubscript{2}O\textsubscript{3} and FeAl\textsubscript{2}O\textsubscript{4}.

2.5.4.2 Heat Balance in CLC

Heat balance is an important criterion in operating both the reactors. Mostly, the oxidation of metals in the air reactor is exothermic in nature. In the fuel reactor, the heat of reaction depends on the specific metal and gas that are involved in the reaction. If the reaction in the air reactor is highly exothermic, it will be reverse in the fuel reactor. Therefore, the heat should be transferred between the reactors. Heat exchange can be performed through the supply of excess metal particles. Inert supports are also useful in transferring the heat between the reactors.

2.5.5 Chemical Looping Reforming

Coal gas contains a higher proportion of CO and H\textsubscript{2}S gas, which deteriorates the performance of fuel cell. Therefore, a highly purified syngas is essential for the fuel cell operation. However, the syngas cleaning process is an energy-intensive operation and lowers the efficiency of the power cycle. However, chemical looping reforming (CLR) technology is the suitable technology for the production of high pure hydrogen, which can be fed directly into the fuel cell system (Ersoz et al. 2006). It is a clean fuel production technology that indirectly converts carbon energy into clean fuel hydrogen energy. It is similar to the CLC process in which a steam reactor is added into the loop for hydrogen generation. In the steam reactor, the supplied steam oxidizes the metal particles to oxides with the production of hydrogen. In the steam reactor,

\[
\text{Me} + H_2O \rightarrow \text{MeO} + H_2 \quad (2.14)
\]

Hydrogen produced from the steam reactor is highly pure and free of coal gas contaminants, and it is suitable for the feed gas in the fuel cell system. The complete conversion in the fuel reactor may not be possible due to the limitation of thermodynamic and kinetic parameters. However, the unconverted metal particles from the steam reactor are further oxidized in the air reactor, and then, they can be recycled to the fuel reactor. This technology converts coal into pure hydrogen, and it can be supplied as a feed to the polymer electrolyte membrane fuel cell (PEMFC).
2.6 Unconventional Coal Technologies

Due to the increased energy demand, it is essential to explore new technologies for the efficient utilization of existing energy resources. Nowadays, unconventional clean coal technologies such as UCG, CBM, and EOR are emerging for the recovery of unmineable deep coal reserves.

2.6.1 Underground Coal Gasification

UCG is an inherent clean coal technology for exploiting deep coal resources. As 37% of Indian coal resources are found at a depth of more than 300 m (Khadse et al. 2007), it is the appropriate technology for the effective utilization of such resources. Coal mining, transportation, and storage are completely eliminated in the UCG process. Further, there is no requirement of surface reactors for the gasification process. As Indian coals are low calorific and contain 40% of ash (Iyengar and Haque 1991), emission of fly ash and handling of ash sludge from the boiler are the major problems in coal industries. These issues can be completely avoided in the UCG process. UCG is an in situ phenomenon that converts coal into calorific gas through combustion, gasification, and pyrolysis. The schematic diagram of various reaction zones of the UCG process is shown in Figure 2.9.

Injection and production wells are required to drill in the UCG site. These two vertical wells in the ground level are linked through a horizontal well in a coal seam. Therefore, the generated syngas can be escaped through the production well. A suitable oxidant and gasifying medium are sent through the injection well, and the syngas produced in the

![Figure 2.9](image_url)  
Schematic representation of the UCG process.
cavity are collected from the production well. The location of the injection spot of the oxidant is unchanged in the conventional UCG technique. However, this location is continuously changed in the controlled retractable injection point (CRIP) method. In the CRIP method (Hill and Shannon 1981), coal is burnt at various locations of the coal seam as soon as it gets consumed. Yang (2003) proposed a blinding-hole UCG technique, which has the potential to convert coal under buildings, railways, and so on. This technique requires an annular pipe, which is to be inserted into the coal seam. The oxidant and gasifying medium are injected into the inner tube, and the syngas is collected at the annular region of the outer pipe.

In the UCG process, the simultaneous solid–gas, gas–gas phase reaction occurs along the entire length of the coal seam. Coal is burnt at the location of oxidant injection, and the flame front is propagated toward the outlet well. The heat evolved in the combustion zone is utilized for the endothermic gasification reaction. As coal gets consumed, the empty space created inside the seam is called cavity. The solid–gas phase reactions (Equations 2.1 through 2.3, 2.15, and 2.16) occur at the surface of cavity. The gas phase reactions (Equations 2.4 and 2.17) occur in the UCG cavity:

\[
C + O_2 \rightarrow CO_2 \quad (2.15)
\]

\[
C + \frac{1}{2} O_2 \rightarrow CO \quad (2.16)
\]

\[
CO + \frac{1}{2} O_2 \rightarrow CO_2 \quad (2.17)
\]

