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Polygeneration with biomass-integrated gasification combined cycle process: Review and prospective

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ABSTRACT

The integrated gasification combined cycle (IGCC) process is an energy conversion system for concurrent power and chemical production. The key capability of this technology is the synthesis of versatile chemical products from various carbonaceous feed material, such as coal, biomass, and by-products from the petroleum refining process. This flexibility places the IGCC as a viable alternative for conventional Rankine cycles which suffer from inflexibility in response to the volatile electricity market. To date, there are few commercial examples of this technology predominantly due to the high capital cost requirement and operation complexity. However, the economic feasibility of the IGCC could be significantly improved with carbon capture obligations. This is due to its lower carbon capture costs as a result of treating high-pressure and high-concentrated CO_2 stream, unlike conventional power generation systems. This paper provides a comprehensive review of polygeneration IGCC process with multiple-feed and multiple-product flexibility. Then process fundamentals are critically reviewed and technological barriers are discussed.

1. Background

Coal has traditionally been the primary source of power generation and currently accounts for approximately 41% of global power generation capacity [1]. The established process for coal conversion to electricity is the pulverised coal combustion (PC) process. Two substantial issues arise from the continued consumption of coal for power generation through this process; *sustainability* and *flexibility*.

Approximately 70% of CO_2 emissions that arise from power generation is attributed to coal consumption which equates to around 40% of global anthropomorphic CO_2 emissions [2]. The carbon to hydrogen ratio of coal is roughly twice that of crude oil and approximately four times that of natural gas. Therefore, direct combustion of coal generates the largest quantity of CO_2 per unit of energy released compared to any other fossil fuel and places this fuel as the least sustainable energy source.

The other critical issue for coal-based power generation relates to process *flexibility*. Generally, large-capacity PC plants are baseload power sources, operating at maximum output, satisfying the demand security objectives [3]. Baseload power plants are not suitable for altering power generation to complement a decrease or increase in power demand (addressed as "load following"). Factors such as the temporal and geographical variability of power demand and supply, the increasing prevalence of intermittent renewable resources and the development of the electricity market have resulted in increased demand for more flexible power generating processes [4]. The high volatility of renewable energy sources will further aggravate the variability of the demand. It is probable that future government policy will mandate that a certain percentage of electricity production be required to come from renewable sources, as evident in several countries [5]. Consequently, power generation processes must be capable to adjust for load fluctuations dynamically and able to optimise for changing electricity market conditions rapidly. Achieving reliable operation of power generation processes in the future will, therefore, mandate the continuous balancing between the production and consumption of resources associated with the electricity network and this may prove economically unviable for high capacity PC plants. Therefore, there is a significant need to design and establish new energy conversion systems that utilise coal in a more flexible and environmentally sustainable system in order to allow a safe and affordable transition to the ideal scenario of a fully renewable global energy supply.

Gasification process involves partial oxidation of a feed material the exothermic energy of which results in the autothermal breakdown of the feed to the smallest stable chemical units that can still carry energy [6]. The final mixture of gaseous products is labeled synthesis gas or syngas. The gasification of coal has been practiced since the late 19th

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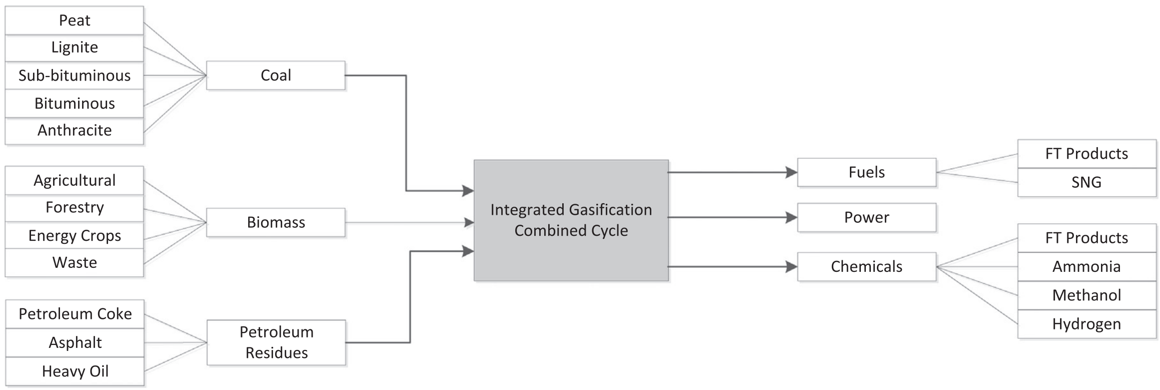

Fig. 1. Co-gasification and polygeneration capabilities of the IGCC process.

century when coal-to-gas plants were common throughout Europe, and coal-derived gas was used for municipal lighting and distributed for lighting, cooking, and heating [7]. In modern applications, the intermediate product of syngas undergoes further downstream processing before conversion to a final product. This includes gas cleaning and a water-gas shift stage. The final product following syngas conversion can be significantly diverse, depending on downstream processing it can vary between gaseous or liquid fuels and chemicals. This system was further advanced through the integration of a gas turbine with the gasification process to increase the diversification of products by generating power. Fig. 1 shows a schematic of a modern polygeneration gasification system with the flexibility of taking multiple feeds and generating multiple products.

