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Coal gasification for advanced power generation

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Abstract

This paper provides a review of the development and deployment of coal based gasification technologies for power generation. The global status of gasification is described covering the various process and technology options. The use of gasification for power generation is then highlighted including the advantages and disadvantages of this means for coal utilisation. The R, D & D needs and challenges are then reviewed including the likely impact of regulatory emissions directives in moving things forward.

Keywords: Fossil fuels; Gasification, R, D&D needs

1. Introduction

Gasification, which is a means to convert fossil fuels, biomass and wastes into either a combustible gas or a synthesis gas for subsequent utilisation, offers the potential both for clean power and chemicals production. This paper provides an international review of the technology and its applications, covering:

- Gasification units that can be fired with coal, coal with biomass and wastes, refinery residues and natural gas.
- Gasification both for power generation and the associated production of chemicals and fuel gases, with emphasis on the issues of coal gasification for advanced power generation.
- R, D&D needs towards clean coal power generation based on gasification technology

2. Fossil fuel gasification technology status

2.1. Numbers and types of plants

On a worldwide basis, there are some 160 modern, gasification plants in operation and a further 35 at the planning stage. The primary products that can be produced in such plants include electricity, ammonia, oxy-chemicals, syngas, methanol, and hydrogen, as summarised in Table 1 [1].

The majority of these plants are located either in Europe or in the USA, of which those plants that either currently are in operation or are planning to produce electricity are shown in Tables 2 and 3, respectively.

2.2. Feedstock options

The feedstocks include coal, natural gas (for reforming applications) [2–4], refinery residues [5–8] and biomass/wastes in combination with coal [9], as summarised in Table 4. This shows that although much R & D attention has been focused on using coal as the primary feedstock, the large majority of gasification projects to date are based upon the use of fuels other than coal.

All coal types can be gasified. However, on economic grounds, low ash content coals are preferred. There is sensitivity to various coal properties depending on the technology used, as described in Section 2.4.

With regard to refinery residues (bottoms), these can take several forms depending on the design of the refineries and their products. The primary bottoms that comprise most of the fuels of interest for energy applications include:

- Atmospheric distillation residue
- Vacuum distillation residue
- Residual tar from solvent de-asphalting/vis-breaking process
- Petroleum coke

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Table 1
Primary products produced through fossil fuel gasification

Product	Primary product		Secondary product
	Operating plant	Planned plant	
Electricity	35	25	6
Hydrogen	11	1	11
Ammonia	34	3	1
Syngas	14	1	2
Methanol	12	1	11
Oxy-chemicals	22	0	1
Carbon dioxide	7	0	5
Others (FT liquids, fuel gas)	25	4	0
Total	160	35	37

Source: Derived from the World Gasification Database, US Department of Energy and the Gasification Technology Council [1].

2.3. Process options

Some 20% of the gasification plants throughout the world that use coal as the feedstock produce electric power [1]. The rest produce chemicals such as ammonia, methanol, oxy-chemicals and syngas. The biomass and biofuels gasification plants, which are small-scale compared to fossil fuel operations, produce electricity and syngas. The heavy petroleum products and refinery residues plants are used extensively to produce chemicals and gases, although power production has been integrated with the more recent units. Natural gas and naphtha are used to produce chemicals and fuels, primarily carbon monoxide, hydrogen, methanol and oxy-chemicals.

2.4. Technology options

There are three technology variants, classified by gasifier configurations according to their flow geometry:

- Entrained flow gasifiers, in which pulverised coal particles and gases flow concurrently at high speed. They are the most commonly used gasifiers for coal gasification.
- Fluidised bed gasifiers, in which coal particles are suspended in the gas flow; coal feed particles are mixed with the particles undergoing gasification,

Table 2
Major electricity producing gasification plants by country

Country	Plant Name	Type	Feedstock	Products	Year
Australia	Whytess gully waste to energy plant	Unknown	Biomass	Electricity	1999
Austria	Zeltweg gasification plant	Unknown	RFD	Electricity	1997
Canada	MSW plant	Thermogenics, Inc.	Biomass	Electricity	2000
Canada	Toronto MSW plant	Thermogenics, Inc.	Municipal waste	Electricity	2000
China	Beijing town gas plant	Texaco	Coal	Town gas and electricity	1995
Czech Rep.	Vresova IGCC plant	Lurgi dry ash	Lignite	Electricity and steam	1996
Finland	Kymijärvi ACFBG plant	FW ACFBG	Biofuels	Electricity and district heat	1998
Germany	Schwarze pumpe town gas plant	Lurgi dry ash	Municipal waste	Electricity and methanol	1964
Germany	Leuna methanol Anlage	Shell	Visbreaker residue	H2, methanol and electricity	1985
Germany	Slurry/oil gasification	Lurgi MPG	Oil and slurry	Electricity and methanol	1968
Germany	Schwarze pumpe power/ methanol plant	BGL	Household waste and Bit. coal	Electricity and methanol	1999
Germany	Schwarze pumpe gasification plant	GSP	Municipal waste	Electricity and methanol	1992
Germany	Fondotoce gasification plant	ThermoSelect	MSW	Electricity	1999
India	Sanghi IGCC plant GTI (IGT)	U-GAS	Lignite	Electricity and steam	2002
Italy	Project	Texaco	ROSE asphalt	Electricity, H2 and steam	2000
Italy	SARLUX GCC/H2 plant	Texaco	Visbreaker residue	Electricity, H2 and steam	2001
Netherlands	Pernis Shell gasif. hydrogen plant	Shell	Visbreaker residue	H2 and electricity	1997
Netherlands	Buggenum IGCC plant	Shell	Bit. Coal	Electricity	1994
Netherlands	Americentrale fuel gas plant	Lurgi CFB	Demolition wood	Electricity	2000
Singapore	Chawan IGCC plant	Texaco	Residual oil	Electricity, H2 and steam	2001
Spain	Puertollano GCC plant	PRENFLO	Coal and petcoke	Electricity	1997
Taiwan	Kaohsuing syngas plant	Texaco	Bitumen	H2, CO and methanol SG	1984
USA	Wabash River Energy Ltd	E-GAS (Destec/Dow)	Petcoke	Electricity	1995
USA	Delaware clean energy Cogen. Project	Texaco	Fluid petcoke	Electricity and steam	2001
USA	Polk County IGCC Project	Texaco	Coal	Electricity	1996
USA	Commercial Demonstration Facility	Brightstar Env. Ltd	Biomass	Electricity	1996
USA	New Bern gasification plant	Chemrec	Black liquor	Electricity	1997
USA	McNeil IGCC Project	Fut. ener. resources	Forest residue	Electricity	1997
U S A	El Dorado IGCC Plant	Texaco	Petcoke, Ref. Waste & Nat. gas	Electricity & HP steam	1996

Source: Derived from the World Gasification Database, US DoE and Gasification Technology Council [1].