The volatile matter of coal seam gets released over the entire seam, and significantly, it occupies a larger portion of the syngas volume. Although the UCG process is beneficial in extracting the deep coal resources, it is a more complex phenomenon. Visualization and control of the deep insight phenomenon of the coal seam are very difficult. Several physicochemical processes occur simultaneously during in situ gasification of coal seam. Water influx into the UCG reaction zone greatly affects the performance of reaction. The underground water body near the coal seam is the source of water influx into the cavity of coal seam. If water influx is uncontrolled, it consumes most of the chemical energy of coal in the form of steam. Chemical energy of coal has been used as the latent heat for the production of steam. Therefore, the outlet gas from the production well is enriched with steam. These problems could be avoided through the UCG operating pressure. However, if the UCG operating pressure is above the hydrostatic pressure of the water body, the gas from the coal seam may get escaped and contaminate the water body. Hence, an optimum pressure of the UCG cavity should be maintained for balancing both the phenomena. The hydrostatic pressure of the underground water body depends on the depth of coal seam and the density of overburden strata. It was reported that a coal seam at a depth of 860 m in Thulin, Belgium, had exerted a pressure range of 300–800 bar (Burton et al. 2006). In a French UCG pilot test, it was found that the coal seam at the depth of 860 m had a pressure of 450 bar (Burton et al. 2006). If a water body is found near the coal seam, the injection pressure of the feed gas is adjusted in such a way that the coal seam cavity pressure is slightly less than the hydrostatic pressure of water. This negative pressure allows a sufficient amount of water seepage into the cavity for the steam generation. Several other parameters such as coal inherent properties, permeability and porosity of coal seam, and geological properties of the surrounding strata affect the performance of the UCG process. In deep UCG process, gas loss is minimized because several impermeable stratas are embedded on the coal seam.
2.6.1.1 Effect of the Inherent Properties of Coal Seam

The conventional UCG technique is not a well-efficient technology for high-ash (~40%) Indian coals. Ash layer accumulation in the coal seam retards the diffusion of oxidant/gasifying medium to the coal cavity surface. Therefore, the CRIP technique is suitable for exploiting high-ash coals. High-moisture lignite coal (~55%) may not be suitable for the UCG process, as it produces a low-calorific gas (Prabu and Jayanti 2012b). High-volatile matter coal (~40%) is more suitable for in situ gasification. It would produce a well-sustained combustion flame front and enhances the efficiency of gasification. However, a high-carbon content coal (~50%) may not be more beneficial, as the ignition of such coal is difficult. It requires a high-temperature fuel source for ignition at the interrupted combustion stages.

2.6.1.2 Choice of the Oxidizing/Gasifying Medium

A suitable oxidizing/gasifying medium is essential for the effective exploitation of deep coal through the UCG process. Oxygen, air, O$_2$-enriched air, water/steam, and CO$_2$ are the various oxidants, and these should be chosen based on the geological and inherent properties of the coal seam. Prabu et al. (2012b) reported that oxygen gasification is suitable for the high-ash coal seams as it creates a high-temperature environment, which balances the ash diffusion barrier for the solid-phase reaction. However, a significant amount of unconverted oxygen is observed in the product gas. As a result, the energy penalty of separation of O$_2$ from air is huge, and it affects the economy of the UCG process. It is also proposed that if the UCG process is coupled with carbon capture and storage (CCS) based power generation system, the unutilized oxygen in the product gas would be beneficial for the oxy-combustion process. However, the installation and operation of the ASU increases the capital and operating cost of the UCG process. Air gasification also leads to uneconomic operation of UCG due to the energy penalty for the compression of air to high pressure. The compression cost of air gasification may be expensive as compared to oxygen separation cost of the ASU in O$_2$ gasification for a deep UCG process.

Air-, water-, and steam-based gasifying agents are favorable for a high-carbon coal seam. The use of high-temperature steam in the inlet feed of UCG requires a proper insulation of deep underground pipelines. It may be uneconomic, and particularly, the sustainability of flame front propagation in the high-ash UCG seam is difficult as the steam temperature drops. The deposition of ash heap on the cavity resists the inlet steam passage and the temperature of steam drops, which results in loss of latent heat. As a result of steam condensation, the flame front may extinguish. In such case, CO$_2$ gasification of UCG is beneficial (Prabu and Geeta 2015). As CO$_2$ gas is readily available and the occurrence of phase change during the diffusion of gas in the ash layer is avoided, it may be a suitable gasifying medium for high-ash coal seams. The flue gas enriched with CO$_2$ due to the oxy-fuel combustion can be recycled and utilized as a feed gas to the UCG seam. Further, the burnt UCG cavity is suitable for the sequestration of CO$_2$ in the un-burnt char of the coal seam.

2.6.1.3 Energy Losses in the UCG Seam

Energy losses of UCG include water influx, gas loss, and pressure drop in the cavity during the UCG operation. Pressure drop may occur in the UCG as coal gets consumed and the cavity enlarges with time (Prabu and Jayanti 2012a). Gas loss to the surrounding strata also results in pressure drop of the cavity. The Lawrence Livermore National laboratory, Livermore, California, performed several UCG real field run and reported their results.
They performed several shallow UCG trials with air, steam, and oxygen as the gasifying medium. It was shown that 10%–12% of coal energy was lost in the form of latent heat (Cena and Thorsness 1981). Further, it was observed that a significant gas pressure drop was prevailed during the UCG operation.

### 2.6.1.4 Application of UCG Syngas

Electricity generation is one of the major applications of UCG syngas. The UCG gas can be used in a similar way of the conventional syngas generated from surface gasifiers. The operating pressure of UCG depends on several parameters such as the depth of coal seam, water influx conditions, and the nature of overburden strata. The inlet gas pressure to the injection hole decides the UCG cavity pressure, and there may be a pressure drop due to factors such as the growth of UCG cavity with time and gas loss to surrounding strata.

