Perspective and Prospect of Coal Gasification Technology to Generate Clean Electricity

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Abstract— **Production of electricity from any form of primary energy has some environmental effect. Environmental and health consequences of electricity generation are important issues, alongside the affordability of the power which is produced. Every 1000 MW power station running on black coal produces CO_2 emissions of about 7 million tonnes per year. If brown coal is used, the amount is about 9 million tonnes. Coal gasification is an alternative technique to generate clean electricity from coal with improves performance. In gasification process the ingredients of coal are decomposed, therefore, it is possible to remove the environmental hazardous partials, also all other particles can be used for individual purpose. The residues of gasification process can be used for commercial purpose. An integrated gasification combined cycle (IGCC) plants use a gasifier to convert coal to syngas, which drives a combined cycle turbine. The future energy dependency on coal, processes of Coal Gasification and the scope of clean electricity generation by employing coal gasification technology is discussed.**

Keywords— **Coal, Coal gasification, Clean electricity, Integrated Gasification Combined Cycle, IGCC, Energy**

I. Introduction

Electricity generation is a significant source of air emissions in worldwide. Environmental Protection Agency (EPA) in 2010, estimated worldwide emissions from human activities totalled nearly 46 billion metric tons of greenhouse gases where electricity generation shares over 76% that was 35 billion metric tons of greenhouse gases, expressed as carbon dioxide equivalents, [1]. Electric power from coal has been predominantly generated using pulverized coal-fired power plants. Due to thermodynamic (the use of water) and metallurgic constraints, the efficiency of such plants is low. Modern pulverized coal-fired power plants achieve efficiency of about 38- 40% (based on the Lower Heating Value of the fuel) operating at 250-300 bar and at maximum temperature of 550-570 °C [2]. However, they are characterized by quite high pollutant emissions especially carbon dioxide (about 800 g for each kWh of electric energy produced). The growing energy demand of the developing countries together with the need of a significant reduction in greenhouse gases are the challenging tasks of future energy policies.

Coal gasification offers one of the most versatile and clean ways to convert coal into electricity, hydrogen, and other valuable energy products. Gasification produces less solid wastes than other coal-based power generation. Additionally, the by-products of coal gasifiers can have commercial value. A study conducted by MIT shows that the cost per tonne of avoided CO_2 emissions is dramatically lower for coal gasification process compared to natural gas combined cycle (NGCC) or pulverized coal. The scenario of worldwide emission due to electricity generation and the future energy dependency on coal are illustrated here. Converting coal energy to electricity, coal gasification is an emerging solution which is discussed in this paper. Also the Integrated Gasification Combined Cycle (IGCC) and Underground Coal Gasification process are shortly discussed. Finally, we discuss the scope of clean electricity generation by employing coal gasification technology including performance analysis.

II. Clean Electricity

Clean electricity refers the pollution-free electricity or that electricity which are produced by very low emission technology. Traditional electricity generation is responsible for the emission of a host of chemicals with widespread environmental impacts. Fig. 1 illustrates that, coal fired power plants have the highest GHG emission intensities on a lifecycle basis.

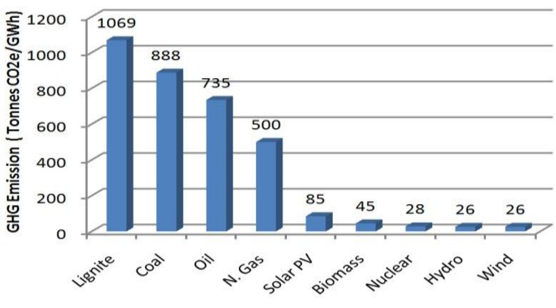


Fig. 1 Lifecycle GHG Emissions Intensity of Different Electricity Generation Methods, [3]

Although natural gas, and to some degree oil, had noticeably lower GHG emissions, biomass, nuclear, hydroelectric, wind, and solar photovoltaic all had lifecycle GHG emission intensities that are significantly lower than fossil fuel based generation.

Worldwide emissions of CO_2 from burning fossil fuels total about 28 billion tonnes per year. About 38% of this is from coal and about 43% from oil. Every 1000 MW power station running on black coal produces CO_2 emissions of about 7 million tonnes per year. If brown coal is used, the amount is about 9 million tonnes, [4].