Table 3
Major planned electricity producing gasifiers by country

Country	Plant Name	Type	Feedstock	Products	Year
Australia	Esperance gasification plant	Texaco	Lignite	F-T liquids/electricity	2007
Brazil	Brazilian BIGCC plant	TPS	Biomass	Electricity	2003
China	Caojing power plant	Shell	Coal	Electricity and syngas	2004
Czech Rep.	Vrecopower/Vresova IGCC Project	HTW	Lignite	Electricity	2003
Europe (unspecified)	Unspecified plant	Shell	Residue	Electricity	2005
France	Normandie IGCC plant	Texaco	Fuel oil	Electricity, steam and H2	2005
India	Bhatinda IGCC	Texaco	Petcoke	Electricity	2005
Italy	Agip IGCC	Shell	Visbreaker residue	Electricity and H2	2003
Italy	Sulcis IGCC Project	Shell	Coal	Electricity	2004
Italy	Sannazzaro GCC plant	Texaco	Visbreaker residue	Electricity	2005
Japan	Unspecified IGCC plant	ICGRA	Coal	Electricity	2004
Japan	Marifu IGCC plant	Texaco	Petcoke	Electricity	2004
Japan	Yokohama Cogen/B	Texaco	Vac. residue	Electricity	2003
Netherlands	Europoort/Pernis IGCC plant	Texaco	Waste plastics	Electricity and CO	2006
Poland	Gdansk IGCC plant	Texaco	Visbreaker residue	Electricity, H2 and steam	2005
Spain	Bilbao IGCC plant	Texaco	Vac. residue	Electr. and H2	2005
UK	Fife Power	BGL	Coal and sludge	Electricity	2005
UK	Fife electric	BGL	Coal and sludge	Electricity	2005
USA	Gilberton culm-to-clean fuels plant	Texaco	Anthracite culm	Diesel and electricity	2004
USA	Site not yet determined	Carbona/enviropower	Biomass	Electricity	2004
USA	Site not yet determined	U-GAS	Biomass	Electricity	2004
USA	Calla GCC plant	U-GAS	Biomass	Electricity	2003
USA	Unspecified plant	Texaco	Coal	Electricity	2006
USA	Port Arthur GCC Proj	E-GAS (Destec/Dow)	Petcoke	Electricity	2005
USA	Lake Charles IGCC Proj.	Texaco	Petcoke	Electricity, H2 and steam	2005
USA	Deer Park GCC plant	Texaco	Petcoke	Elect., syngas and steam	2006
USA	Polk County gasification plant	Texaco	Petcoke	Electricity	2005
USA	Kingsport IGCC plant	Texaco	Bit. coal	Electricity	2007

Source: Derived from the World Gasification Database, US DoE and Gasification Technology Council [1].

- Moving bed (also called fixed bed) gasifiers, in which gases flow relatively slowly upward through the bed of coal feed. Both concurrent and counter-current technologies are available but the former is more common.

Each has advantages and disadvantages together with differing commercial track records. In overall terms, with regard to suppliers, Shell and Texaco entrained flow gasifiers are used in nearly 75% of the 160 projects referred to above [10]. Of the rest, Lurgi moving bed gasification technologies are also used to a significant extent. For the 'planned' gasification projects, it is understood that approximately 75% of these will also use either the Texaco or Shell designs. The suppliers of the major gasification installations are listed in Table 5.

2.4.1. Entrained flow gasifiers

Entrained flow gasifiers are the most widely used gasifiers with seven different technologies (BBP, Hitachi, MHI, PRENFLO, SCGP, E-Gas and Texaco) available [11,12]. In these gasifiers, coal and other solid fuel particles concurrently react with steam and oxygen or air in suspension (i.e. entrained) fluid flow mode. Coal can either be fed dry (commonly using nitrogen as transport gas) or wet (carried in a water slurry) into the gasifier. Entrained flow gasifiers usually operate at high temperatures of 1200–1600 °C and pressures in the range of 2–8 MPa with most of the large plants operating at around 2.5 MPa. Raw gas exiting the gasifier usually requires significant cooling before being cleaned. There are two main methods of cooling the gas, either by using a high temperature

Table 4
Feedstocks used in gasification plants

Feedstock	Operational plant	Planned plant
Coal	27	14
Coal/petcoke	3	1
Petcoke	5	7
Natural gas	22	0
Biomass	12	3
Fuel oil/heavy petroleum residues	29	2
Municipal waste	5	0
Naptha	5	0
Vacuum residue	12	2
Unknown	40	6
Total	160	35

Source: Derived from the World Gasification Database, US DoE and Gasification Technology Council [1].

Table 5
Technology suppliers for gasification projects worldwide

Technology supplier	Gasifier type	Solid fuel feed type	Oxidant	Major installations
Chevron Texaco, USA	Entrained Flow	Water Slurry	O_2	Tampa Electric IGCC Plant, Cool Water IGCC Plant, Chevron Texaco Eldorado IGCC Plant, Eastman Chemical, Ube Industries, Motiva Enterprises, Deer Park
Global Energy E-Gas, USA	Entrained flow	Water slurry	O_2	Wabash River IGCC Plant and Louisiana Gasification Technology IGCC Plant
Shell, USA/The Netherlands	Entrained flow	N_2 carrier/dry	O_2	Demkolec IGCC Plant (Buggenum, Netherlands) Shell Pernis IGCC Plant, Netherlands, Harburg
Lurgi, Germany	Moving bed	Dry	Air	Sasol Chemical Industries and Great Plains Plants
British Gas/Lurgi Germany, UK	Moving bed	Dry	O_2	Global energy power/methanol plant, Germany
Prenflo/Uhde, Germany	Entrained flow	Dry	O_2	Elcogas, Puertollano IGCC Plant (Spain), Furstenhausen in Saarland
Noell/GSP, Germany	Entrained flow	Dry	O_2	Schwarze Pumpe, Germany
HT Winkler (HTW) RWE Rheinbraun/ Uhde, Germany	Fluidised bed	Dry	Air or O_2	None
KRW, USA	Fluidised bed	Dry	Air or O_2	Sierra Pacific (Nevada, USA)

syngas cooler, which can also include recycling a portion of cooled gas to the gasifier, or by quenching the gases with water. Such units, with a gas residence time of a few seconds, have a high load capacity but this requires the solid fuel to be pulverised to <1 mm. That said, rapid changes in fuel for loading are difficult to handle as the fuel:oxidant ratio has to be maintained within a narrow range in order to keep a stable flame close to the injector and maintain the stability of operation.

