A Literature Review on Coal Gasification as Part Transition in SA Thermal Coal Power Generation

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Abstract

South Africa uses direct combustion of coal for its bulk power generation. The air emissions of noxious gases which includes carbon emissions is a continuous challenge. South African power stations have historically employed best practices for managing air emissions. South Africa has also pioneered the coal to gas to liquid technology in the production of synfuels; Sasol. South Africa is in need for a just transition away from direct coal combustion. This paper explores the theory and global practices of coal gasification, reviews the recent research efforts on advances in the processes and questions if the approach could be a partial contribution towards a just transition in South Africa's bulk power generation. The South African economy is a coal driven economy and every engineering contribution that includes the management and use of this natural resource has merit. In conclusion, the paper explores the idea of introducing the required heat for gasification from a small modular nuclear reactor; to go one step ahead in terms of introducing the emerging hydrogen economy whilst UNFCCC puts to rest the old coal economy by 2050.

Keywords
Coal Gasification, Syngas, Air Emissions, Power Generation.

1. Introduction

South African natural coal resources are widely available at surface level; it can be collected, bagged and sold for individual and local use by residents, commercial and industrial activities. The net result will be open and exposed fires with direct exhaust of all emissions into the atmosphere. To counterbalance this past and potential practice, South Africa must provide affordable electricity for all. In addition, the South African economy is historically built on coal. Millions of jobs are dependent on coal. South Africa like most countries utilizes coal as its major energy resource, with over 70% of the country's energy needs been provided for by this fossil fuel (Ratshomo and Nembahe, 2018). Lack of alternatives, the expected growth in the country's population, and the continuing need for energy security will see this percentage potentially increase in the next two decades.

The country requires an engineered and just transition path towards meeting its global obligations on carbon emissions and climate change (The Paris Agreement, 2015). Switching from direct coal combustion to coal gasification could be one step in the just transition path towards zero carbon emissions by 2050.

Coal gasification is coal to gas conversion process that produces a combination of fuel gases, carbon monoxide (CO), methane (CH_4) and hydrogen gas (H_2), collectively referred to as synthetic gas or syngas. Coal gasification as an alternative to coal combustion could have reduced pollutant formation, by process management, and could be considered a cleaner coal technology. In South Africa, the state-owned enterprise, Eskom, is currently facing great difficulty in supplying affordable electricity to citizens, although the country has abundant coal reserves. An estimated 45 billion tons of coal is trapped underground. One option is to explore underground coal gasification (UCG) with the capability to power South Africa for centuries at a lower cost (Mathu and Chinomona, 2013).

2. Coal Gasification

Coal gasification is simply reacting solid coal with a gasifying agent such as oxygen, steam, and air to produce a gas called synthesis gas. Also regarded as the incomplete combustion of coal, where the main difference between this process and complete combustion are the final products. Gasification produces hydrogen sulfide (H_2S) and ammonia (NH_3) as opposed to sulfur dioxide (SO_2) and nitrogen oxides (NO_X) produced by complete combustion. Coal gasification is regarded as clean technology as a result of reduced emissions associated with it, it is considered to have better environmental performance.

Coal gasification is deeply rooted in as early as the 17th century, where blue water gas and town gas were manufactured, Scotch engineer, Murdock first produced coal gas in 1792 through the Fontana process, which he used to light his house(Shadle *et al.*, 2007). The type of product in coal conversion is a result of the operating conditions and the type of reactor used, operating conditions include pressure and temperature variations, type of coal, and oxidant used amongst others. To this day, the type of reactor denotes the product produced, coal conversion technologies are classified as combustion, pyrolysis, coking, cyclic gas generator, and gasification, these processes make use of coal and insufficient air to produce a variety of solid fuels, tar, and gases(Shadle *et al.*, 2007).