If the outlet pressure of UCG gas is below 10 bar, it can be coupled with a steam turbine (ST) system for power generation. High-pressure UCG gas (>10 bar) can be coupled with the gas turbine system such as IGCC. In case of Chinchilla UCG plant (Queensland, Australia), the pressure of the UCG syngas has been increased by using compressors in order to integrate with the gas turbine system. Further, it is proposed to utilize the UCG syngas in a fuel cell system after the removal of gas impurities (Prabu and Jayanti 2012a). Gas purification may be a major issue in UCG syngas. As the released volatile matter does not undergo thermal decomposition in the coal seam, syngas gets enriched with higher hydrocarbons such as tar in vapor form. Liu et al. (2006) studied the volatilization of arsenic, mercury, and selenium in coal during UCG experiments. It is found that mercury and selenium show 90% volatility, and arsenic has 60% volatility to the syngas. Hence, it should be removed prior to the usage. After the removal of impurities, UCG gas can be utilized directly in a solid oxide fuel cell (SOFC), which operates under high temperature. The calorific gases, other than hydrogen gases, such as CO, CH\textsubscript{4}, and C\textsubscript{2}H\textsubscript{6}, are internally reformed with steam and converted into hydrogen in a high-operating temperature fuel cell. However, this can also be achieved in a low-temperature fuel cell such as PEMFC using an external gas reformer. If the purification of UCG syngas is found to be more difficult or uneconomic, it can be converted into highly pure hydrogen using the CLR process. These hydrogen gases can be utilized as the feed source to fuel cells.

UCG gas at low pressure can be effectively transformed into electric power through supercritical CO\textsubscript{2} (SCCO\textsubscript{2}) turbines. The UCG energy losses could be compensated if they would be integrated with suitable renewable energy sources. Integration of solar energy with UCG is one of the feasible ways of efficient power generation and could increase the efficiency of the thermal power plant system. The generation of steam through solar energy could be advantageous for steam-based UCG, and further, heating and reheating of turbine inlet fluid operating streams (steam/SCCO\textsubscript{2}) using solar energy enhance the performance of power system.

CO\textsubscript{2}-enhanced UCG process may generate CO-enriched syngas. Prabu (2015) proposed that CO-enriched UCG syngas is more suitable for producing power through CLC of fuel for achieving CCS. CO-enriched syngas eliminates the complexity of thermal balance between the fuel reactor and the air reactor in the CLC process. The result of power simulation studies (Prabu 2015) shows a higher efficiency of the CLC systems compared to the conventional power generation systems. UCG gas can be utilized as a feedstock for the manufacture of chemicals. Syngas can be converted into liquid hydrocarbon chemicals using the Fischer–Tropsch (FT) process. It is proposed that ammonia can be synthesized effectively using an integrated UCG process.
2.6.2 Coalbed Methane

CBM is a recent emerging clean coal technology in India. Fossil fuels such as coal, gas, and oil resources are formed due to the sediments of organic matter such as plants and animals. These sediments are converted into fossil fuels after a prolonged period of deposition. Inherently, coal contains a significant amount of volatile matter, which gets released on heating. Methane gas produced during coal formation process (coalification) is entrapped on the pores of coal due to high pressure in the underground deposits. On mining, methane gets desorbed and diluted with the atmospheric air. It may also lead to fire hazard. Methane is a greenhouse gas, and it can entrap more heat than CO₂. Thus, release of methane directly into the atmosphere causes global warming.

Capturing methane gas from coal seams prior to mining is a feasible solution and is known as coalbed methane. The CBM gas can be collected through dewatering of the coal seams by releasing the hydrostatic pressure of coal seam. Figure 2.10 shows the schematic diagram of the UCG integrated CBM process.

Water pumping reduces the pressure in coal seams, and the methane gets desorbed and collected at the surface. However, it does not desorb methane content completely. The residual methane content is desorbed through the ECBM. Injecting CO₂ into the coal seam desorbs the residual methane, and it gets adsorbed on the pores of the coal seam. This

![Schematic representation of the UCG-integrated CBM process.](image-url)
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is similar to the process called EOR, which is practicing in oil reservoirs. CO\(_2\) has more adsorption affinity toward coal than methane. Hence, there is a mutual benefit that methane can be recovered upon CO\(_2\) sequestration in the coal seam. It is estimated that two moles of CO\(_2\) can be sequestered per mole methane desorption.

As India has 37% of its total coal reserves in the deep underground, ECBM is a feasible technology for methane recovery and CCS implementation. Prabu and Mallick (2015) estimated the CBM resources of India using Kim’s correlations (Kim 1977). It is estimated that 116.79 and 94.3 billion m\(^3\) of methane gas are entrapped in bituminous coal and lignite coal, respectively (Prabu and Nirmal 2015). More than 40% of CBM is found at a depth of more than 300 m. Therefore, ECBM is a suitable technology that can exploit the methane gases effectively. Further, it is also estimated that 4400 million tons of CO\(_2\) can be sequestered in the available coal resources. Prabu and Nirmal (2015) discussed the feasibility of integration of UCG with the ECBM technology. CO\(_2\) sequestered through ECBM in a coal seam may act as a gasifying medium in a UCG operation. However, CO\(_2\) gasification of UCG seam requires a high-temperature flame front (>900°C) to enhance the Boudouard reaction.

\[
C + CO_2 \rightarrow 2CO
\] (2.2)

Air as an oxidizing medium does not sustain a high-temperature reaction front as it is diluted with 79% of nitrogen gas. Therefore, the supply of pure oxygen to the CO\(_2\)-impregnated coal seam maintains a high-temperature flame front, which enhances the Boudouard reaction. This may improve the reactivity of CO\(_2\) and produce CO-enriched UCG syngas. Integration of these technologies would reduce the operating cost of both the processes. Methane can be utilized as a feedstock for chemical production. It can also be utilized as a source for power production through thermal and fuel cell power plants. Methane from the CBM source is known as sweet gas, as it is free from H\(_2\)S content. It contains more than 90% of methane and a less content of ethane, propane, and CO\(_2\).