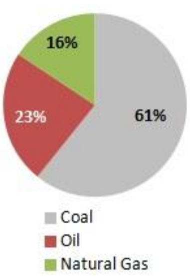
According to Environmental Protection agency-USA, the average emission rates in the United States from coal-fired generation are: 2,249 lbs/MWh of carbon dioxide, 13 lbs/MWh of sulphur dioxide, and 6 lbs/MWh of nitrogen oxides [5] which accounts for about 26 percent of global greenhouse gas emissions double that of the transportation sector [6]. So to reduce this emission it's important to choose an efficient energy and a low emission energy conversion technology as soon as possible.

III. Coal Is the Ultimate Fuel for Future

Coal is readily available all over the world and has risen only moderately in price compared with gas. As a result, coal-fired power plants are a fundamental element of the world's energy supply. The use of coal is expected to rise by over 60% by 2030, with developing countries responsible for around 97% of this increase. China and India alone will contribute 85% of the increase in demand for coal over this period [7]. Most of this is in the power generation sector, with coal's share in global electricity generation set to increase from 41% to 44% by 2030, according to the International Energy Agency (IEA). Table I summarized the proved reserve of fossil fuel, it is clear from Table I, that we must have to depend on coal for electricity generation in future.

TABLE I
Fossil Fuel Proved Reserve, 2013, [8]

Fossil Fuel	Reserve	Oil Equivalent Billion Barrels
Coal	860,938 Million Tonnes	4304
Oil	1669 Billion Barrels	1669
Natural Gas	6614 Trillion Cubic Ft.	1,190



Oil Equivalent

Conversion : WCA standard, [9]
1 Mil. tonnes hard coal
= apprx. 5 Million barrels oil eqv.
1 Tri. cubic feet NG = 0.18 Bill. barrels oil eqv.

World proved reserves of coal in 2012 were sufficient to meet 109 years of global production, by far the largest R/P ratio for any fossil fuel, as in Fig. 2. Europe & Eurasia holds the largest regional reserves while North America has the highest R/P ratio. The US holds the largest individual reserves, followed by Russia and China.

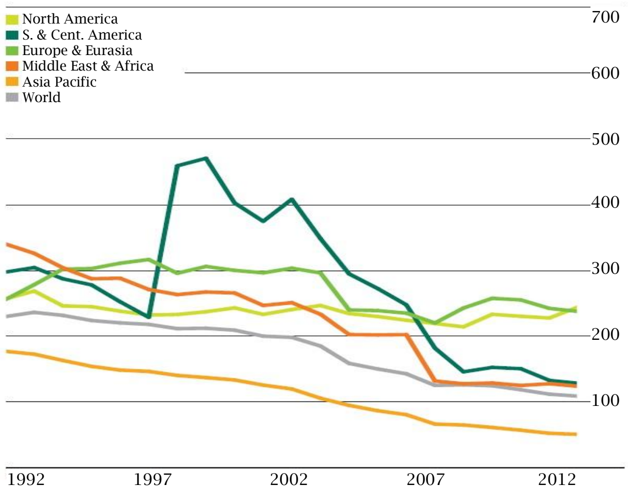


Fig. 2 Coal Reserves-to-production (R/P) ratios, [8]

But, Coal is a dirty fuel to burn. Coal combustion results in greater CO_2 emissions than oil and natural gas per unit of heat output because of its relatively higher ratio of carbon to hydrogen. It emits sulphur dioxide (SO_2), nitrogen oxides (NO and NO_2,) mercury (Hg) compounds, and many other trace elements that can cause acid rain, ash, and mercury pollution, not to mention the carbon dioxide, a greenhouse gas that is frequently in the news because of its link to climate change. The solid fuel coal is more difficult to burn than liquid or gases and also its Physical transport is difficult compare to other. Also Coal mining involves considerable environmental costs.

