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Opportunities for development and deployment of coal-based gasification for both power and combined heat and power, fuel cells, production of chemicals, and specialist products

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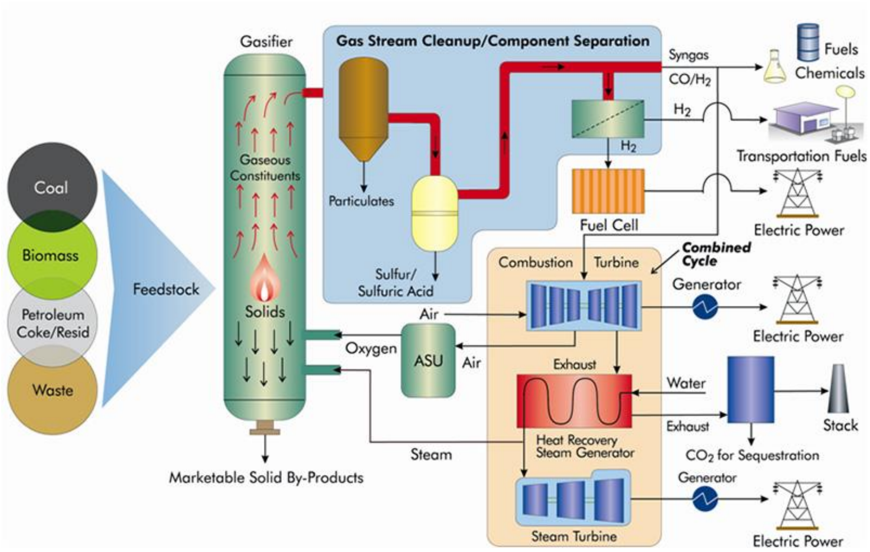
I. Introduction

1. Gasification is a technological process that can convert any carbon-based raw material such as coal, biomass and organic wastes into fuel gas, also known as syngas (netl, 2021). Gasification typically takes place in a high temperature pressure vessel where oxygen (or air) and steam are directly contacted with the coal or other feed material, that results in the formation of a syngas and ash/slag residues. Syngas mostly comprises carbon monoxide (CO) and hydrogen (H_2), together with minor quantities of methane and water vapour that can be removed. The CO/H_2 mixture can either be used directly for various applications or reacted with additional steam over a catalyst in a water-gas-shift reactor to produce hydrogen and carbon dioxide (CO_2). These two products can be readily separated to produce concentrated gas streams of a valuable clean energy source and a high carbon gas that can be either used in various processes or stored in geological formations.

2. Options for utilising either the original syngas or the hydrogen end-product include power generation, combined heat and power, production of a wide range of products such as fertilisers and ammonia as well as gasoline and diesel fuel. Within one plant it is possible to make a range of such products as well as produce power, which is known as poly-generation, and is uniquely possible with gasification technologies. Figure I provides a conceptual representation of a gasification process for coal, depicting both the feedstock flexibility inherent in gasification, as well as the wide range of products and usefulness of gasification technology.

Figure I
Gasification options for power and products production (netl.doe, 2021)

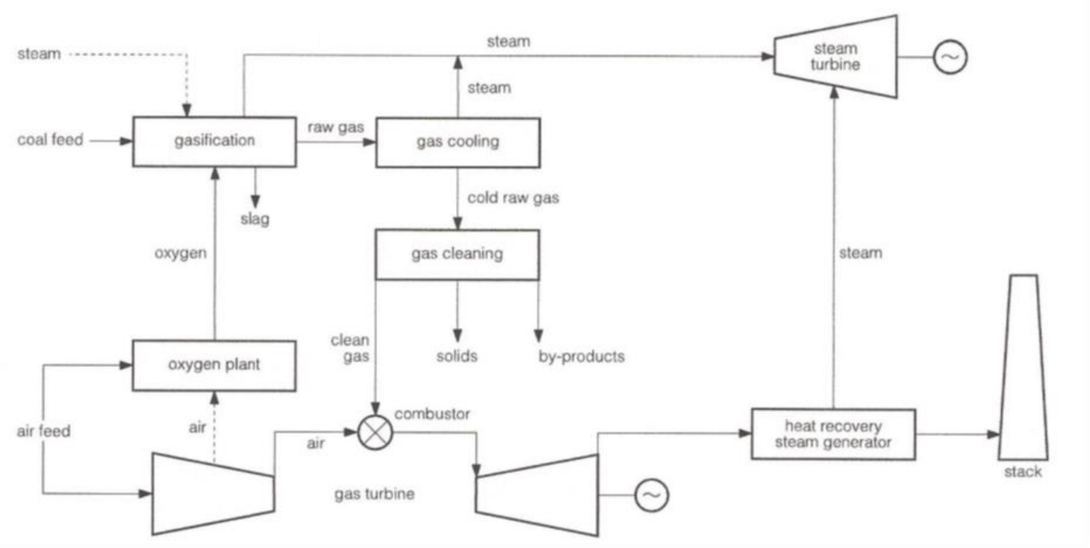


II. IGCC for power production/combined heat and power: technology development and deployment status

A. Industrial applications

3. In an integrated gasification combined cycle (IGCC), the carbonaceous feedstock is gasified and the syngas produced (mostly comprising CO and H_2) is purified to remove gaseous pollutants and particulates before being fired to drive a gas turbine. Heat recovered from the gas turbine exhaust gas can be used to raise steam to drive steam turbines that raise additional power (Figure II). It is also possible to use the lower grade heat for industrial and domestic heating applications, although this requires considerable infrastructure for piping hot water to factories and apartment blocks.