The idea of coupling the production of syngas through gasification with a gas turbine for power generation was initially proposed in 1950 [8]. The integrated gasification combined cycle (IGCC) process involves the combustion of syngas in a gas turbine attached to a steam cycle in a combined cycle to accomplish a high-efficiency power generation process. IGCC is being increasingly evaluated as a potential clean coal power generation process with inherent advantages compared to PC with respect to CO_2 emissions mitigation. When attempting to capture the CO_2 emissions from the PC process, there is a significant reduction in overall process efficiency, referred to as an energy penalty. This energy penalty is a result of the low CO_2 content (< 15% by volume) of the exiting low-pressure flue gas. The consequence of this energy penalty is the need to deploy significant additional capacity solely to enable the capture process, this, in turn, necessitates an increase in coal consumption to achieve the same power output. With IGCC, CO_2 capture and sequestration can occur with a significantly lower energy penalty as the majority of gas handling occurs in the syngas that is contained at high pressure and has not been diluted by combustion air. Therefore, CO_2 removal can be more effective and economical than cleaning up large volumes of low-pressure flue gas as required following PC. Furthermore, overall emissions from an IGCC plant are around one-third to one-tenth of those for a PC plant at equivalent power outputs [8]. There are also additional environmental benefits from IGCC when compared to PC, such as approximately 30% less water consumption and lower leachability of fused slag [9]. All these are making IGCC as a favorite option for addressing energy security and sustainability problems concurrently, and the literature shows increasing attention to this technology in recent years [10].

Currently, the gasification of carbonaceous feed material is performed in around 300 plants, utilizing approximately 800 gasifiers across 29 different countries [6]. From 2006–2013 the operating global gasification capacity doubled and further growth is expected [6]. Producing chemical products is the dominant application for gasification, as evident in Fig. 2. Approximately 25% of global ammonia production and 35% of global methanol production are an end product of gasification [6].

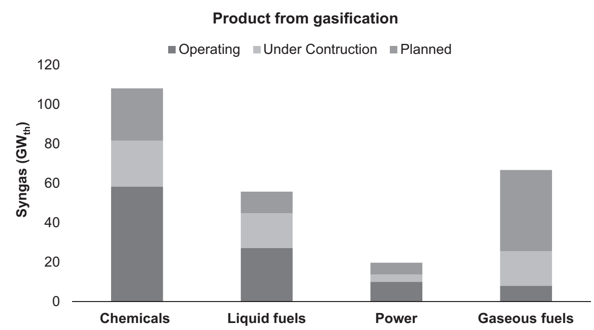

Fig. 2. Global product distribution from gasification in 2013 and future predictions [83].

2. IGCC with multiple feed flexibility

Generating power from the gasification of coal and other carbonaceous feed material enables a degree of flexibility unattainable for conventional power generation processes. The IGCC process enables polygeneration of power, in addition to fuels and chemicals, based on varying syngas processing. The polygeneration of power, fuels, and chemical allows an aggregated allocation of energy sources in a wide range of power outputs and chemicals for a wide range of applications. This enables flexible modes of operation where the combination of multiple products for different markets can allow tailored income generation by switching between different portfolios of products based on market conditions. The diversification of the product portfolio reduces risk and enables profit maximisation. Therefore, processes, such as IGCC, that enable polygeneration have the potential to overcome the issues that arise from the variability of demand in the power sector. Additionally, polygeneration allows the units that are common to multiple processes to operate at a higher capacity and under continuous operating conditions thereby reducing risks associated with thermal load oscillations. Further increasing flexibility and the ability to exploit market conditions for the optimisation of profit is the potential for co-gasification. As previously stated, any carbonaceous feed material can undergo gasification, this includes different ranks of coal as well as a broad array of biomass and petroleum residues. It should be noted that the heterogeneity of coal, biomass and petroleum residues will undoubtedly result in an increase to the fluctuation of syngas quantity and composition produced from the gasification process and therefore for the co-gasification process to achieve an acceptable degree of consistency coal must act as the buffer. The choice between carbonaceous feed material and selected final product will present a complex technical and economical optimisation problem with potentially multiple solutions. Understanding market drivers and influences for feed materials and products in additional process limitations will aid in the development of decision support tools, such as an optimised operational