### 2.7 Coal-Based Power Generation Systems

The conversion of coal into a clean fuel consumes energy, and the implementation of clean coal technologies is energy intensive in terms of CCS. However, the energy penalty can be compensated by increasing the efficiency of power plants. The major use of coal is the production of electricity through thermal power plants. The power plant efficiency can be improved through the advanced power generating systems. The various coal-based power generation systems are given as follows:

1. Subcritical ST cycle
2. Supercritical and ultra-supercritical boiler STs
3. Supercritical carbon dioxide turbine system
4. IGCC
5. IGFC
6. Integrated CLC (ICLC) cycle
7. Integrated gasification solar combined cycle (IGSC)
The gross efficiency of these integrated advanced power generation systems is high and the energy penalty of CCS can be adjusted by integrating with the suitable technologies. Proper heat integration is necessary for the efficient usage of thermal energy. In case of CCS-integrated power system, the air separation system (ASU) and the CO₂ compression system (CCU) are the auxiliary units of the thermal power plants. The compression of CO₂ and air takes place in the ASU and the CCU, respectively. Multistage compression of the gases is carried out with intermediate cooling of these gases. Hence, a significant amount of heat energy generated during compression can be utilized in the power generation system. The preheating of feed water for the boiler input stream can be carried out using the leftover energy of the auxiliary units.

2.7.1 Subcritical ST Cycle

STs are operated based on the Rankine cycle (de Souza 2012). In this cycle, saturated liquid (water) is compressed using a water pump (isentropic process). High-pressure liquid is converted into a superheated steam by means of chemical energy of syngas in a boiler. Electrical energy is produced in the turbine system by isentropic expansion of the steam. Finally, the low-quality heat is rejected in the condenser. In conventional subcritical STs, the energy loss is high in terms of unutilized low-quality steam (through latent heat). The temperature of the ST is restricted to a maximum temperature of 540°C due to the operation limit. Therefore, less significant energy is produced in the ST-based system. In this system, solid coal or atmospheric pressure syngas is utilized as a fuel in the boiler for the generation of high-pressure steam. This high-temperature steam is supplied to the various STs operating at different pressures. High-pressure turbine (HPT), medium-pressure turbine (MPT), and low-pressure turbine (LPT) are integrated sequentially for the recovery of thermal energy in terms of electric power. Figure 2.11 shows the schematic diagram of the ST system.

Water is pressurized to 170 bar, and it is converted into steam in the boiler. The steam from the boiler drives the HPT, and the outlet steam is reheated in the reheater and sent to the MPT. The LPT is driven by the outlet steam of the MPT. There are several steam outlets in these turbines, and they are used for preheating the feed water to the boiler.

2.7.2 Supercritical and Ultra-Supercritical Boiler STs

Rankine cycle-based supercritical STs are the advanced power generation systems. Supercritical steam as the operating fluid enhances the net thermal efficiency of the power plant system. The supercritical pressure and temperature of steam are 22.06 MPa and 374°C, respectively (Breeze 2014). The fluids behave as an intermediate to the property of liquids and gases. In the subcritical steam boiler, water is pumped to a subcritical condition of 170 bar and heated to 540°C. STs, which are operating under subcritical, supercritical, and ultra-supercritical conditions, have maximum operating pressures of 170, 270, and 370 bar, respectively. In the ultra-supercritical boiler, the steam is heated to a temperature of 700°C, whereas it is 600°C in the supercritical boiler. Table 2.4 shows the net thermal efficiency of the UCG-based thermal power plants operating in the CLC mode of combustion (Prabu 2015).

The difference in the net thermal efficiency of the power plant system is increased by 3% on the order of subcritical, supercritical, and ultra-supercritical conditions of the boiler. The gain in thermal efficiency directly leads to a reduction in the unit cost of power and CO₂ emissions. However, the major concern of the supercritical technology
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TABLE 2.4
Overall Energy Analysis for the O₂/CO₂-Based UCG Integrated with CLC-Incorporated ST Power Plants