Figure II
Simplified schematic of a coal based IGCC power generation process (Henderson 2008)



B. Coal gasification technology options

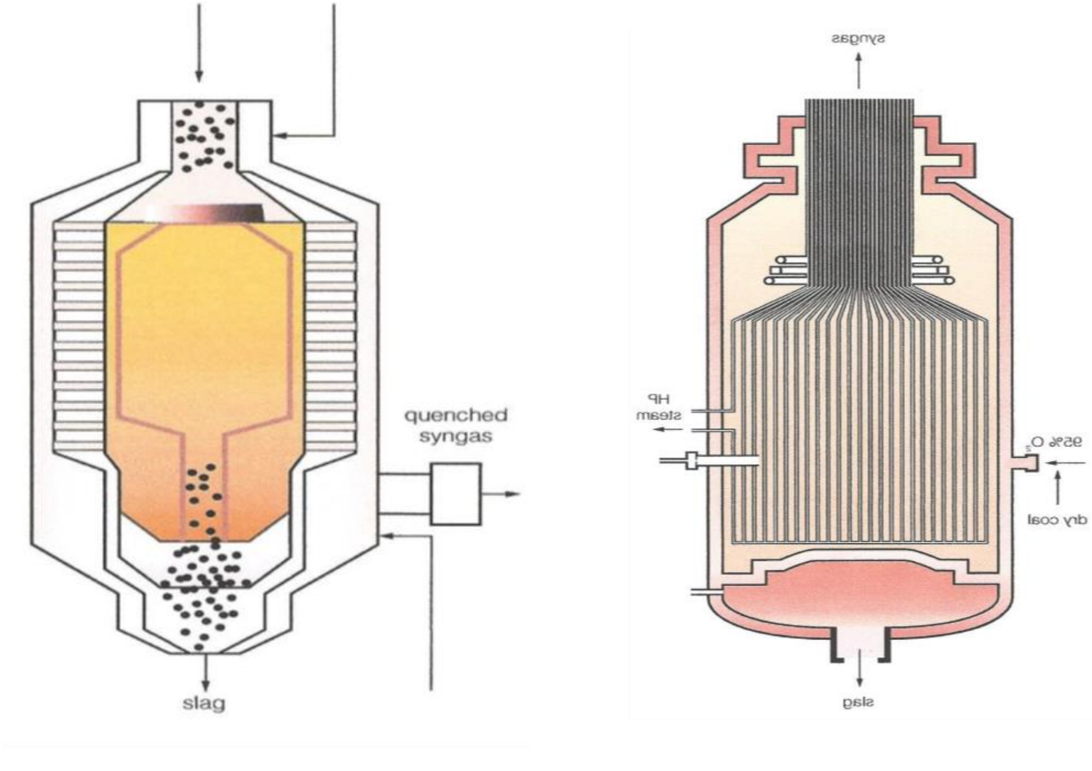
4. The IGCC technology is complex. It includes various key subsystems, all of which can influence the overall efficiency and other performance-related characteristics, such as cost and reliability. These are:

- choice of gasifier
- gas cleaning approach
- oxygen production unit
- gas turbine system
- syngas cooler, heat recovery steam generator, steam turbine cycle
- CO_2 capture systems based on a water-gas-shift reactor to produce hydrogen (not shown in this figure).

5. Of these, the gasification system is the novel component since all other systems listed are proven technologies, albeit for other applications. There are three main types of coal gasifiers, namely entrained flow, moving bed, and fluidised bed, which differ in relation to what rank of coals they are most suitable for, whether the ash conditions are dry or slagging, the size of the coal feed and the type of feed system, whether the oxidant is oxygen or air, how the slag is handled and the operating pressure, temperature and the exit gas temperature (Fernando R, 2008).

6. Most IGCCs incorporate entrained flow gasifiers because of their fuel flexibility, their production of high- pressure steam, and the lack of tars in the product gas. These operate in slagging mode, at high temperatures between 1200°C and 1600°C with pressures typically around 2.5 MPa, so that the coal ash is liquid, while almost all are oxygen blown (Figure III). The gases exiting the gasifier require significant cooling before being cleaned. The two methods of cooling the gas are either to use a high temperature syngas cooler (e.g. Shell) or to quench with water (e.g. GE).

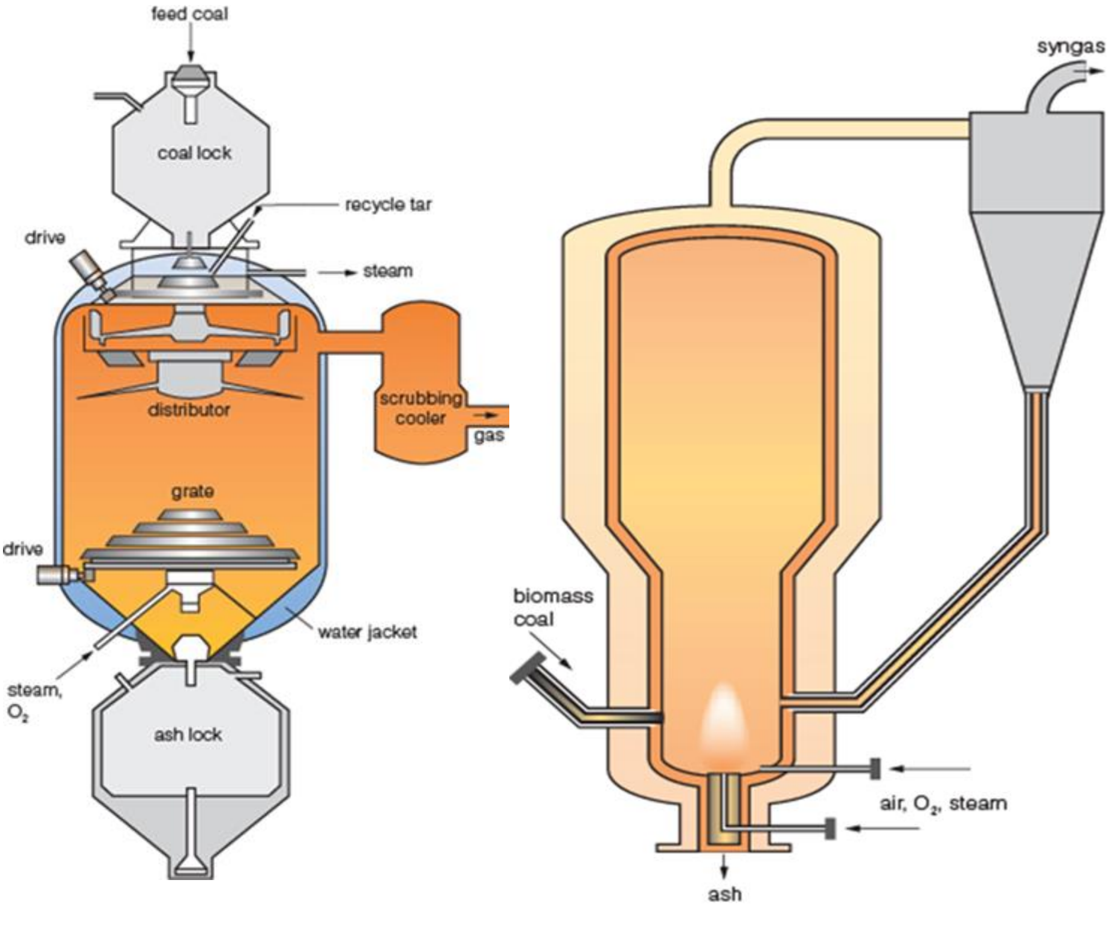
Figure III
Examples of a Shell dry feed entrained flow gasifier and a GE slurry fed entrained flow gasifier (netl, 2013b)