IV. Coal Gasification Technology

A promising solution comes with coal gasification process which makes possible to separate the good parts from the bad. Gasification avoids burning coal altogether: it turns coal into gas. One of the major environmental opportunities of this technology is the fact that impurities can be almost entirely filtered out when coal is transformed from a solid into a gas, alleviating many of the environmental concerns of coal-fired power plants. In fact, gasifying coal is one of the best ways to clean pollutants out of coal, and many experts predict that coal gasification will be the heart of clean coal technology for the next several decades. In a gasifier, the carbonaceous material undergoes several different processes:

1. The *dehydration* or *drying* process occurs at around 100°C. Typically the resulting steam is mixed into the gas flow and may be involved with subsequent chemical reactions, notably the water-gas reaction if the temperature is sufficiently high enough.
2. The *pyrolysis* process occurs at around 200-300°C. Volatiles are released and char is produced, resulting in up to 70% weight loss for coal. The process is dependent on the properties of the carbonaceous material and determines the structure and composition of the char, which will then undergo gasification reactions.
3. The *combustion* process occurs as the volatile products and some of the char reacts with oxygen to primarily form carbon dioxide and small amounts of carbon monoxide,

which provides heat for the subsequent gasification reactions. Letting C represent a carbon-containing organic compound, the basic reaction here is, $C+O_2 \rightarrow CO_2$

4. The gasification process occurs as the char reacts with carbon and steam to produce carbon monoxide and hydrogen, via the reaction, $C+H_2O \rightarrow H_2+CO$

5. In addition, the reversible gas phase water-gas shift reaction reaches equilibrium very fast at the temperatures in a gasifier. This balances the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen.

$$CO+H_2O \leftrightarrow H_2+CO_2$$

Table II listed the ingredients and their percentage produced in coal gasification process.

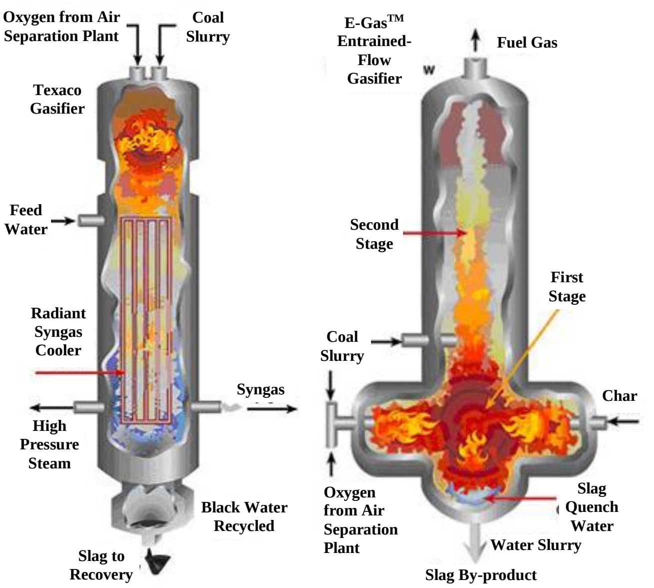
TABLE II
PERCENT OF COMPONENT PRODUCED IN COAL GASIFICATION PROCESS, [10]

Main Components		**Harmful Substance & contaminants**	
H_2	25 – 30 Vol.%	H_2S	0.2 – 1 Vol.%
CO	30 – 60 Vol.%	COS	0 – 0.1 Vol.%
CO_2	5 – 15 Vol.%	N_2O	0.5 – 4 Vol.%
H_2O	2 – 30 Vol.%	Ar	0.2 – 1 Vol.%
CH_4	0 – 5 Vol.%	NH_3 + HCN	0 – 0.3 Vol.%

Although there are various types of gasifers (gasification reactors), different in design and operational characteristics, there are three main gasifier classifications into which most of the commercially available gasifier fall. These categories are as follows:

(a) Fixed (moving) bed gasifier,
(b) Entrained-flow gasifier (Fig.3), (c)Fluidized-bed gasifier

Commercial gasifier of *"GE Energy"*, *"ConocoPhillips E-Gas™ "* and *"Shell SCGP"* are examples of entrained-flow types. Fixed-or moving-bed gasifier includes that of *"Lurgi"* and *"British Gas Lurgi (BGL)"*.



a. (source: GE Energy) b. (source: ConocoPhillips)

Fig. 3 Entrained-flow types Commercial Coal Gasifiers (a) *GE Energy*, (b)*ConocoPhillips E-Gas™*