<table>
<thead>
<tr>
<th>Power Plant System</th>
<th>Subcritical Condition</th>
<th>Supercritical Condition</th>
<th>Ultra-Supercritical Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR temperature (°C)</td>
<td>916</td>
<td>1100</td>
<td>1200</td>
</tr>
<tr>
<td>FR temperature (°C)</td>
<td>885</td>
<td>1000</td>
<td>1100</td>
</tr>
<tr>
<td>Power consumption in the auxiliary units (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASU load to UCG (P_{O₂, ASU})</td>
<td>16.05</td>
<td>16.05</td>
<td>16.05</td>
</tr>
<tr>
<td>Oxygen compression to UCG (P_{O₂, com})</td>
<td>2.19</td>
<td>2.19</td>
<td>2.19</td>
</tr>
<tr>
<td>CO₂ compression to UCG (P_{CO₂, com})</td>
<td>7.18</td>
<td>7.18</td>
<td>7.18</td>
</tr>
<tr>
<td>CCU load for sequestration (P_{CCU})</td>
<td>30.05</td>
<td>30.05</td>
<td>30.05</td>
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<tr>
<td>Water pumping (P_{WP})</td>
<td>3.55</td>
<td>5.06</td>
<td>6.19</td>
</tr>
<tr>
<td>Power production (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPT</td>
<td>29.81</td>
<td>33.43</td>
<td>40.97</td>
</tr>
<tr>
<td>MPT</td>
<td>44.09</td>
<td>52.12</td>
<td>58.89</td>
</tr>
<tr>
<td>LPT</td>
<td>152.18</td>
<td>159.83</td>
<td>162.30</td>
</tr>
<tr>
<td>Gross power production</td>
<td>226.08</td>
<td>244.85</td>
<td>262.16</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross efficiency</td>
<td>39.81</td>
<td>43.22</td>
<td>46.25</td>
</tr>
<tr>
<td>Net efficiency with CCS</td>
<td>29.42</td>
<td>32.55</td>
<td>35.40</td>
</tr>
</tbody>
</table>

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is the availability of material for construction to withstand such a high temperature and pressure. High tube wall temperature increases the corrosion problem. Therefore, the development of materials to operate under supercritical conditions enables the technology for commercialization.

2.7.3 Integrated Gasification SCCO₂ Turbine Cycle (Brayton Cycle)

CO₂ acts as a supercritical fluid above the critical temperature of 303.98 K and the critical pressure of 7.38 MPa (Muñoz-Antón et al. 2015). In SCCO₂, the energy loss due to the change of phase from liquid to gas in a supercritical steam cycle is completely avoided. The CO₂ gas in the supercritical stage is compressed to a high pressure using compressors. And it is heated in the boiler using thermal energy of fuel. This SCCO₂ drives the gas turbine and the electric power is generated. CO₂ is removed from the turbine in the supercritical stage just above its critical point. Again it is recycled for the process. Atmospheric pressure syngas can be utilized efficiently for power production in SCCO₂ based Rankine cycle system.

2.7.4 Integrated Gasification Combined Cycle

The integration of both Rankine and Brayton cycles is termed as the combined cycle system. Figure 2.12 shows the UCG integrated combined cycle power generation system with CCS. The Brayton cycle (de Souza 2012) requires a high-pressure syngas and air, which is pressurized using the compressor. These gases are burnt in the combustor and expanded in the gas turbine, which generates electricity. The residual heat from the outlet gas from the gas turbine is used to operate the ST in the Rankine cycle.

High-pressure coal syngas generated from the conventional gasifier is utilized for the power generation system. Gas turbine requires the syngas purification system that removes the particulate matter, tar, and sulfur compounds. The particulate matter is removed using cyclone separators. Tar compounds are removed through the wet scrubbing process. Sulfur compounds can be removed through the amine absorption process. After the removal of impurities, the gas is sent to the combustor with the supply of high-pressure oxidant using the compressor, which is integrated with the gas turbine. Figure 2.12 shows the schematic representation of the IGCC-integrated UCG system (Prabu and Geeta 2015).

Table 2.5 represents the overall comparison of the net thermal efficiency of the UCG-integrated combined cycle system. It is reported that 4% efficiency gain is estimated for rise in the operating pressure from 9 to 27 bar in a UCG-integrated gas turbine.

High-pressure (>10 bar) and high-temperature gas (1000°C–1250°C) from the combustor drives the gas turbine and generates the electrical power. The residual heat energy from the exhaust gas of the turbine at atmospheric pressure is recovered in the heat recovery steam generator (HRSG). The final flue gas is sent to the sequestration unit. The gas turbine is operated based on the Brayton cycle. The steam generated in the HRSG is utilized to drive the ST through the Rankine cycle. The coupling of both cycles is termed as the combined cycle. IGCC produces a higher net thermal efficiency compared to the ST system. However, coal needs to be gasified, and further, it should be purified for the IGCC process. Hence, there is a significant loss of energy. Particularly, if syngas contains higher hydrocarbons in terms of tar, the sensible heat of the syngas is lost because of the wet scrubbing process for the removal of tar.
FIGURE 2.12
Schematic representation of the IGCC-integrated UCG system.
2.7.5 Integrated Gasification Fuel Cell System

In the IGFC system, coal is gasified into syngas using the conventional coal gasifier. Hydrogen is the feed for the fuel cell power generation. Carbon monoxide, methane, and ethane from syngas are converted into H\(_2\) through water–gas shift reactors:

\[
\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \quad (2.18)
\]

\[
\text{C}_2\text{H}_6 + 2\text{H}_2\text{O} \rightarrow 2\text{CO} + 5\text{H}_2 \quad (2.19)
\]

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \quad (2.4)
\]

After the conversion of carbon fuel into hydrogen, the trace quantity of CO is converted into CO\(_2\) through partial oxidation. The final gas contains pure H\(_2\) and CO\(_2\), which is sent as a feed to the fuel cell. A high-purity syngas is required for fuel cell operation. The

---

**TABLE 2.5**

Overall Energy Analysis for the CO\(_2\)-Blown UCG-Integrated Power Plant Systems