7. Entrained flow gasifiers can be used to gasify all coal types regardless of coal rank, caking characteristics and proportion of fines, although feedstocks with lower ash contents are preferred to achieve high operational efficiency at acceptable capital cost. The slag viscosity must be sufficiently low to enable the slag to flow down the walls of the gasifier. The residence time is only a few seconds, which enables high-load capacity but requires the coal to be pulverised to <0.1mm. The reactors operate at a uniformly high temperature to ensure high carbon conversion and produce a syngas free of tars and phenols. There is a relatively large oxidant requirement and there is a large amount of sensible heat in the raw gas. The high operating 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.

8. Another variant is the moving bed gasifier where lump coal is fed through the top of the unit while the oxygen and steam are introduced at the bottom. The gases flow upwards through the bed of coal and the ash, either dry or as a slag, is withdrawn through the bottom. There are two technology variants, namely the Lurgi-Sasol dry bottom and the British Gas/Lurgi slagging systems.

Figure IV
Schematic of the Lurgi-Sasol dry bottom gasifier and a U Gas fluidised bed gasifier (NETL 2013a and 2013c)



9. The Sasol-Lurgi dry bottom gasifier comprises a double-walled pressure vessel, operating at 3MPa, in which the space between the walls is filled with boiling water (Figure IV). This enables intensive cooling of the walls while generating steam. The oxygen and steam enter the reactor at the base and are distributed across the bed by a grate, while lump coal is introduced at the top. The coal must be non-caking with a size range of 5–50 mm so that the oxidants flow freely through the reactor. The gasifier uses a high ratio of steam-to-oxygen, which keeps the temperature in the combustion zone at about 1000°C, i.e. below the ash fusion temperature. The high level of steam produces a high H_2 to CO ratio in the syngas. Due to the lower temperature, the process is most suited to reactive coals. The gases leaving the gasification zone enter the upper zones of the reactor where the incoming coal is dried,

preheated and devolatilised. In the process the syngas is cooled from about 800°C to about 550°C at the reactor outlet. The ash is removed in a revolving grate and depressurised in another lock hopper. The ash is cooled by the incoming oxygen and steam to 300°C to 400°C. The relatively low outlet temperatures result in relatively high concentrations of methane, tars and phenols in the outlet syngas. It is necessary to quench the outlet of the reactor so that the unwanted hydrocarbons and dust are washed out. The liquor resulting from the quench is first treated by mechanical tar separation, followed by an extraction process in which raw phenol is recovered. Sour gas and ammonia are then selectively stripped out.

10. The British Gas/Lurgi (BGL) technology is a slagging version of the Lurgi gasifier that is suitable for coals with low ash melting points while able to accept both lump and fine coal. Compared to the Lurgi gasifier, the BGL gasifier has an increased CO yield and increased reactor throughput. There is a higher conversion efficiency from coal to syngas, with lower steam consumption. The mineral matter is removed as a non-leachable glassy solid (Collot, 2002). There is no fly ash produced and the slag is a dense glassy frit, which is non-leachable, encapsulates the trace elements and is suitable as a building material. Unlike in an entrained flow gasifier, the BGL gasifier does not produce high pressure steam because heat recovery essentially takes place between the product gas and the coal bed. This makes it appropriate for the generation of syngas to produce chemicals, since steam is not needed.

11. There is also a fluidised bed gasifier option (Figure IV) that can comprise either bubbling or circulating technology, in which the fuel is gasified in a bed of hot non-combustible particles suspended by an upward flow of fluidising gas. The bed comprises a mixture of sand, coke, char, sorbent or ash, depending on the application. Crushed coal, in the size range 0.5–5 mm, enters the side of the reactor while the steam and air or oxygen enter mainly at the bottom and fluidise the bed. The residence time of the feed in the gasifier is typically between 10–100 seconds. High levels of back mixing ensure a uniform temperature distribution in the gasifier. These gasifiers operate at temperatures below the ash fusion temperatures of 900–1050°C to prevent ash melting, to avoid clinker formation and the loss of fluidity in the bed. They are air based. The low operating temperatures can result in incomplete gasification and the char particles entrained in the raw gas leaving the gasifier are usually recovered by a cyclone and recycled back to the gasifier. These operating temperatures also mean that fluidised bed gasifiers are most suitable for relatively reactive fuels such as lignite and biomass. The sizing of the particles is also important. If the material is too fine, it will be entrained in the syngas and leave the bed though it should be partially captured in the cyclones and returned. The quantity of char drained from the gasifier bed and the carbon in the filter dust escaping the gasifier and cyclone affect the upper limit of carbon conversion.