The coal is fed into a high-temperature pressurized container (gasifier) and combined with hot steam and controlled amounts of air or oxygen under high temperatures (up to 2600 °F) and high pressures (up to 1200 psig) to generate synthetic gas or 'syngas.' The composition of the syngas can vary depending upon the conditions in the gasifier and the coal that is used, but typically it is a mixture of carbon dioxide, hydrogen, methane, and nitrogen and carbon monoxide. The gas is cooled, and as much as 99% of the pollutant-forming impurities are removed. To increase efficiency even further, the cleaned as is burned in a conventional gas turbine to produce electrical energy, and the hot exhaust gas is recovered and used to boil water, creating steam for a steam turbine that also produces electrical energy. It can be turned into pipeline quality natural gas and piped directly into people's houses. It can also be used as a building block to manufacture more complex products in refining and petrochemical industries. Fig 4 illustrates the whole process of Coal Gasification plant.

A. *Integrated Gasification Combined Cycle*

An integrated gasification combined cycle (IGCC) is a technology that uses a gasifier to turn coal into synthesis gas (syngas). It then removes impurities from the syngas before it is combusted. Some of these pollutants, such as sulphur, can be turned into re-usable by-products. This results in lower emissions of sulphur dioxide, particulates, and mercury. Excess heat from the primary combustion and syngas fired generation is then passed to a steam cycle, similar to a combined cycle gas turbine. These results in improved efficiency compared to conventional pulverized coal. IGCC-based electrical power generation is proven to be economical. In addition, co-firing coal with opportunity materials such as municipal waste and biomass feedstock in this context may enable IGCC-based power generation to more quickly gain a foothold in the market if certain drivers develop as expected, including alternative fuels initiatives and more stringent greenhouse gas emissions limitation requirements.

As far as IGCC power generation is concerned, there are six coal based units producing 1745MW electricity worldwide (illustrate in Table III).

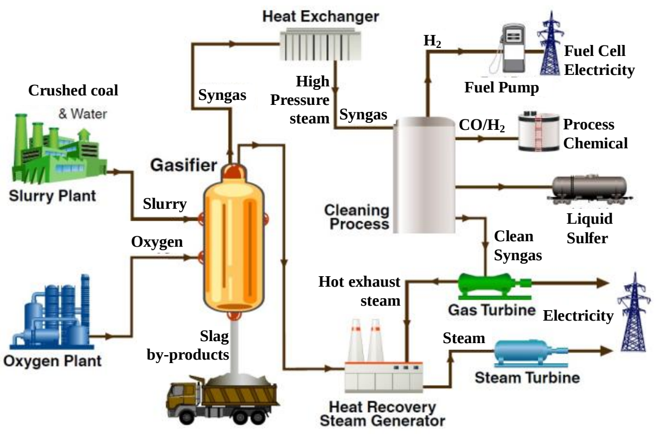


Fig. 4 Process flow of the IGCC Power plant [12].

TABLE III
EXISTING COAL BASED IGCC POWER PLANT IN OPERATION WORLDWIDE [10]

Coal based IGCC Plant	1 Willem-Alexander	2 Wabash River	3 Tampa	4 Puertollano	5 Vresova	6 Nakoso
Location	Buggenum, Netherland	Indiana, USA	Florida, USA	Ciudad Real, Spain	Czech Republic	Fukushima, Japan
Commissioning yr.	1994	1995	1996	1998	1996	2004
Electrical Capacity	253MW	262MW	250MW	300MW	430MW	250MW
Feed Fuel	Black coal + Biomass	Black coal + Petroleum coke	Black coal	Black coal + Petroleum coke	Lignite	Black coal
Gasifier Type	O_2-blown Dry-feed Prenflo	O_2-blown Dry-feed E-Gas	O_2-blown Slurry-feed GE	O_2-blown Slurry-feed Shell	O_2-blown Dry-feed GSP	Air-blown Dry-feed HMI
Coal Consumption	2000 TPD	2500 TPD	2600 TPD	2500 TPD	2000 TPD	1700 TPD
Net efficiency	43%	39%	41%	42%	44%	42%

B. *Underground Coal Gasification*

Another gasification process is “Underground coal gasification (UCG)” by which coal is converted to gases and liquids in-situ (i.e. while it is still underground) via controlled partial combustion as shown in Fig. 5. This process avoids the need for coal mining, transportation, preparation, gasifier equipment and the transportation as well as disposal of ash, which has cost, labour and environmental benefits.