<table>
<thead>
<tr>
<th>Power plant system</th>
<th>Operating pressure, bar</th>
<th>CO(_2)/O(_2) ratio</th>
<th>Power production (MW)</th>
<th>Power supply from the gas turbine (MW)</th>
<th>Power consumption in the auxiliary units (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.5</td>
<td>2.03</td>
<td>27</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.5</td>
<td>2.03</td>
<td>27</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td></td>
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<td></td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas turbine</td>
<td>303.21</td>
<td>303.28</td>
<td>371.21</td>
<td>372.35</td>
<td></td>
</tr>
<tr>
<td>High-pressure ST</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Medium-pressure ST</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Low-pressure ST</td>
<td>53.32</td>
<td>53.57</td>
<td>35.73</td>
<td>35.88</td>
<td></td>
</tr>
<tr>
<td>Oxygen compression to CMOC combustor</td>
<td>9.64</td>
<td>9.67</td>
<td>10.86</td>
<td>10.93</td>
<td></td>
</tr>
<tr>
<td>CO(_2) compression to CMOC combustor</td>
<td>53.83</td>
<td>49.66</td>
<td>71.35</td>
<td>66.67</td>
<td></td>
</tr>
<tr>
<td>Gross electrical power production (MW)</td>
<td>293.06</td>
<td>297.52</td>
<td>324.73</td>
<td>330.63</td>
<td></td>
</tr>
<tr>
<td>ASU load for UCG</td>
<td>18.67</td>
<td>16.67</td>
<td>21.42</td>
<td>17.52</td>
<td></td>
</tr>
<tr>
<td>ASU load for CMOC combustor</td>
<td>26.08</td>
<td>26.14</td>
<td>26.26</td>
<td>26.43</td>
<td></td>
</tr>
<tr>
<td>Throttle valve loss</td>
<td>3.24</td>
<td>3.25</td>
<td>3.25</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>Amine pumping cost in gas purification unit</td>
<td>0.018</td>
<td>0.018</td>
<td>0.051</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>Reboiler duty in H(_2)S stripper</td>
<td>1.05</td>
<td>1.06</td>
<td>1.05</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Cooling load of turbo machinery</td>
<td>0.041</td>
<td>0.037</td>
<td>0.39</td>
<td>0.037</td>
<td></td>
</tr>
<tr>
<td>Oxygen compression to UCG</td>
<td>6.46</td>
<td>5.75</td>
<td>9.53</td>
<td>7.80</td>
<td></td>
</tr>
<tr>
<td>CO(_2) compression to UCG</td>
<td>7.09</td>
<td>12.95</td>
<td>10.34</td>
<td>16.77</td>
<td></td>
</tr>
<tr>
<td>CCU load for sequestration</td>
<td>25.33</td>
<td>24.19</td>
<td>26.79</td>
<td>22.71</td>
<td></td>
</tr>
<tr>
<td>Water pumping</td>
<td>0.043</td>
<td>0.044</td>
<td>0.029</td>
<td>0.029</td>
<td></td>
</tr>
<tr>
<td>Total power consumption in the auxiliary units (MW)</td>
<td>88.02</td>
<td>90.11</td>
<td>99.11</td>
<td>95.66</td>
<td></td>
</tr>
<tr>
<td>Total useful output (MW)</td>
<td>205.04</td>
<td>207.41</td>
<td>225.62</td>
<td>234.97</td>
<td></td>
</tr>
<tr>
<td>Thermal energy of the coal (MW)</td>
<td>548.43</td>
<td>554.14</td>
<td>550.21</td>
<td>555.08</td>
<td></td>
</tr>
<tr>
<td>Gross efficiency</td>
<td>53.43</td>
<td>53.69</td>
<td>59.02</td>
<td>59.57</td>
<td></td>
</tr>
<tr>
<td>Net efficiency (with CCS)</td>
<td>37.39</td>
<td>37.43</td>
<td>41.00</td>
<td>42.33</td>
<td></td>
</tr>
</tbody>
</table>

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produced syngas should be free of CO, sulfur compounds H₂S, SO₂, and NOₓ. Also the trace component of Hg is also limited to parts per million level in fuel cell feed gas. The trace level of these gases severely affects the performance of fuel cell. The purified gases are sent to the fuel cell at the anode side. Air is supplied at the cathode side. Fuel cells are classified based on their electrolytes. In proton exchange membrane (PEM) fuel cell, hydrogen on the anode side is dissociated into electrons and protons. Electrons pass over the external load circuit and protons are permeated through the polymer electrolyte membrane. Hence, PEM fuel cell is otherwise termed as PEMFC. However, these fuel cells operate at low temperatures of 30°C–100°C (Larminie and Dicks 2003).

At the anode side:
\[ H_2 \rightarrow 2H^+ + 2e^- \] (2.20)

At the cathode side:
\[ 2H^+ + 2e^- + \frac{1}{2} O_2 \rightarrow H_2O \] (2.21)

Alternatively, another fuel cell called solid oxide fuel cell (SOFC) operates at a high temperature in the range of 500°C–1000°C (Larminie and Dicks 2003). The electrolyte is a solid membrane, which has higher thermal stability. As it operates at high temperature, the syngas is reformed internally into hydrogen. Carbon monoxide, methane, ethane, and higher hydrocarbons are reformed into hydrogen fuel with excess supply of steam to the anode side along with the syngas. Therefore, the SOFC does not require any external reformer for water–gas shift reaction. Steam is sent in excess than stoichiometric to avoid the coking of membrane. In the SOFC, oxygen gets reduced at the cathode side, and the solid oxide electrolyte conducts the reduced oxygen ions to the anode side.