12. The operation of fluidised bed gasifiers is affected by many factors including coal properties, in particular the reactivity of coal derived char which must be sufficiently high. Rapidly decreasing reactivity of char as gasification progresses is a major issue that needs to be overcome to improve carbon conversion in these gasifiers. Hence reactive coals such as brown coals, lignites, subbituminous and to an extent high volatile bituminous coals are usually recommended for fluidised bed gasifiers. The mineral matter in the coal forms a major constituent of the bed material and hence coal ash characteristics can impact gasifier operation.

C. Status of IGCC global deployment

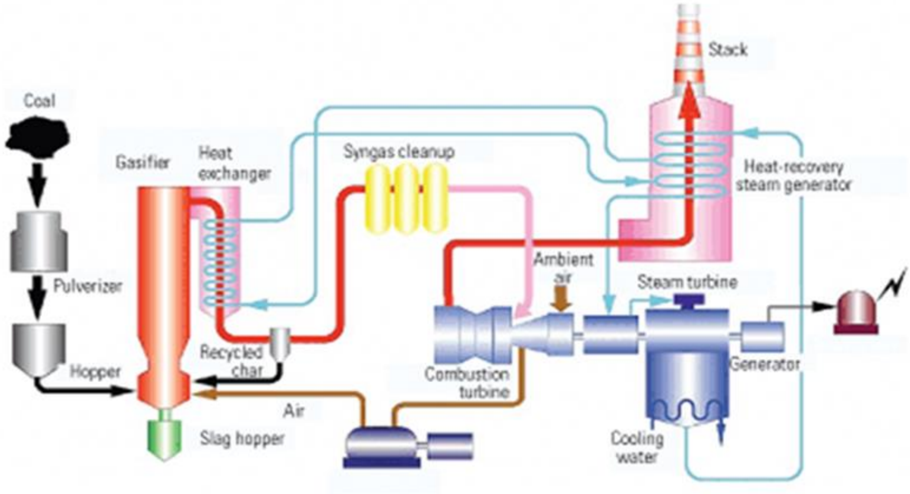
13. To date, the number of coal gasification power plants that have been deployed is very limited, reflecting in part the conservative nature of the power sector and the concerns that first of a kind units carry additional costs that will make them less attractive than modern coal fired combustion units. From 1994 through to 2016, seven commercial scale demonstration units (Buggenum, The Netherlands; Wabash River, USA; Polk Power, USA; Puertollano, Spain; Nakoso, Japan, Coolgen, Japan: Huaneng, China), one industrial pilot unit (EAGLE, Japan), one retrofit (Vresova, Czech Republic) and one commercial unit (Edwardsport, USA) were established.

14. Subsequently the Nakoso 250 MWe unit was put into full commercial operation while two scaled-up plants, each of 540MWe, based on the Nakoso design are being constructed.

15. These demonstration units featured various gasification technologies based either on oxygen or air operation, a range of environmental control techniques and gas turbine systems, with various levels of system integration. In all but the latest units (Nakoso, Edwardsport and Huaneng) there have been various technical issues that needed addressing to achieve acceptable system reliability and associated operational availability. In summary, gasification-based coal power plants have complex operational set-ups. Thus, higher degrees of integration favour higher thermal efficiency but such designs require long start-up times, as individual process areas need to be brought on-stream in correct sequence, and some flexibility is lost in comparison with less integrated, lower efficiency designs. Partial integration is favoured for future designs as it gives more rapid start-up and greater operating flexibility, while maintaining the efficiency advantage of gas turbine air extraction.

Figure V

Nakoso 250 MWe IGCC demonstration plant (Mitsubishi Power, 2021)



III. Gasification for CHP applications

Background

16. In many industrialising nations, the traditional means for heating domestic dwellings, typically tower blocks, and industrial premises was by using the residual heat from a coal fired power plant. This required major infrastructure to be built for transporting the low-grade steam from the power plant to the domestic and industrial locations. However, while such arrangements showed higher system efficiencies than the power-only systems, the actual distribution of energy was often not effective with little scope for individual control of the energy supplied.

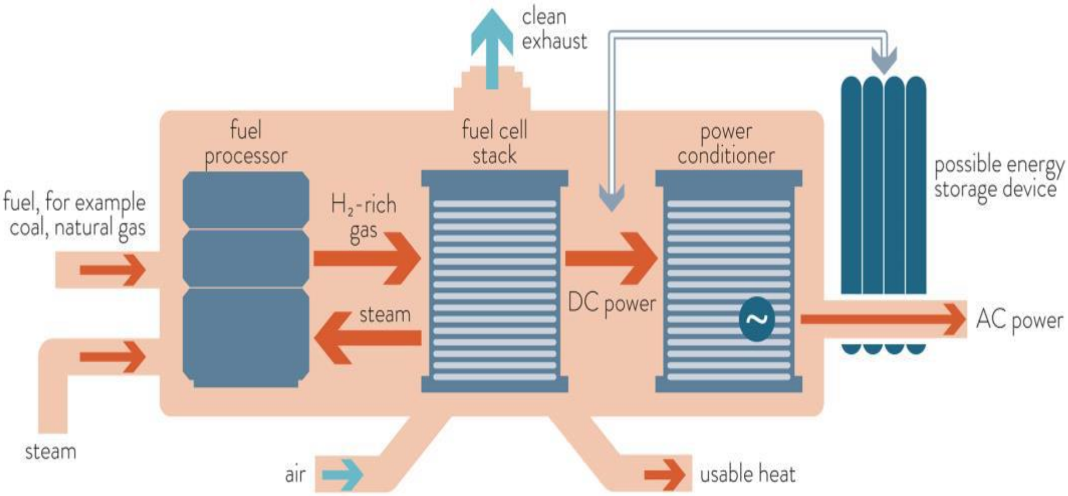
17. There has been a drive to establish Combined Heat & Power gas fired options, typically based on gas fuelled reciprocating piston engines, often driven by either natural gas, liquified petroleum gas or biogas. In such systems, the CHP engine drives an alternator to generate electricity while the heat from that engine is recovered and made available as hot water or steam. Such an approach gives a high operational efficiency. However, in such carbon constrained times, there are concerns about the use of all fossil fuels with consequent demands to limit coal and gas for further energy applications. This is too simplistic a view since there are means to utilise both coal and gas with close to zero carbon emissions while still achieving high efficiencies.