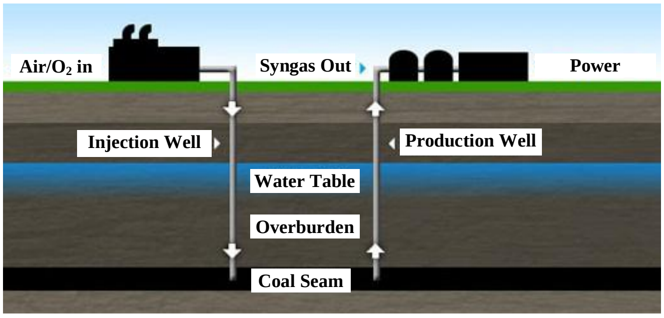


Fig. 5 Underground Coal Gasification Process

Renewed interest in UCG technology has recently occurred in most coal producing regions of the world, led largely by Australia where entrepreneurial companies are harnessing the potential for power generation and gas to liquids manufacturer. Other important regions of activity include New Zealand, South Africa, China, USA, Eastern Europe, India, Indonesia, Vietnam, Pakistan and the UK, which has recently issued a number of licenses to exploit UCG offshore. UCG is especially suitable for low-rank coals like lignites and sub-bituminous coal, which produce less heat and more CO_2 when burned. In addition, the UCG process is an effective generator of large quantities of hydrogen, now in demand as a feedstock for the combined cycle power plant and Fuel cell plant to produce clean electricity.

V. ADVANTAGES & DRAWBACKS OF COAL GASIFICATION

In order to discuss the advantages and drawbacks of any technology, a baseline for comparison must be established. For gasification technology, that baseline is comprised of a range of other technologies that either produce the same products or use the same feedstock. The most significant application of gasification technology in the near term is in the production of electricity from coal, so generally the most appropriate comparison for the technology is to other current coal power plant technologies like subcritical and supercritical pulverized coal combustion. Gasification differs in many areas from these alternatives, and the advantages – and in some cases disadvantages – are discussed in the following sections:

A. *Multiple Uses*

Major advantages of gasification include its abilities to produce different forms of energy and create useful by-products. People can use the energy immediately in the form of electricity or store it as a fuel for future and portable consumption. By-products of gasification include sulphur and ammonia, both of which have important industrial applications. This improves the supply of such commodities and helps make gasification more economical for its operators. We can achieve advantages from basic three steps of Coal gasification process like...

1. *Coal gasifier by-products:*
   -Coal tar, can be used to produce bitumen
   -Ash, can be use in cement, brick and concrete
2. *Syngas purifier by-products*:
   -H_2, electricity generation by Fuel cell
   -CO/H_2, used in process chemical
   -CO_2, used in oil refinery, underground storage
   -Sulphur, raw gas for producing Sulphuric Acid and industrial purposes.
   -Ammonia, raw gas for producing Urea, Ammonium nitrate and Ammonium sulphate.
   -Methanol, uses in chemical industries.
3. *Cleaned syngas:*
   -Electricity generation by combustion turbine
   -Secondary Electricity generation by steam turbine
   -Burn bricks in brick field
   -Ceramics & glass industry, Steel industry
   -Any kind of thermal process
   -Producing liquid fuel, substituting natural gas.

B. *Efficiency*

Gasification has the potential for highly efficient power generation. While a conventional subcritical pulverized coal (PC) power plant has a typical plant efficiency of about 35%, an integrated gasification combined cycle (IGCC) power plant can have plant efficiency from 38 to 41% depending on the gasification and heat recovery technologies employed and the degree of plant integration with other processes, like air separation, for example. When coupled with other advanced technologies under development, like hydrogen turbines and solid oxide fuel cells, a gasification power plant can have efficiencies as high as 60%—a very substantial gain over conventional technologies. From the practical experience, average net efficiency of six existing IGCC plant is 41.8% where the maximum efficiency in 430MW Vresova IGCC plant by 44% and the minimum efficiency found in 262MW Wabash River IGCC plant, USA by 39%, [10].