At the anode side:
\[ H_2 + O^{2-} \rightarrow H_2O + 2e^- \] (2.22)

At the cathode side:
\[ \frac{1}{2} O_2 + 2e^- \rightarrow O^{2-} \] (2.23)

At the anode side, hydrogen is converted into steam with the liberation of electrons. These electrons are passed through the external load for power production. As the chemical energy of fuel is directly converted into electrical power, energy loss is minimized in the IGFC cycle. Therefore, the IGFC cycle has higher efficiency than the IGCC and ST cycles. Figure 2.13 shows the schematic diagram of the IGFC-integrated UCG system (Prabu and Jayanti 2012c).

Table 2.6 shows the comparison of net thermal efficiency of the UCG-integrated fuel cell system with the conventional power generating system.

Integration of SOFC with UCG enhances the net thermal efficiency 6% higher than the ST system. Integration of the coal gasification unit with the fuel cell cycle leads to high electrical efficiency. It is beneficial in terms of the CCS. In the oxy-fuel combustion-integrated CCS system, the conventional boiler in the IGCC and ST systems requires an ASU system for the separation of oxygen from air. In the IGFC system, fuel cell electrolyte membrane acts a selective absorber of oxygen ions from atmospheric air. The membrane inherently separates oxygen from air, and the final flue gas is enriched with CO₂. Therefore, IGFC is inherently a carbon capture system without energy penalty.
### TABLE 2.6
Overall Energy Analysis for the UCG-Integrated SOFC and SMOC Power Plant

<table>
<thead>
<tr>
<th></th>
<th>UCG + SMOC (kW)</th>
<th>UCG + SOFC (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power production from SOFC</td>
<td>—</td>
<td>231,543</td>
</tr>
<tr>
<td>High pressure steam turbine (HPST)</td>
<td>47,979</td>
<td>—</td>
</tr>
<tr>
<td>Medium pressure steam turbine (MPST)</td>
<td>80,335</td>
<td>—</td>
</tr>
<tr>
<td>Low pressure steam turbine (LPST)</td>
<td>146,771</td>
<td>57,454</td>
</tr>
<tr>
<td>Gross electrical power production</td>
<td>275,085</td>
<td>288,997</td>
</tr>
<tr>
<td>Power consumption (ASU + O₂ compression)</td>
<td>59,939</td>
<td>37,010</td>
</tr>
<tr>
<td>CO₂ compression</td>
<td>27,638</td>
<td>26,125</td>
</tr>
<tr>
<td>Water pumping</td>
<td>6,395</td>
<td>62</td>
</tr>
<tr>
<td>Total power consumption</td>
<td>93,972</td>
<td>63,197</td>
</tr>
<tr>
<td>Total useful output</td>
<td>181,113</td>
<td>225,800</td>
</tr>
<tr>
<td>Thermal input to UCG (coal seam)</td>
<td>698,324</td>
<td>698,324</td>
</tr>
<tr>
<td>Gross efficiency</td>
<td>39.39</td>
<td>41.38</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>25.94</td>
<td>32.33</td>
</tr>
</tbody>
</table>

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### FIGURE 2.13
Schematic representation of the IGFC-integrated UCG system.

![Schematic representation of the IGFC-integrated UCG system.](image-url)
2.7.6 Integrated Gasification Chemical Looping Combustion Cycle

In the ICLC system, coal is processed in two ways. First, it is gasified into syngas using the conventional gasifier. The generated syngas is sent as a feed to the fuel reactor. Alternatively, coal is fed into the fuel reactor directly, and it is gasified \textit{in situ} (fuel reactor itself) with the supply of gasifying medium (\ce{CO2/H2O}). Therefore, coal is converted into fuel gas in the reactor, and it reacts with metal oxides. Metal oxides such as NiO, CuO, Fe$_2$O$_3$, CoO, and Mn$_3$O$_4$ are used in the fuel reactor for the oxidation of syngas. The inert support material used for the entrapment of these metal oxides in the CLC process are Al$_2$O$_3$, SiO$_2$, TiO$_2$, ZrO$_2$, NiAl$_2$O$_4$, MgAl$_2$O$_4$, and so on (Fan 2010). Coal gasification and CLC occur simultaneously in the fuel reactor.

\begin{align*}
\text{Coal} & \rightarrow \text{volatile matter (CO, H}_2, \text{CO}_2, \text{CH}_4) + \text{char} \\
\text{C + CO}_2 & \rightarrow 2\text{CO} \\
\text{C + H}_2\text{O} & \rightarrow \text{CO} + \text{H}_2 
\end{align*}

These fuel gases are converted into \ce{CO2} and \ce{H2O} in the fuel reactor, and the final flue gas is enriched with \ce{CO2} and it is readily available for sequestration. In the air reactor, atmospheric air is used as an oxidant. After the oxidation of metal particles in the air reactor, oxygen-depleted air is sent to the atmosphere after the recovery of thermal energy. Figure 2.14 shows the schematic representation of CLC-integrated UCG system (Prabu 2015). Table 2.7 shows the net thermal efficiency of the CLC-based UCG integrated

\textbf{FIGURE 2.14}
Schematic representation of the CLC-integrated UCG system.
with combined cycle power generation system. Integration of CLC with UCG enhances the net thermal efficiency of about 5% higher than the ST system.