IV. Potential role for fuel cells under development

18. One approach under development is hydrogen powered fuel cells that electrochemically convert chemical energy in fuels into electrical energy (and heat) and can produce power efficiently with low environmental impact. Applications for fuel cells include large scale stationary power generation, distributed combined heat and power (CHP), and portable power, based around various fuel cell options (Zhang, 2019).

Figure VI

Schematic of a fuel cell power system (Nehrir and Wang, 2016)



19. Fuel cells are electrochemical devices that convert the chemical energy of the reactants directly into electricity and heat with high efficiency. They generate electricity continuously, provided there is a source of fuel. The one-step nature of this process from chemical to electrical energy has several advantages over conventional power generation methods, which have multiple steps from chemical to thermal to mechanical to electrical energy. The potential advantages include high efficiency with combined heat, cooling and power (electrical efficiency of up to 60%, combined efficiency in cogeneration of more than 90%), high power density, small carbon footprint, low emissions, low noise and high-quality power. Fuel cells integrated with coal-fired power plant could produce concentrated CO_2 ready for capture. They are modular in nature and do not suffer large energy penalties when scaled down to a small size.

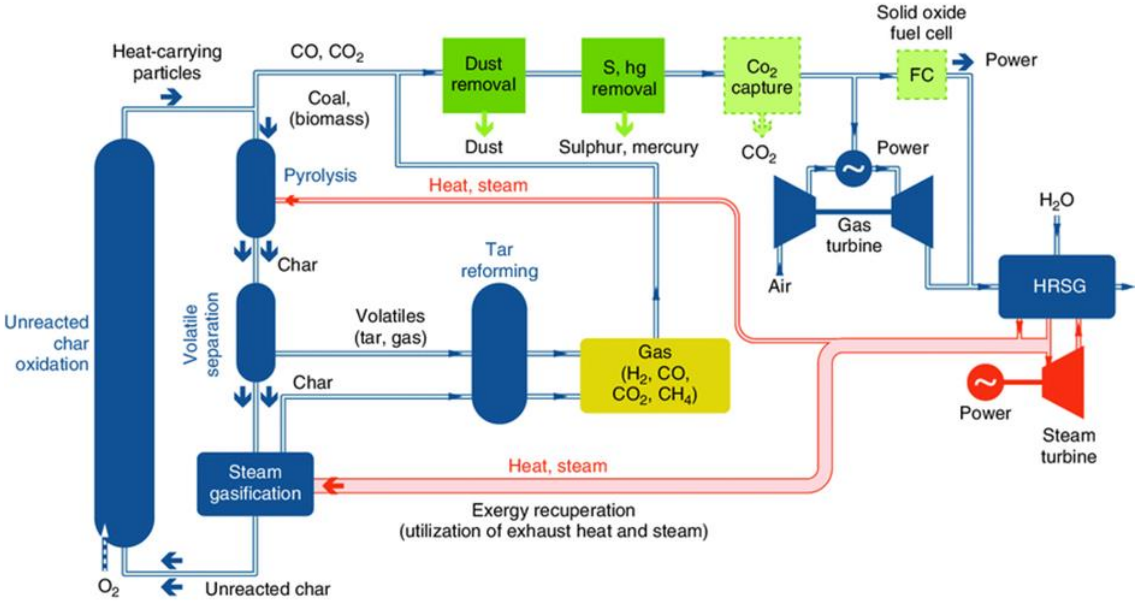
20. For large-scale stationary power generation, integrating a coal gasification process with high temperature fuel cells (IGFC) is an option to create ultra-high efficient and low emissions power generation systems. The US Department of Energy (DOE) promotes R&D on fuel cell technologies through research programmes such as the ‘Solid State Energy Conversion Alliance (SECA)’ and aims to demonstrate a 10 MW IGFC system and a 50 MW IGFC system by 2025. The overall challenges for stationary fuel cells are cost and cell durability. The expectation is that an IGFC demonstration plant should lead to the further development of the technologies with reduced costs, making them a promising option for power generation.

21. The first IGFC demonstration plant with Government Agency support is the Coolgen project, which is underway in Japan. As indicated in Figure VII, this comprises a 166MW oxygen blown entrained flow IGCC, with the option to produce hydrogen by passing a proportion of the syngas through a catalytic reactor, with the CO_2 by-product being removed for either utilisation or storage. This allows the IGCC to be fuelled solely by hydrogen and there is scope to take a side-stream of the gas to fuel a fuel cell. Initially the plant will be fuelled by a mix of syngas and hydrogen with enhancement of performance provided by the integration of the output from the fuel cell.

22. To date, the operability of the IGCC has been proven and the intention is now to prove that at least 90% of the CO_2 gas stream arising from the shift reactor can be captured and transported from the plant. This will be followed by proving the operation of the fuel cell to

generate power using the hydrogen created in the shift reactor. The overall goal is to demonstrate by 2025 that the IGFC can achieve a net thermal efficiency of 55%.