C. *Environment*

The environmental benefits of gasification stem from the capability to achieve extremely low SOx, NOx and particulate emissions from burning coal-derived gases. Sulphur in coal, for example, is converted to hydrogen sulphide and can be captured by processes presently used in the chemical industry. In some methods, the sulphur can be extracted in either a liquid or solid form that can be sold commercially.

In an Integrated Gasification Combined-Cycle (IGCC) plant, the syngas produced is virtually free of fuel-bound nitrogen. NOx from the gas turbine is limited to thermal NOx. Diluting the syngas allows for NOx emissions as low as 15 parts per million. Selective Catalytic Reduction (SCR) can be used to reach levels comparable to firing with natural gas if required to meet more stringent emission levels. Other advanced emission control processes are being developed that could reduce NOx from hydrogen fired turbines to as low as 2 parts per million.

An inherent advantage of the IGCC process is the potential for low emissions by using fuel gas clean up - instead of flue gas clean up. Because of the high partial pressures, impurities can be removed more effectively and economically compared to conventional clean up of the large volume flow of the combustion flue gas. Coal gasification makes easier to capture carbon and store it, which add a great advantage to generate clean electricity. Table IV shows the environmental performance of IGCC compared to conventional steam power plants.

TABLE IV

COMPARISON BETWEEN EMISSION OF CONVENTIONAL PULVERIZED COAL POWER PLANT AND IGCC POWER PLANT [13].

Pollutant	Advanced PC	IGCC	Change
SO_2 (lb/MMBtu)	0.1	0.025	Decrease 75 %
NOX (lb/MMBtu)	0.06	0.0075	Decrease 87.5 %
CO_2 (kg/kWh)	7.66	6.64	Decrease 13.3 %

Commercial processes such as MDEA and Selexol can remove more than 97 % of the sulphur so that the clean syngas has a concentration of sulphur compounds < 20 ppmv [14]. The commercial technology for mercury removal is available, 99.9% Hg removal from syngas has been demonstrated [15]. The cost of Mercury removal has been estimated to $ 3,412/ lb for IGCC vs. $ 37,800/ lb for Pulverized Coal plants. Also the IGCC plant uses 20 % to 50 % less cooling water than conventional coal plants, [15].

D. Cost

One of the major disadvantages of coal gasification is the cost to set up and maintain the necessary facilities. The U.S. Energy Information Administration (EIA) summarizes the updated cost estimates for generic utility-scale generating plants, including seven powered by coal, illustrated in Fig 5. The problem being that based purely on cost of electricity (COE), IGCC is not competitive with traditional pulverized coal or natural gas. As additional emissions restrictions are imposed on electricity generators, IGCC is expected to become the lowest cost solution especially if carbon capture and sequestration is required. Table-V illustrates different types of plant cost.

TABLE V

UPDATED ESTIMATES OF POWER PLANT CAPITAL & OPERATING COSTS, [16]

Plant Type	Overnight Capital Cost ($/kW)	Fixed O&M Cost ($/kW-yr)	Variable O&M Cost ($/MWh)
Coal-Adv. Pulverized	$ 3,246	$ 37.80	$ 4.47
Coal-Adv. PC with CCS	$ 5,227	$ 80.53	$ 9.51
Coal-Adv. IGCC	$ 4,400	$ 62.25	$ 7.22
Coal-Adv. IGCC with CCS	$ 6,599	$ 72.83	$ 8.45
NG Adv. CC	$ 1,023	$ 15.37	$ 3.27
NG Adv. CC with CCS	$ 2,095	$ 31.79	$ 6.78
Fuel Cells	$ 7,108	$ 0.00	$ 43.00
Dual Unit Nuclear	$ 5,530	$ 93.28	$ 2.14
Biomass CC	$ 8,180	$ 356.07	$ 17.49
Biomass BFB	$ 4,114	$ 105.63	$ 5.26
Onshore Wind	$ 2,213	$ 39.55	$ 0.00
Offshore Wind	$ 6,230	$ 74.00	$ 0.00
Solar Thermal	$ 5,067	$ 67.26	$ 0.00
Photovoltaic	$ 4,183	$ 27.75	$ 0.00
Geothermal –Dual Flash	$ 6,243	$ 132.00	$ 0.00
Geothermal –Binary	$ 4,362	$ 100.00	$ 0.00
Conventional Hydro	$ 2,936	$ 14.13	$ 0.00

The Pacific Northwest National Laboratory indicates that gasifier refractoriness typically last about one year to 450 days at most, costing roughly one million dollars to replace. They also take approximately 21 to 42 days to install, during which the gasification facility cannot operate. This raises the cost of energy and chemicals produced by such plants, making it more difficult for them to compete with equivalent products generated using conventional methods.