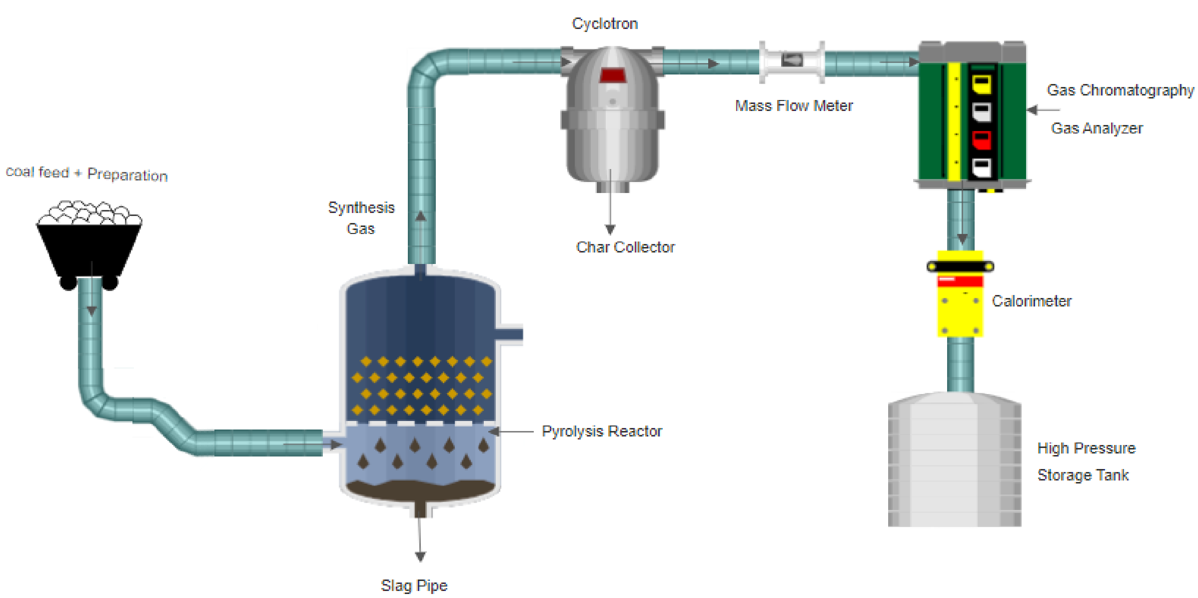

Figure 1 Process Setting

Coal gasification is a complex process with changes both physically and in chemical structure, all occurring in a gasifier, Figure 1 shows the process and technology status of the process and how coal flows from solid to gas in a general set up, initially, coal is heated to remove moist which is followed by the process of drying, these processes occur between 150℃ and 300 ℃ where the temperature is a function of the type of coal and heating method being used (Tremel *et al.*, 2012). When the labile bonds in coal cleave, the fragments that have a lower molecular weight vaporize and leave the gasifier as gas, the process is known as pyrolysis or devolatilization and accounts for most of the coal loss, fragments that are higher in weight remain in the gasifier to form char also referred to as metaplasm (Model, Chen and Chyou, 2015) (Tremel *et al.*, 2012).

The gas flowing through the tube moves into the cyclotron which separates the gas and particles for further purification, the syngas goes through a mass flowmeter, which measures the mass flow rate of the gas moving through the tube. The syngas additionally goes into a gas chromatography or gas analyzer to determine the composition of the product gas, while a calorimeter determines the heating value of the gas before storing the gas into compressed gas storage for gas fuel purposes.

2.1 Chemistry of Synthesis Gas
Figure 1 showed the general set up for the process of coal gasification, however, to produce synthesis gas there is a string of changes occurring to the coal that are both physical and chemical, the partial combustion and gasification processes are both illustrated in Figure 2

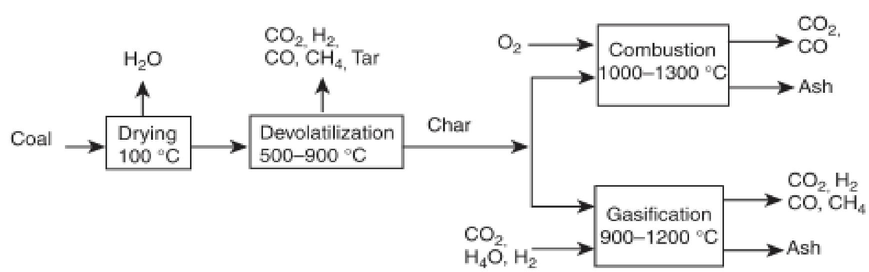

Figure 2 Physical and Chemical changes in coal

The technology that produces synthesis gas or in short syngas are categorized into gasification and reforming, the process depicted in Figure 2 shows the conversion from solid to gas, while syngas can be produced from biomass, natural gas or any feedstock that contains hydrocarbon, to produce synthetic liquid fuels by Fischer-Tropsch process and gases (Schlögl, 2017). This case study for power generation is narrowed down to syngas from coal. Where the gasification process starts with partial combustion given by the reaction:

$$(1+\lambda)C + CO_2 \rightarrow 2\lambda\, CO + (1-\lambda)CO_2 \qquad \Delta H^o{}_{298K} = 172.5\lambda - 393.5\ kJ/mol$$