Entrained flow gasifiers are the most versatile type of gasifiers as they can accept both solid and liquid fuels and operate at high temperature (above ash slagging temperatures) to ensure high carbon conversion and a syngas free of tars and phenols. However, such high temperatures have an impact on burners and refractory life and require the use of expensive materials of construction as well as the use of sophisticated high temperature heat exchangers to cool the syngas below the ash softening temperature in order to avoid fouling and control corrosion problems. The ash fusion temperature (or melting point) of the coal/solid fuel should preferably be low so that molten ash can flow down the reactor walls and drain from the gasifier. Fluxes like limestone can be added to reduce the coal ash melting point [13]. Even so, the composition of the coal slag can have a major influence on gasifier refractory life. With the high chrome refractory materials usually used in commercial gasifiers, the slag can penetrate deeply into the refractory before solidifying. As a result, changes that occur in the microstructure and the properties of the refractory give rise to cracks that ultimately lead to material loss [14]. Refractories are expensive parts of the equipment of a gasification plant and to be economically advantageous they should last for a minimum of 2–3 years [15].

Coals with a low ash content are preferred for both economical and technical reasons [16–18]. If gasifier operating conditions are kept constant, an increase in coal ash content will lead to a decrease in gasification efficiency and an increase in slag production and disposal. These three factors contribute to an increase of the overall cost of the process. The decrease of gasification efficiency is mainly due to an increase in oxygen consumption necessary to melt the minerals as well as a thermodynamic penalty since the heat in the slag exiting the gasifier cannot be fully recovered. However, each technology has slightly different coal ash requirements depending on their design. There is a minimum ash content required for the SCGP (>8 wt%), the BBP (>1 wt%) and the Hitachi gasifiers

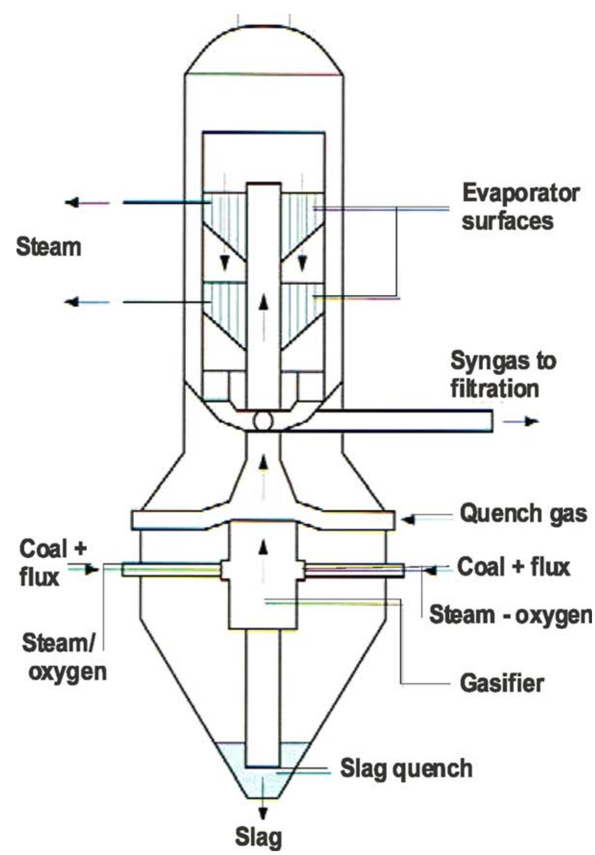

Fig. 1. The Prenflo Gasifier [12].

because of a slag self-coating system on the wall of the gasifiers, which has to be covered by slag to function and minimise heat loss through the wall (Fig. 1).

The tolerance of entrained flow processes to sulphur and halogen species also differs with each process. It depends on the composition and resistance of the material used in the cooling, cleaning and tapping systems but also on the operating conditions of the gasification process (especially gasifier temperature), as well as the processing capacity of the downstream equipment, such as the sulphur recovery plant.

2.4.2. Fluidised bed gasifiers

There are six types of gasification processes (BHEL, HTW, IDGCC, KRW, Transport reactor, Mitsui Babcock ABGC) using fluidised bed gasifiers although the majority have yet to be developed to the demonstration scale (see below) [11,12].

Fluidised bed gasifiers can only operate with solid crushed fuels (0.5–5 mm), with the exception of the transport reactor, which is midway between a fluidised bed and an entrained flow gasifier and as such operates with pulverised fuel (i.e. coal $<$ 50 μm). The coal is introduced into an upward flow of gas (either air or oxygen/steam) that fluidises the bed of fuel while the reaction is taking place. The bed is either formed of sand/coke/char/sorbent or ash. Residence time of the feed in the gasifier is typically in the order of 10–100 s but can also be much longer, with the feed experiencing a high heating rate on entering the gasifier. High levels of back-mixing ensure a uniform temperature distribution in the gasifiers, which usually operate at temperatures well below the ash fusion temperatures of the fuels (900–1050 °C) to avoid ash melting, thereby avoiding clinker formation and loss of fluidity of the bed. There are both dry ash and agglomerated ash systems. One of the main advantages of these types of gasifier is that they can operate at variable loads which gives them a high turndown flexibility.

A consequence of the low operating temperatures is the incomplete carbon conversion in a single stage, leading to lower cold gas efficiency than in the other types. In order to avoid the production of fly ash with high carbon concentration, many of the fluidised bed gasification processes are now equipped with a fly ash recirculation unit. Nevertheless, depending on the coal used, this can lead to an increase of the ash content of the bed. Hybrid systems, in which coal is first gasified in a fluidised bed followed by char combustion in a fluidised bed combustor, can solve this problem and increase carbon conversion leading to higher cold gas efficiency [19]. Because of the low operating temperatures in fluidised bed gasifiers, reactive coals such as lignites and brown coals are the coals of choice [20,21]. Fluidised bed gasifiers with agglomerated ash operation can however process higher rank coals as they have a higher cold gas efficiency than dry ash systems.