### 2.7.7 Integrated Gasification Solar Cycle

Integration of renewable energy with coal greatly reduces CO$_2$ emission. Renewable energy sources such as sunlight and biomass are suitable for integrating with coal for power generation. Co-combustion of coal and biomass reduces the consumption of fossil fuel and promotes the utilization of seasonal biomass. Similarly, solar energy is another renewable energy, and the proper integration with the power generation cycle increases the net thermal efficiency of the system. In the ST system, solar energy can be utilized for preheating the feed water to the boiler (Suresh et al. 2010). Further, it is utilized for reheating the outlet steam of the HPT and MPT. In the IGSC system, the production of the gasifying medium such as steam and the preheating of feed water for the ST can be carried out using solar energy. In addition, syngas and oxidant can be preheated before sending them to the combustor. Hence, integration of solar energy with the coal power system is one of the feasible solutions for the reduction of CO$_2$ emission.

### TABLE 2.7

Overall Energy Analysis for the O$_2$/CO$_2$-Based UCG Integrated with CLC-Incorporated Combined Cycle Power Plant System

<table>
<thead>
<tr>
<th>Power Plant System</th>
<th>IUGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure (bar)</td>
<td>9.5</td>
</tr>
<tr>
<td>CO$_2$/O$_2$ ratio</td>
<td>0.99</td>
</tr>
</tbody>
</table>

**Power production (MW)**

- Gas turbine | 89.72 |
- Air turbine | 254.62 |
- Low pressure ST | 65.88 |

**Power supply from the gas turbine (MW)**

- Air compression to CLC air reactor | 115.98 |
- CO$_2$ compression to CLC fuel reactor | 4.24 |
- Gross electrical power production (MW) | 290.00 |

**Power consumption in the auxiliary units (MW)**

- ASU load for UCG ($P_{O_2,as}$) | 18.67 |
- Oxygen compression to UCG ($P_{O_2,com}$) | 6.45 |
- CO$_2$ compression to UCG ($P_{CO_2,com}$) | 7.07 |
- CCU load for sequestration ($P_{CCU}$) | 24.47 |
- Water pumping ($P_{FWP}$) | 0.056 |
- Total power consumption in the auxiliary units (MW) | 56.76 |
- Total useful output (MW) | 233.24 |
- Thermal energy of the coal (MW) | 548.43 |
- Gross efficiency | 52.88 |
- Net efficiency (with CCS) | 42.53 |

*Source:* Reprinted from the publication *Appl. Energy*, 140, Prabu, V., Integration of in-situ CO$_2$-oxy coal gasification with advanced power generating systems performing in a chemical looping approach of clean combustion, 1–13, Copyright 2015, with permission from Elsevier.
Clean Coal Technologies

2.8 Coal to Liquid

Coal to liquid (CTL) is a clean coal technology for the conversion of solid fuel into liquid fuel. This can be carried out using direct CTL and indirect CTL methods. In the direct conversion method, coal is broken down into smaller molecules using suitable organic solvents (solvent dissolution methods) such as tetralin, quinoline, and naphthol (Hernández et al. 2012). These solvents dissolve the organic matter of coal and reject the mineral matter (ash content) and sulfur content of coal. Also hydrogen from these solvents is donated for the liquefaction process, and also the addition of pure hydrogen stabilizes the pyrolyzed lighter gas from coal into soluble products. Light, medium, and heavy oils are separated through vacuum distillation. However, further upgradation of the obtained liquid fuel is necessary for the removal of impurities. The obtained liquid product is enriched with a variety of hydrocarbons (naphtha, fuel oil, etc.), which is more aromatic in nature. Also it contains sulfur, oxygen, and nitrogen impurities, and requires further downstream processing for the purification. Approximately, the final product contains a yield of 28% of naphtha, 11% of C₂–C₄ liquified petroleum gas (LPG), 11% of light distillate, 19% of gas oil, and 31% of heavy distillate (Bellman 2007).

In the indirect CTL method, coal is converted into syngas using the conventional gasifier. After the removal of CO₂, sulfur, and acid gas impurities, syngas is converted into liquid by means of the FT synthesis process (Riazi and Gupta 2015). FT reactions are carried out at 150°C–300°C, and these reactions are exothermic. The removal of heat is essential to obtain the desired product. The liquid fuel obtained through the indirect method is free of contaminants and can be utilized directly. The final liquefied product contains 21% of naphtha, 14% of C₃–C₄ LPG, 18% of distillate, and 47% of wax. Hydroisomerization of these liquid products yields 20%–54% of gasoline, 17%–36% of jet fuel, and 16%–55% of diesel (Bellman 2007).

2.9 Conclusion

Coal plays a vital role in the energy sector for electricity production and will continue for several decades. Hence, it is essential to implement the developed clean coal technologies for efficient energy production as well as pollutant reduction. The integration of these technologies in appropriate way is the viable solution for the efficient utilization of the existing resources. It is essential to progress the basic and applied research on the conversion of coal into a clean fuel. Research level technological outcomes on clean coal technologies should be implemented to large scale for creating a clean environment.

Retrofitting of the existing technologies is another option for the economic recovery of fuel. The combustion modification technique should be implemented for the pollutant reduction. India contains huge coal resources, and nearly 37% of the resources are found at a great depth; the development of unconventional technologies is crucial for its recovery. Further, integration of coal technologies with renewable energy should be implemented for the reduction of pollutants.
Acknowledgment

The author expresses his gratitude to Elsevier for granting permission to reuse tables and figures from my publications with them.

References