Figure VII
Simplified process streams schematic for the Osaki Coolgen project (Zhang X (2018)



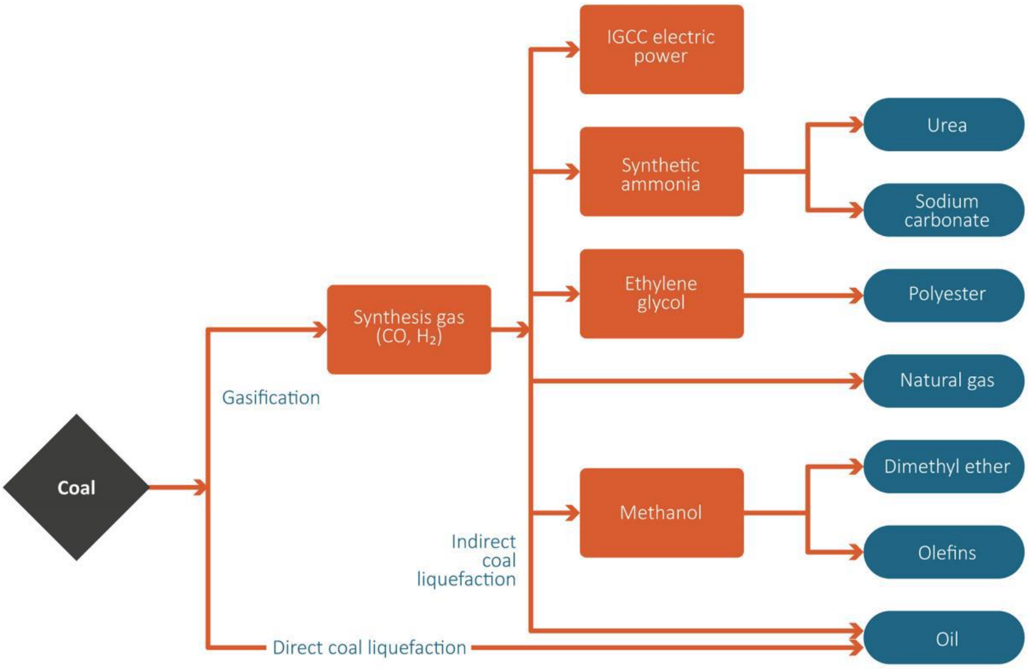
23. To date, the basic performance of the oxygen-blown IGCC, which is a core technology of the integrated coal gasification fuel cell combined cycle (IGFC) has been proven, including an assessment of the operating characteristics and economics. Efforts are now being directed to the demonstration of oxygen-blown IGCC with CO_2 capture. In the third step, the scope for efficiency improvements by combining fuel cells with the oxygen-blown IGCC system will be explored, with a 2025 timeline for completion (Osaki Coolgen Corporation 2021).

V. Use of coal gasification to produce chemicals and future fuels

A. Introduction

24. The gasification of coal to produce a syngas (CO + H_2) is a process that not only can provide hydrogen but one that can also with further processing result in these primary products being converted to produce higher value, more amenable products including a wide range of chemicals, together with future fuels such as methanol, dimethyl ether, synthetic natural gas and liquid transport fuels (Figure VIII).

Figure VIII
Schematic of the end-product flexibility of the gasification process (Seeking Alpha, 2012)



25. In principle, this can fulfil an important strategic need, particularly in various developing and industrialising countries where coal is the primary fuel source while oil and gas availability can be limited. It offers the means to balance the energy trilemma of energy security, economic attractiveness and, with the appropriate control systems, acceptable environmental impact.

26. There are several pre-requisites for establishing this technology (Minchener 2019), which include the need to:

- have available large reserves of low-cost gasifiable coal, typically as stranded assets due to either low quality or location
- have a host government with the ability and will to provide enabling support for the very large capital investments that are required
- be able to cover the costs for infrastructure needs both for the supply of feedstocks and for transporting the end-products; and
- have the means to ensure adequate institutional capacity requirements can be met.

B. Technology deployment

27. The original extensive commercial deployment was in South Africa, arising from the period when imports of oil by that country were politically problematical. Since then, their coal-to-liquids synfuels production has been maintained while their major coal-to-chemicals production has been converted to use natural gas as the feedstock instead of coal (Sasol, 2010).

28. A large-scale demonstration of coal-to-synthetic natural gas (CTSNG) production was subsequently established in the USA but not taken further due to lower-cost alternative gas sources being available (netl, 2020).

29. China is now the technology leader having established and financially underpinned a major commercial-scale coal conversion sector based on low-grade coals. It offers a template for large-scale coal-to-chemicals, gaseous and liquid fuels deployment for all stages of the industrial development cycle. China’s chemical sector required 250 Mt of coal in 2019, and this figure will rise substantially as new manufacturing capacity becomes operational (Reid 2021). Major investment continues with 150 new facilities added between 2018 and 2020, and a further 220 plants being planned for completion by 2023.

30. Within the synthetic fuel subsector, the leading options include coal-to-liquid fuels and coal-to-synthetic natural gas. Such large-scale projects represent a massive up-front capital investment to cover the coal conversion plant itself and the associated infrastructure needs. The production cost of the coal can be reasonably well-estimated and normally is relatively stable. In contrast, the costs of oil and gas, from which the end-products can also be made, have always been more volatile. Consequently, the overall profitability is very difficult to estimate, for the nominal 50-year's lifetime of the process, since there will be times when oil- and gas-based end-products are more competitive than the coal-based versions (Minchener, 2019).

31. Both within and outside China, concerns remain about high supply costs and uncertainty of forward oil and gas prices. For example, the major slump of international oil prices in 2014 from over 100 US$ per barrel (bbl) to as low as 30 US$/bbl had a major impact on the overall coal conversion sectoral programme in China. The breakeven oil price at which these future fuel processes will be nominally financially attractive is when crude oil international prices are above 60 US$/bbl, although there is a range of breakeven values depending on the process, the cost of coal and the local circumstances.