Sulphur which is found in the gas stream as H_2S and COS can be partly retained in the bed (up to 90%) by sorbents such as limestone. This leads to a considerable reduction of the H_2S concentration in downstream equipment and hence a decrease in material corrosion. A consequence of the use of sorbents to retain sulphur compounds in beds, as well as the low operating temperatures in fluidised bed gasifiers, allows the use of cheaper materials for the building of heat exchangers and cleaning devices. Fluidised bed gasification systems are more tolerant to sulphur than entrained flow systems. However, coals with very high sulphur contents are not recommended as they would require a further addition of sorbent leading to an increase in the volume of solids discharged by the process and hence in its overall cost.

2.4.3. Moving bed gasification processes

There are only three types of gasification processes using moving bed gasifiers (BGL, BHEL, Lurgi dry ash) developed at industrial scale though they are the most mature of the three generic types of gasifier [11,12,22,23]. Moving bed gasifiers can be either slagging (BGL) or dry ash (Lurgi, BHEL) gasifiers. They are only suitable for solid fuels and can process coals with biomass and/or wastes. The major difference between the two types of gasifiers is that dry ash gasifiers use a much higher ratio of steam to oxygen than the slagging gasifier, resulting in a much lower temperature in the combustion zone (1000 °C) and making the dry ash system more suited to reactive coals like lignites. Moving bed gasifiers can process coals with a relatively high ash content. It is claimed that coals with ash contents of up to 35% can be processed in the Lurgi dry ash gasifiers at Sasol and at the BHEL pilot plant gasifier.

Lump coal (5–80 mm) is fed into the top of the gasifier via a lock hopper system. Processing may be needed to achieve this size as a very fine coal feed will tend to blow straight out of the gasifier. A mixture of steam and oxygen is introduced at the bottom of the reactor and runs counter-flow to the coal. Coal residence times in moving bed gasifiers are of the order of 15–60 min for high pressure steam/oxygen gasifiers and can be several hours for atmospheric steam/air gasifiers. The pressure in the bed is typically 3 MPa for commercial gasifiers with tests realised at up to 10 MPa. Coal enters the top of the gasifier and is preheated, dried, devolatilised/pyrolysed, gasified and combusted while moving towards the bottom of the gasifier. Moisture is first driven off in the drying zone then coal is further heated and devolatilised by the hotter product gas while moving down to the gasification zone where it is gasified by reacting with steam and carbon dioxide. The remaining char is finally completely burnt in the combustion zone where the bed reaches its highest temperature. Maximum temperatures in the combustion zone are typically in the range 1500–1800 °C for slagging gasifiers and 1300 °C for dry ash gasifiers. As the flow is countercurrent, the gas leaving the gasifier is cooled against the incoming feed and typical gas exit temperatures are 400–500 °C. Thus the use of expensive syngas coolers is not required in moving bed gasifiers. Nevertheless, the temperature at the top of the gasifier is usually not high enough to break down the tars, phenols, oils and low boiling point hydrocarbons produced in the pyrolysis zone and carried out with the gasifier product gas. Recent design changes incorporate

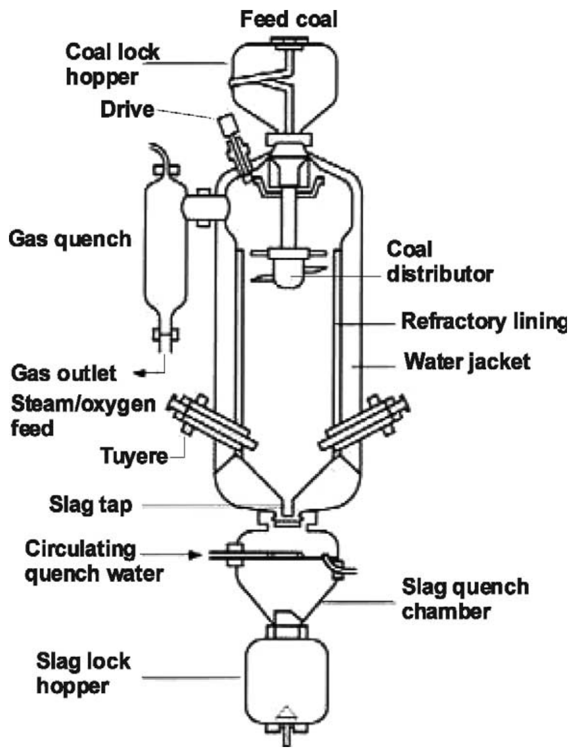

Fig. 2. The British Gas Lurgi Gasifier [22].

recycling which helps to consume these by-products to extinction. Ash is removed either as a dry ash or as a slag, depending on the gasifier type.

In order to ensure efficient heat and mass transfer between solids and gases, good bed permeability is needed to avoid pressure drops and channel burning that can lead to unstable gas outlet temperatures and composition as well as a risk of a downstream explosion. Bed permeability depends among others, on coal particle size, thermal fragmentation, caking propensity and ash fusion temperature. Depending on the gasifier design and other characteristics of coal, such as caking propensity, the tolerance of the different gasifiers for coal fines varies from 5% at the Dakota Gasification plant to up to 50% fines (30–40% solid fines and slurry of up to 30% fines) in the BGL gasifier (Fig. 2). The latter involves cautious screening prior to gasification and possibly briquetting of the fines. Caking coals have to be blended with low caking coals to be processed in the Lurgi dry ash gasifier at Sasol. The BGL gasifier can tolerate strongly caking coals when a stirrer is connected on the coal distributor. Coal ash fusion temperature (AFT) is also a parameter to consider for dry ash and slagging gasifiers. A low ash fusion temperature can result in the formation of fused ash in the ash bed of dry ash gasifiers, hence an ash fusion temperature higher than the maximum operating temperature of the dry ash gasifier is recommended.

3. Gasification for power generation

Fig. 3 shows a schematic of an IGCC power plant, while Table 5 lists the technology suppliers for the major gasification projects worldwide (both for power and chemicals production). As noted above, the majority of the major IGCC projects are based on Shell and Texaco gasification technology [24–26]. There was one IGCC demonstration project using the KRW fluidised bed technology (Piñon Pine) in the USA but this has faced numerous problems since its commissioning and has now been closed [27]. There is also a project in the Czech Republic to develop an IGCC based on the HTW gasification technology to replace old moving bed gasifiers [28]. There is one coal IGCC plant operating with moving bed gasifiers in Germany (Schwarze Pumpe, BGL technology) for the processing of wastes and coal [29].