VI. FUTURE OF COAL GASIFICATION TECHNOLOGY

Gasification is a simple and commercially well-proven technology. The gasification database (April 2014) of National Energy Technology Laboratory, USA, shows that total 98 gasification projects worldwide having commercial potential where, 35 IGCC(Integrated Gasification Combined Cycle), 12 SNG(Synthetic Natural Gas), 25 CTL(Coal-to-Liquids), 9 CTC(Coal to Chemicals), 8 BTL(Biomass to Liquids), 3 WTE(Waste-to-Energy), 1 WTEth(Waste-to-Ethanol), 1CBTL(Coal-Biomass-to-Liquids), 3 GTL(Gas-to-Liquids), 1 PTL(Petcoke-to-Liquids) and 1 BTG(Biomass to Gas) [17]. However, a small number of new projects have been initiated worldwide, each at some stage of planning or construction. According to National Energy Technology Laboratory, already 35 projects are under construction in worldwide to generate 20,730MW electricity by IGCC plant where the US proposed the maximum individual IGCC plant (11,775MW by 20 projects), followed by UK (2,540MW by 4 projects), Saudi Arabia (2,400MW by 1 project) and China (1,0505MW by 2 projects), [17]. Another source states that, China plans to build 50 coal gasification plants in less populated north-western parts of the country, using the gas produced to generate electricity in the more populated areas, where smog is prevalent, [18]. Future concepts that incorporate a fuel cell or a fuel cell-gas turbine hybrid could achieve efficiencies nearly twice today's typical coal combustion plants. If any of the remaining heat can be channelled into process steam or heat, perhaps for nearby factories or district heating plants, the overall fuel use efficiency of future gasification plants could reach 70 to 80 percent, as in [19].

There are many research agencies and institute Worldwide developing coal gasification technologies to minimize the environmental impact and improve the process efficiency for maximum energy utilization. Some of them are, National Energy Technology Laboratory (NETL)-USA, Commonwealth Scientific and Industrial Research Organisation (CSIRO)–Australia, Massachusetts Institute of Technology (MIT)-USA, World Coal Association (WCA)-UK, International Energy Agency- IEA Clean Coal Centre (CCC)-UK, Gasification Technologies Council (GTC)-USA, Institute of Clean Coal Technology (ICCT)-China, Canadian Centre for Clean Coal/Carbon and Mineral processing Technologies (C5MPT)-Canada. Future work on clean electricity generation by coal gasification technology will focus on improving the reliability & performance of the gasifier and finding the best process for Syngas cooling, Water gas shift reaction (WGSR), Acid gas removal (AGR) mechanism, etc.

Technical trends, which help gasification, include improving gas turbines and poly-generation. Each increase in combined-cycle efficiency directly reduces the size and cost of the gasification facility required to fire that combined cycle. Advanced intercooled, recuperated, reheat gas turbines have the potential of power-to-cogeneration heat ratio that is an order of magnitude higher than that possible with steam turbines. Poly-generation is unique to gasification and, with deregulation, this concept will develop. Gasification has strategic emission, efficiency, and economic flexibility for the future.

VII. Conclusions

The importance of coal as ultimate fuel of future is discussed. The drawback of conventional coal based power plant and need to move towards Integrated Gasification Combined Cycle (IGCC) power plant is discussed. Many countries are introducing coal gasification technology to meet their electricity demand with confirming the energy security and environmental issue. The capability to produce electricity, hydrogen, chemicals, or various combinations while eliminating nearly all air pollutants and potentially greenhouse gas makes coal gasification one of the most promising technologies for clean power generation. The present scenario of IGCC and the underground coal gasification process is shortly discussed. The performance of electricity generation by coal gasification technique in terms of efficiency, application, cost and environmental issues as compared conventional coal fired power plant is discussed. Finally the future prospects of coal gasification technology are discussed.

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