32. The coal to chemicals programme is driven by the State Government via the National Development and Reform Commission (NDRC) in China, which formulates policies for economic and social development, maintains the balance of economic development, and guides restructuring of the economic system (Woodall B, 2014). As part of its plans to limit possible future vulnerability to lower-cost imports for some products, it introduced centralised approval for new coal conversion projects. As well as introducing various constraints regarding water use, energy efficiency and environmental protection, it has also included the need for project developers to show that they have the capability to be able to subsequently address CO_2 emissions intensity.

33. In the sector, coal-to-methanol, dimethyl ether and hydrogen are all considered as mature technologies. Hydrogen from coal offers a competitive option for a carbon free fuel and feedstock for use in manufacturing and industry processes such as cement production and steelmaking, transportation, industrial feedstocks production, heating/power in buildings, as well as power generation.

34. Coal-to-liquid fuels processes, after considerable challenges, now operate adequately, with scale-up to commercial prototype plants underway (e.g. the 2Mt/year coal to liquids in Ningxia Province). In contrast, for coal-to-synthetic natural gas, due in part to the type of gasifier selected for the first demonstration units, operational performance has been problematical with the required environmental standards not always being met. The government has reworked its approach with a greater emphasis on gas imports while tightening the approval process for further units in line with the national policy.

C. Status of hydrogen from coal processes

35. There is a growing interest in hydrogen as a zero carbon alternative to various fossil fuels. Total annual global hydrogen demand in 2018 was some 115 Mt, which was produced almost entirely from fossil fuels (coal and natural gas) and local to the point of consumption. Coal currently accounts for around 27% of the hydrogen production based on the energy input required to produce it, with natural gas accounting for over 70% of the remainder (Kelsall 2021). Annual hydrogen global demand for 2050 is forecast to increase to some 650 Mt, representing around 14% of the expected world total energy demand (Kelsall, 2021).

36. Clean hydrogen is likely to be adopted in applications where it is the only viable decarbonisation alternative, or where it has a proven advantage over competing solutions. This includes feedstock uses in the chemical industry, feedstock use in iron and primary steelmaking industries, fuel for long-distance shipping and storage uses in 'island' power systems. Additional application where hydrogen could become the preferred decarbonisation solution include fuel use in aviation, fuel use for long-distance road-based haulage applications, use in buildings to complement electrification and storage/buffering use in interconnected power systems. The coal-based approach can produce a stream of hydrogen of around 99.8 % purity. While the leading global producer is China, other countries are also

moving forward. Japan developed a strategic plan in 2017 and is driving the need to establish hydrogen as a key fuel for several applications. South Korea followed closely behind with its own roadmap to developing a hydrogen society with a strong focus on the transport sector.

37. Driving forward deployment will require policy actions that include support for sending positive long-term signals to potential investors, stimulating demand for clean hydrogen in existing and new markets, reducing investor risk and developing business models, setting the agenda for technology R&D, and supporting the establishment of a regulatory framework (Kelsall, 2021).

D. Environmental challenges

38. From an environmental perspective, water availability in the more arid northern parts of China where most of the suitable coal is located is a concern. For all conversion processes, full attention needs to be given to both limiting water usage through process optimisation and to recycling water wherever it is practicable. Again, the Government has set tough standards for ensuring maximum water recycling, and these needs must be included in the process design and operational plan, which represents a key part of the approval procedure. This has led to a range of innovative techniques being established. However, this issue could ultimately lead to a limit as to how large this coal conversion sector can become.

39. The other issue is the release of CO_2 into the atmosphere. While the end-products have high amenity value and are clean, compared to low-grade coal, their production results in higher releases of CO_2 than would be the case if that coal had been combusted. Should the sector continue to grow, this level of greenhouse gas release might impact adversely on China's declared intention to peak its national CO_2 emissions by 2030. However, as described previously, the coal conversion process results in the CO_2 being concentrated prior to its release, which then offers a potentially low marginal cost route for it to be captured and used to enhance oil recovery. In China, many of the coal gasification sites are significant large-scale emitters of concentrated streams of CO_2, but equally importantly, there are clusters of such sites in various industrial locations reasonably close to oil wells. The marginal cost of adopting this approach is low compared to establishing CO_2 capture on a coal-fired power plant. Hydrogen production from coal gasification with carbon removal is lower cost than hydrogen production based on water electrolysis, typically by a factor of around three, at some 1.9-2.4 US$/kg H_2 with costs as low as US$ 1.6/kg H_2 in China. Learning by doing through large scale commercial roll-out together with savings through technology innovations should reduce the costs further by 2050. In terms of emissions, the carbon intensity of this process to below 3 $kgCO_2/kg\ H_2$. This rate could be increased by coprocessing a portion of either biomass or organic waste with the coal feedstock, which could lead to net zero or even negative CO_2 /kg H_2.

40. It is very significant that the Sinopec Group, which includes the China Petroleum and Chemical Corp and is the world's largest refiner by volume, has started construction work on the country's first million-tonne-level CCUS project in East China's Shandong Province (China Daily, July 2021), with operations scheduled to start by end 2021. This CCUS project will capture 10.68 million tonnes of CO_2 from Sinopec's Qilu refinery and during the next 15 years will inject it into the Shengli Oilfield to enhance oil recovery by some 2.97 million tonnes. This represents the first commercial prototype CCUS demonstration project to be taken forward in China, with the expectation that once this is shown to be an effective approach then other such projects will follow, including various opportunities on coal to chemicals /future fuels sites.

41. The project will also provide a solid foundation for Sinopec to implement its larger-scale CCUS projects, thereby helping China to honour its pledge to peak carbon emissions by 2030 and achieve carbon neutrality by 2060.

42. Recently, other countries have declared intended investment in coal gasification for fuels and fertiliser; these include Indonesia and India together with Pakistan and various African countries via the Belt and Road Initiative (Reid I, 2021).