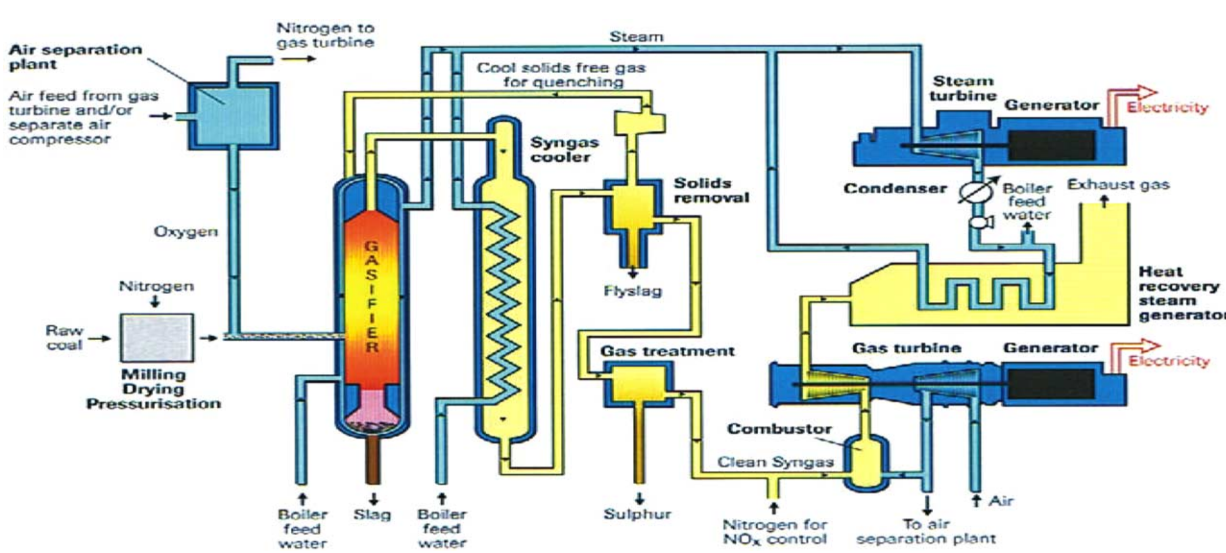

Fig. 3. Schematic of IGCC showing key system components.

Table 6
Details of flagship IGCC projects in Europe and the USA

Project/ Location	Combustion turbine	Gasification technology	Net output MW	Start-up date
Wabash River, IN	GE 7 FA	Global E-Gas (formerly Destec)	262	Oct 1995
Tampa Electric, FL	GE 7 FA	Texaco	250	Sept 1996
Demkolec (now NUON), Buggenum, Netherlands	Siemens V 94.2	Shell	253	Jan 1994
Elcogas, Puertollano Spain	Siemens V 94.3	Krupp-Uhde Prenflo	310	Dec 1997

The ‘flagship’ coal based IGCC projects for Europe and the USA are shown in Table 6, which lists the gasifier and gas turbine technology choices.

In overall terms, the development of the IGCC market has been driven by the need to gain added value from refinery residues and this is indicated in Fig. 4, which shows the size and commissioning dates for the major IGCC projects worldwide. This indicates that while the initial IGCC project was coal-based the great majority of the more recent units have been built to utilise the refinery residues. A more detailed assessment of IGCC deployment on a geographic basis is provided below.

3.1. EU situation

In the EU, many companies have actively been developing IGCC technology. The following ‘commercial’ power projects are either in operation or under development:

- *Buggenum, Netherlands*, firing coal only (plus some part biomass trials). This is a 283 MW electric power plant that uses Shell gasification technology. It has been in operation since 1994 [30,31].

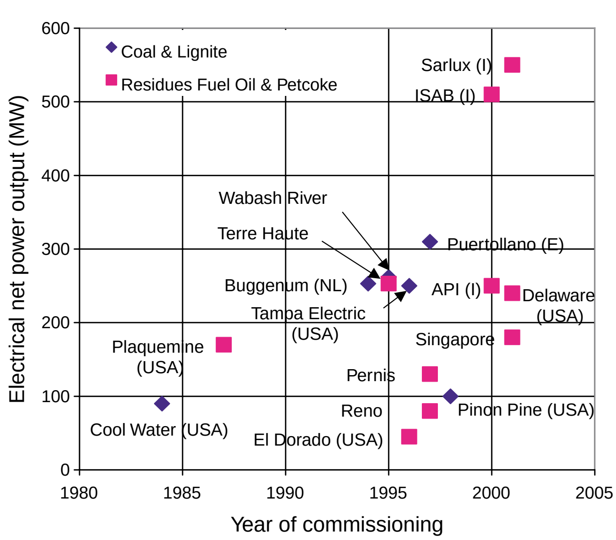

Fig. 4. Deployment of IGCC units.

- *Puertollano, Spain*, a 335 MW e IGCC demonstration plant firing a 50:50 blend of petroleum coke and coal (Fig. 5). The project received a subsidy from European Commission’s Thermie programme with a grant of 50 million ECUs (∼$60 m). The project uses a PRENFLO entrained-flow system with dry feeding, supplied by Krupp Uhde [32– 37].
- *Shell Pernis Refinery, Netherlands*. This project uses Shell gasification technology to convert vacuum cracked residue and asphalt to electricity. It has a total capacity of 1650 T/d residue and produces 130 MW of electricity [24].
- *Sarlux, Italy*. This project gasifies 3424 T/d (3771 short-t/d) of visbreaker residue to produce steam, 550 MW of power, and hydrogen in a Texaco gasifier at the Saras refinery in Sarroch, Cagliari [38].
- *ISAB, Italy,* uses a Texaco quench gasifier to convert 130 T/h of de-asphalter bottoms from the ISAB refinery in Priolo Gargallo, Siracusa, Sicily, to produce a nominal 510 MW of power [38].
- *API, Italy*. This project uses a Texaco gasifier to gasify 1335 t/d (1470 short-t/d) of visbreaker residue from the API refinery in Falconara to produce steam and 280 MW of power [39].
- *Schwarze Pumpe, Germany,* converts a mix of 450, 000 T/annum of solid waste, and 50,000 T/annum of liquid wastes into electricity, steam, and methanol feedstock using four solid-bed gasifiers made by a variety of manufacturers, and firing visbreaker residue [29].
- *Sulcis, Italy,* in development for a 450 MW e coal-based power plant using the Shell gasification technology. The plant will be in operation in 2005 [40].
- *Agip, Italy,* in development for use of high-viscous bottom tar from a visbreaking unit and produce clean syngas for a power generation unit, where it will be co-fired with natural gas. The plant will use Shell gasification technology and is planned to be in operation in 2004.
- *Piemsa, Spain,* commissioning for 2004/2005 is planned for this IGCC complex that will use refinery heavy stocks to produce 784 MW of net power, hydrogen, sulphur and metals concentrate using Texaco gasification technology [41,42].

3.2. USA situation

Thirty-eight gasification projects are either in operation or at the planning stage within the USA. Of these, eight are based on coal (of which it is known that three use bituminous coal, one uses anthracite culm and one uses lignite coal). Half of the projects produce chemicals as their primary products; the others produce electricity. Only 4 of the 19 plants that produce chemicals use coal as their feedstock. More than one-half of the gasifier projects in the USA use the Texaco gasification technology, although almost every gasifier type that has been developed has been tested [10].

Six of the IGCC projects for electric power have received financial incentives from the US government, mostly capital to buy-down the cost of the equipment. These are:

Fig. 5. ELCOGAS 335 MW e IGCC plant at Puertollano, Spain.

- Polk County IGCC project (funded under the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) Demonstration program) [43].
- Wabash River Energy Limited (funded under the CCT program) [44,45].
- Pinon Pine IGCC Power Project (funded under the CCT program) [27].
- Kentucky Pioneer Energy AFT-IGCC project (funded under the CCT program) [46].
- Calla IGCC plant.
- Boise Cascade project.

4. Gasification for non-power applications

Chemical gasification plants based on entrained flow and more especially on moving bed technologies are at present operating all over the world, with the biggest plants located in South Africa (Sasol).

4.1. EU situation

In the past, there was considerable interest in Europe in the gasification of coal to produce syngas to be used either as a fuel or as a feedstock (e.g. in chemicals production). However, with the major switch to natural gas, that interest has declined as the near-to-medium-term market prospects are limited. A variety of technologies have been developed in Europe to either demonstration or commercial scale. For example, Lurgi offers a circulating fluidized bed (CFB) gasification technology, which is suitable for the treatment of brown coal/lignite. Such CFB type gasification technology can also be offered by Foster Wheeler (Finland/USA). The Rheinbraun Winkler/HTW bubbling fluidised bed coal gasification (FBG) technology is established at demonstration scale in Berrenrath, Germany for the production of methanol and synthetic raw gas from brown coal. Recently, the emphasis has been on trying to establish the technology for IGCC power production, with EC financial support being offered for a demonstration plant in Eastern Europe [28].

4.2. USA situation

The chemicals-producing gasification projects in the USA are largely located at petrochemical plants, refineries, gas plants and chemical plants. They produce a range of important products including: acetic anhydride, ammonia, hydrogen, methanol, oxychemicals, synthetic gas, and diesel fuel. Most are located in Texas and Louisiana where many of the refineries and chemical plants in the USA are located [1].

4.3. South African experience

One variant on chemicals production that is well established in South Africa is the use of gasification for the production of syngas as a feedstock for liquefaction. Thus South Africa has an industry that produces 40% of its gasoline and diesel fuel using modern liquefaction technologies. It has had a synthetic fuels industry since the 1950s when Sasol Limited was created by the South African government to reduce the country's dependence on imported oil by making liquid fuels from coal via gasification and subsequent liquefaction of the resulting fuel gas. The gasification technology in use is the Lurgi dry ash system [47–49].

Sasol has the capacity to produce 150,000 b/d of liquid fuels [47]. In 1987, as part of a complementary initiative, the South African Government approved the Mossgas project for the production of synthetic fuels from offshore natural gas [3,4]. Two years later, Mossgas (now PetroSA) was established and production began in 1993. The Mossgas project involves extracting natural gas and associated condensate (unrefined petrol and diesel) from two offshore fields, delivering it to the offshore drilling and production platform and separating the gas from the condensate. PetroSA then delivers both substances to the onshore refinery near Mossel Bay through a 90-km pipeline and converts them to high quality diesel and gasoline, liquid petroleum gas, kerosene and alcohol using the Sasol process obtained under licence. PetroSA has the capacity to produce 45,000 b/d of liquid fuels.

5. Coal gasification R, D&D needs and challenges

This section provides information on the continuing R, D&D activities needed to develop and establish gasification both for direct power generation and also for the supply of gas for other applications, e.g. hydrogen production to support fuel cells and transport.

5.1. Overview of R, D&D needs

It is generally recognised that IGCC represents a primary option for efficient, environmentally compatible electricity production using coal resources [50,51]. Indeed, it is capable of providing the cleanest coal-based power production process, to standards well beyond current environmental requirements. However, the major problems for coal fuelled IGCC are the capital cost, and the present uncertainty concerning its operational track record. Thus, further R&D and commercial scale demonstrations are required to take forward the commercialisation of the technology. This must include the introduction of more efficient and flexible designs incorporating improved components together with advanced gas turbines. At the same time it is essential to recognise that IGCC offers several strategic opportunities above and beyond the very important prospect of providing the cleanest generation of power from coal.

First, there is increasing interest in the option of IGCC as a source of syngas for chemicals production, not just from coal but especially in the petrochemical process industry from opportunity feed-stocks such as coke and refinery residues [52]. Within such a framework, for coal, its use as a raw material to produce hydrogen may provide a major impetus to establish the technology, provided that the use of hydrogen as a transport fuel can be fully established. This opens up the prospect of multi-product IGCC systems, producing electricity and hydrogen, fired on coal in conjunction with other opportunity fuels as circumstances permit. From a strategic perspective, in Europe and the USA it is recognised that any transition towards a hydrogen based economy will depend on fossil fuels for the production of hydrogen for some considerable time.

At the same time, when hydrogen is produced via IGCC the resulting by-product is a concentrated stream of CO_2. Consequently, IGCC is the technology of choice when CO_2 capture is required since, in contrast to combustion applications, the capture step can be integrated within the overall process. As such in the medium to long term, IGCC offers a very significant prospect for the most cost effective means for providing a near zero emissions power generation technology based on coal and other fossil fuels. Indeed, the USDoE and others identified that IGCC plants also offer significant opportunity for the effective capture and sequestration of carbon dioxide, compared to other clean coal technologies [53,54].