VI. Other coal to product options

43. While gasification provides an effective means to convert coal into high quality chemicals and fuels, there are alternative approaches that can produce a growing number of non-energy products with high amenity value that also compete with oil and gas derivatives (Reid I, 2018). The outputs include pitch, critical elements, activated carbon, pitch carbon fibre, electrode materials and nanomaterials although commercial and environmental challenges remain. Nevertheless, the feasibility of using coal as the feedstock to make such products has increasingly led to commercial fabrication facilities being established worldwide (Reid, 2021).

44. The more promising options are listed below:

(a) Pitch carbon fibre is derived from coal tar, which is a by-product of the high temperature coking of coal for the manufacture of metallurgical coke. This is the most promising low-cost route for fibre deployment in transport and construction. Carbon fibre has largely replaced fuselage metals in aeroplane manufacture due to the cost-benefit of higher strength/reduced weight. There is also scope for use in electric cars since these are currently hampered by the weight of battery arrays and require a means to offset this by reducing vehicle weight. There may be additional benefits since this fibre offers additional benefits including chemical inertness and thermal conductivity that may extend battery life. There may also be scope within the construction business with carbon fibre products showing potential to be tailored for lightweight insulation materials or structural components (Reid, 2021);

(b) Graphene is a novel, planar form of carbon with special properties. Possible uses include its inclusion in sensors, medicine, composites, batteries, coating, electronics, textiles, and automotive applications (Graphene-Info, 2019). Manufacturing routes are still being developed, with four promising options including chemical and molten salt techniques, together with a flash joule heating method that may be the most easily scaled method to produce graphene for commodity products;

(c) The use of lignite in agriculture, either partially oxidised or in its raw state, can counter deterioration of soil through use as a humate based fertiliser;

(d) The other key option is the extraction of minerals from coal since they offer an alternative resource for the extraction of rare earth elements (REE) that are crucial to modern communications, aerospace, electric transport industries and various variable renewable energy technologies. There is a strategic need to secure supplies of such elements. This can be achieved from the processing of coal wastes, with initial trials exceeding targeted REE purity levels, while measures such as x-ray sorting aim to reduce the impact of the lower concentration of REE in coal compared to REE ores. Novel techniques offer non-chemical routes from coal to REE with the potential to reduce waste management. This has potential for REE extraction as part of procedures for restoration of disused mine workings.

VII. The way forward: key takeaways

A. Coal gasification for power and CHP applications

45. Gasification offers an alternative to more established ways of converting feedstocks like coal, biomass, and some waste streams into electricity and other useful products. The advantages of gasification in the power sector is that it offers a potentially lower cost route for CO_2 removal while still achieving higher cycle efficiencies than coal combustion systems. Development of further technological advances in integration, turbine design and supporting processes will enable IGCC to achieve yet higher efficiencies. However, it is a more complex system with higher capital costs and to date there are few commercial scale units deployed. Japan is driving the technology forward, but it remains to be seen whether this will be maintained, given their recent policy shift at the 2021 G7 meeting. That said, production of hydrogen from coal gasification with CCUS for near zero carbon power generation is a promising option.

46. The technology's placement markets with respect to many techno-economic and political factors, including costs, reliability, availability, and maintainability (RAM), environmental considerations, efficiency, feedstock and product flexibility, infrastructure, national energy security, public and government perception and especially policy will ultimately determine whether gasification for power generation and CHP realises its full market potential.

B. Fuel cells for CHP

47. Stationary fuel cell systems can be part of the solution to meeting environmental targets for emissions and increasing power generation efficiency. The big challenges are the cost and cell durability. Thus, while a hydrogen-based fuel cell for CHP is an attractive option, it has yet to be proved at commercial scale. Again, Japan is a global leader with a strategic agenda while South Korea and the USA are also undertaking significant research and development.

48. Until now, fuel cells and related technologies have been built at very low volumes since market demand has been insufficient to enable investment in advanced manufacturing. Reducing the cost of manufacture can benefit all aspects of fuel cell systems, including hydrogen production and storage systems, and hydrogen infrastructure. Support from governments in the near-term is critical to progress stationary fuel cell applications until they are ready to enter the market.

C. Coal gasification to produce chemicals and future fuels

49. Gasification for gaseous and liquid fuels production (future fuels) can fulfil an important strategic need, particularly in various developing and industrialising countries where coal is the primary fuel source with oil and gas energy security of supply an issue. However, the commercial deployment of these technologies in such countries can be problematical for various technical and economic reasons. China is continuing to drive technological advancement and has established a commercial scale industrial sector with a focus on converting low-grade, low-value, coals to high-value chemicals including liquid- and gas-based future fuels. It offers a template for all stages of this industrial development cycle, including the means to financially underpin such coal conversion projects, and the associated infrastructure needs.

50. There remain concerns about CO_2 release from the various chemicals production processes, but this can be overcome by the inclusion of a shift reactor to provide a concentrated stream of hydrogen and a waste flow of CO_2.The latter can either be stored or utilised thereby achieving a near zero carbon output.

51. At the same time, it is important to ramp up production, with the need for near-term actions to overcome barriers and reduce costs to increase the uptake of hydrogen. This includes policy actions to send positive long-term signals to potential investors, stimulate demand for clean hydrogen in existing and new markets, reduce investor risk and develop business models, set the agenda for technology research and development (R&D) and finally to support the establishment of a regulatory framework.

D. Coal to critical minerals, rare earth elements and non-energy products

52. This technology approach complements the coal gasification options in that it is seeking to use coal as a resource to produce high value products. For critical minerals and rare earth elements, there is a strategic need since traditional sources of these materials are very limited and they are used to produce components that are critical for most modern communication devices, for example. Equally important, using coal as a source of transformative carbon-rich materials is a ground-breaking means to upgrade coal use. The opportunities for commercial exploitation are considerable and in market sectors that previously had little connection to coal. As such, there are major R&D programmes underway to establish efficient processing techniques to provide this range of products for these new market sectors.

VIII. References

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