Ultimately, if IGCC is to move forward, there is a strong need to establish state of the art units that can demonstrate the design and performance improvements that have been established via studies and smaller scale testing. In this way, there is scope to show that the problems that dogged the early demonstration units have been overcome. The timescale for such demonstrations need to be compatible with the timescale for introducing new coal fired plant into the power generation mix.

In Europe, for example, the projections suggest that in the EU-15 alone over the period to 2030, some 550 GW of new generation plant will have to be installed, to meet new demand, and to replace ageing power stations. The prevailing view is that the future energy needs of the enlarged EU will be so significant that the full range of available fuels (including renewables, nuclear, natural gas and coal) will have to be utilised to meet the demand. This presents two problems:

- The new plant that is to be built will itself have a lifetime of about 40 years and so will be operating during the onset of the transition away from oil and gas, and with the associated price increases that will inevitably occur;
- The scale of operations, costs, and the need for reliability in the new plant, will make it difficult to accommodate the large-scale introduction of new, unproven and essentially small-scale energy technologies such as biomass, wave or tidal power.

Consequently, a very large proportion of this new and replacement plant will have to be coal fired. However, such plant will need to achieve a much higher environmental performance than existing units in order to meet future EU environmental standards. At the same time, if the need to achieve near zero emissions is factored into the deliberations then by, say, 2020 it will be necessary to have available coal fired technologies with integrated CO_2 removal processes.

This suggests that the prime need is to ensure that gasification technology can achieve high efficiency with proven reliability at acceptable capital cost. The key requirements over a 5–10 year timescale include:

- Gasifier component development, including improved materials of construction for refractories and HRSGs, improved feeding and handling systems.
- Gas turbine combustor development to ensure the efficient use of hydrogen rich fuels.
- Ancillary component development, including lower cost air separation units.
- Complementary design and optimisation studies, including full integration of CO_2 capture.
- Associated level playing field techno-economic studies, taking into account the global market possibilities.

Beyond this, over the 10–15 year period, strong consideration must be given to technology demonstration, with the possibility that this could include CO_2 capture and storage.

5.2. R, D&D in USA

IGCC system development has been and continues to be a very important component of the US DoE Fossil Energy R, D&D programme for more than 20 years. Between 1978 and 1999, the USDoE invested more than US$2.4 billion on gasification, which was focused primarily on coal as a fuel. Of this, about 50% was committed to demonstration and commercialisation of technology, and $600 million was committed in the 1990s to the demonstration of three near-commercial IGCC technologies within the Clean Coal Technology partnerships. Except for an early $13 million investment supporting the commercial-scale Great Plains gasification facility in North Dakota, the remainder was used for basic component research, bench scale and pilot plant testing of process components. The DoE investment in demonstration and commercialisation has amounted to about one-half of the cumulative IGCC budget since 1978. The parallel industrial investment in development of IGCC technology, including the investigation of gasifier options over approximately the same period, is estimated to be about $2.2 billion [55,56].

This joint DoE/US industry initiative established certain modern technology variants for the gasification of coal and other fossil fuels for commercial applications worldwide. For power generation applications, the concept of thermally efficient and environmentally benign electricity production from different kinds of coal in an IGCC system has been demonstrated at a commercially viable level using three different gasification technologies, although as noted above the economics need further support. That said, thermal efficiencies up to the mid-40% range have been achieved, while achieving air pollution emissions a small fraction of US New Source Performance Standards, with recovery of sulphur as a commercial by-product. Emissions of air-toxic compounds have been minimal, contaminated water discharges negligible, with solid wastes produced as vitrified material impervious to leaching in storage.

This has not only represented a long-term investment in coal-fueled energy options, but now represents an important option in DOE's Vision 21 programme for the development of advanced power generation systems for commercial applications beyond 2015 [57,58]. This is the US DOE long-term initiative for developing the technology needed for ultra-clean fossil fuel-based energy plants. It is a cost-shared partnership between industry, academia and government, and it is based on three premises:

- The USA will need to rely on fossil fuels for electricity and transportation fuels well into the 21st century.
- It makes sense to rely on a diverse mix of energy resources rather than on a limited subset of resources.
- Better technology can make a difference in meeting environmental needs at acceptable cost.

The ultimate aim is to effectively remove all of the environmental concerns traditionally associated with the use of fossil fuels for producing electricity, transport fuels, and chemicals, and to achieve this through an intensive, long-range (15–20 year) research and development effort that stresses innovation and technology commercialisation. The intention is to develop the technology basis for energy plants with unprecedented efficiency and near-zero environmental impact, for a diverse mix of energy resources, and to leapfrog performance improvement.

Specific types of plant and plant configurations are not emphasised because it is not known what kinds of plant, feedstocks, and products the market will favour in 15–20 years time. However, a series of technology roadmaps has been produced that provide a breakdown of each key Vision 21 technology into its principal R&D areas, combustion, gasification, air separation, gas purification, gas separation, CO_2 sequestration, fuels and chemicals, fuel cells, turbines, advanced materials, systems integration, sensors and controls, and computational modelling and virtual simulation.

The Vision 21 approach commits the stakeholders and the DOE to a long-term, focused strategic R&D programme. It removes the environmental barriers to fossil fuel use and so expands the energy options for the USA. In addition, because near-zero emissions will be achieved independently of fuel type, the integrated use of energy resources is encouraged to maximise efficiency and minimise environmental impact and cost.

Within this activity, a further initiative, FutureGen, has been established [59,60]. The FutureGen programme is aimed at the development of a 275 MWe coal-fuelled IGCC power station, which includes the demonstration of integrated hydrogen production and of CO_2 separation and geological sequestration. It has a nominal budget of $1 billion, and the Federal contribution is to be about 80%. The USDoE expect to see a major return on investment through sales and worldwide exports of US power plant equipment.

The intention is to design, construct and operate a plant at a scale capable of producing 1 million tonnes of CO_2 for validation of the integrated operation of IGCC and the receiving geological formation. At least 90% abatement of CO_2 will be required, with the potential for nearly 100% removal. The associated aims include determining the safety and permanence of CO_2 sequestration, technologies standardisation together with protocols for CO_2 monitoring and verification. The economic targets include:

- Electricity costs to be no greater than 10% compared to non-sequestered systems;
- Hydrogen wholesale price to be no greater than 4.00 US$ million Btu, which is equivalent to 0.48 US$/gallon of gasoline.

5.3. R, D&D in Japan

Japan has been experimenting with gasification for many years with the technology approaching commercial scale. The major coal gasification developments in Japan have been based on fluidised bed and entrained flow technologies [60–65].

For power generation, a consortium of nine Japanese power companies, the Electric Power Development Company Ltd, Clean Coal Power R&D Co. Ltd, and the Central Research Institute of Electric Power Industry are undertaking a significant IGCC Project. All have agreed to build and operate by 2009 a 250 MW air-blown dry feed gasification plant. The project will be part financed by a subsidy from the Agency of Natural Resources and Energy (30% of the cost), with the other named participants providing the balance.

In addition to using IGCC for power generation, coal gasification technology is being developed for industrial use. These include:

- Hydrogen production technology using coal. This technology is in the early stages of development. However, plans are to accelerate development to complete pilot plant testing by around 2010 so that demonstration and commercial units can be put into place by 2015 and 2020, respectively.
- *Hydro-gasification technology*. Under the New Sunshine Plan, the first phase of this development program was completed in 2000. Plans are to continue research and development aiming at commercialisation of the technology before 2020.
- Multi-purpose coal conversion technology (Entrained-Bed Coal Flash Pyrolysis). During 1996 – 1998, design, manufacturing, installation and cold test runs were completed. Plans are to develop a commercial version of this technology by around 2010.

5.4. R, D&D in Europe

Within Europe, there has been significant development, to the commercial prototype phase, of various gasification technologies and overall gasification combined cycle systems, with funding via industry, various nation states and the European Commission. The demonstration at the commercial prototype scale of two coal-fuelled variants of the entrained bed concept has been undertaken via Buggenum, The Netherlands, and Puertollano, Spain (the latter with funding from the EC Thermie Programme within earlier Framework Programmes).

There has also been significant R&D effort supported by the EC and ECSC (now carried forward under the Research Fund for Coal and Steel) for various added-value activities for the various concepts. In overall terms, such R&D work splits into several types of activities:

- Component development for overall system integration [66 – 72];
- Supporting R&D for demonstration activities in the EU [73,74];
- Generic activities to characterise fuel behaviour and environmental performance [75 – 78];
- Techno-economic studies examining system variants [79 – 82].

Based on much of this development work, the European Commission supported various techno-economic cycle studies that were focused on the Puertollano plant. These showed that the design efficiency could be readily increased to 46.8% from the 45% design specification [79–82]. This could be achieved by increasing the turbine inlet temperature (TIT) from 1120 to 1190 °C and by improving the heat recovery steam generator and steam cycle. It was also shown that a further raise in TIT to 1250 °C, in line with state of the art units as of the mid 1990s, could raise the overall efficiency by a further 1%–48%. These studies were continued, with the objective of modelling the benefits of a major system redesign. On the basis that world-market coals were used as the feedstock, these showed that 51.5% should be readily achievable at a specific plant cost of ~1100US$/kW. It was suggested that a coal based IGCC could attain efficiencies up to ~58% with a TIT of 1400 °C ISO, reheating of the gas turbine, optimised humidification, hot gas clean up, supercritical live steam in a bottoming steam cycle, and staged gasification with chemical quench. It was also noted that with a solid oxide fuel cell as a topping cycle, even higher efficiencies should be possible.

More recently, the Commission has provided only limited support for IGCC development although there is a limited programme for the development of IGCC towards a near zero emissions technology via H_2 shift and CO_2 capture. However, there has not been scope for support for the R&D required to improve IGCC efficiency and overall operational performance combined with a reduction in capital costs.

However, the drive for reduced oil-dependence and pollution in the transport sector has created a great deal of support for the development and establishment of the so-called Hydrogen Economy. The difficulty with this concept is that hydrogen is not actually a fuel, but rather an energy vector, and as such must be manufactured from other sources. While there has been much interest in hydrogen from renewable sources, there are inadequate resources available to make a significant impact.

In contrast, as noted above, coal gasification is an established route to the production of hydrogen and there is considerable potential for the concept of multi-faceted hydrogen-producing IGCC plants. If such high efficiency units were established with integral CO_2 capture and storage, they would represent a major step towards the introduction of hydrogen as an energy vector into the EU economy and elsewhere. This is, in part, the rationale for the Hypogen Project, which in overall terms is designed to encourage the development of the infrastructure, networks and knowledge needed to get a genuine hydrogen economy up and running. This includes the possibility of a demonstration of hydrogen and power production form fossil fuels, which would be undertaken via a phased programme ultimately leading to a demonstration of a commercial prototype IGCC system.

6. The way forward

At present coal fired IGCC is not the technology of choice for power generators since it is deemed to be a more expensive fossil fuel technology compared to alternatives. Thus in the near term, when coal fired systems are introduced, it is likely that there will be an emphasis on pulverised fuel systems with best practice NO_x and SO_2 control and advanced steam conditions. There will also be a significant market for CFBC again with advanced steam conditions. However, from a longer-term strategic perspective IGCC is seen as the more promising route towards near zero power generation. This vision will only be achieved if in the first instance the technology can achieve an improved operational track record for a lower capital cost system. There are clear R&D requirements needed to achieve this position. Ultimately, there is a need to establish commercial prototype demonstrations of IGCC technologies that can achieve the performance required by the market. Such an IGCC will need to demonstrate reduced energy use and capital cost with improved operational flexibility. There will need to be integrated CO_2 separation from fuel gas that has undergone a hydrogen shift stage. Alongside this will need to be gas turbines that can utilise hydrogen as the fuel gas while still meeting all necessary performance requirements. For example, such a demonstration should use coal, maybe in combination with other low-cost and readily available fuels. It should be designed to produce electricity, heat and synthesis gas. The plant should be located near an industry that could use the synthesis gas to produce high valued chemical by-products, such as hydrogen, ammonia and methanol. At the same time such a demonstration would provide the means to showcase the integrated capture and utilisation or sequestration of some of the carbon dioxide that is produced. The timing for this activity is probably 15–20 years although there may well be opportunities that might arise, which could allow the timings to be advanced.

Especially in the USA, there is a strong R, D&D programme in place to take forward such concepts, while Japan is also pursuing a long-term perspective for such technology development and demonstration. In Europe, although there are many coal and refinery residue fuelled units, there has not been a significant programme to take the technology forward, However, that situation may well be changing with the recognition that coal based gasification may offer the most promising route towards the establishment of a hydrogen based economy.

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