Where λ ranges between 0 for pure carbon dioxide product and 1 for pure carbon monoxide product, and depends on the gasification conditions but is always close to 1 as gasification aims to produce more carbon monoxide than carbon dioxide(J. van de LoosdrechtJ. W. Niemantsverdriet, 2012). The char continues to react further at a slow rate to form a reversible gasification reaction with CO_2, H_2O and H_2

$$C + CO_2 \leftrightarrow CO_2 \qquad \Delta H^o{}_{298K} = 172.5\ kJ/mol$$
$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H^o{}_{298K} = 131.3\ kJ/mol$$
$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H^o{}_{298K} = -74.8\ kJ/mol$$

The conversion of coal to syngas is an endothermic reaction that requires very high temperatures to occur. The water to gas shift reaction is given below, where the syngas is shifted completely into hydrogen by making use of the carbon monoxide as a reducer, this occurs at temperatures ranging between 300 and 500 degree Celsius, and at a pressure swing that will support the production of hydrogen of the highest purity (Speight, 2015).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^{o}{}_{298K} = -41.2\ kJ/mol$$

2.2 Coal Gasification Parameters

The quality of the gas produced from coal gasification is dependent on parameters of the processes including the moisture and composition of the coal to be used as feedstock, the type of gasifying agent used (air, oxygen or steam), the gasifier and technology associated with it as well as the conditions of the reactions inclusive of the temperature and pressure. The feedstock properties are the most important parameters affecting the quality of the syngas produced during coal gasification, the quality, composition, and reactivity of coal affects the calorific value of the gas, carbon conversion in the process and the efficiency of the gasification process.

The quality of the coal is determined by the carbon content of the coal further classified as coal ranks, together with how coal reacts when the heat is introduced into a process. Low-rank coal generally has a carbon content of 85% or lower, the medium rank coal is set at between 85% and 91% carbon content and high rank is any coal with a carbon content greater than 91%(Żogała, 2014). The carbon content determines how porous the feedstock is, where low ranked coals are more porous and in turn tend to be more reactive as their crystallites are smaller and require less heat to break down.

The composition of the feedstock includes how much moisture, oxygen, and volatile substances is within the coal. The higher the moist the coal is the less the energy produced from the coal while requiring more energy from the equipment to extract the syngas(Brar *et al.*, 2012), more porous coal is moister and is more oxidized because high-rank coals are less moist, such coals produce more energy compared to the low-rank coals, therefore to balance the content issue that rises in low-rank coal much greater stock is required to produce the same amount energy as that of high-rank coals (Mishra, Gautam and Sharma, 2018). The relationship of oxygen content in low-rank coals is the same as that of moisture and yields the same results. Volatile content of coals differs from places of origin however coals with less volatile substances require less complex treatment equipment in the gasification process.

One parameter that influences the quality of the gas produced is the operating temperature within the gasifier, this affects the composition of the syngas which in turn directly affects the calorific value of the gas. Temperature affects the chemical reactions in coal gasification, the shift reaction of water to gas, and produced hydrogen and carbon oxide, while the Boudouard reaction extricates the carbon dioxide to produce carbon monoxide(Brar *et al.*, 2012), temperature affects both reactions. Temperature ranging between 800-850-degree Celsius results in a high concentration of both hydrogen and carbon monoxide within the syngas while showing a reduced concentration of methane and hydrocarbons. Gasification temperatures over 1000 degree Celsius increase the gasification time with the ability to reduce the time required to gasify the coal by 50% while producing gas with little to no tar, although this is favorable, such high temperature give rise to challenges of sintering, defluidization and low volume of carbon dioxide for carbon-capturing (Karimipour *et al.*, 2013).

Pressure also affects the composition of synthesis gas produced in coal gasification, at high pressure the concentration of methane and ethane is high due to the hydrogasification other bi-products of the process, this parameter affects the general structure of char formed, at high pressure the structure of the char tends to be that of a sponge, this affects the reactivity of the char which in turn is reduced (Mishra, Gautam and Sharma, 2018). Pressure ranging between 5-10 MPa results in gas with low volatile yield while increasing the tar in the product gas.

2.3 Coal Gasifiers

A gasifier is the most important component for the process of coal gasification, as it is where all the changes of coal to gas occur and the type of gasifier used influences the final gas produced. There are mainly three types of gasifiers, namely, the bubbling gasifier, commonly known as Fixed bed gasifier, Fluidized bed gasifier, and Entrained flow gasifier. Each type offers a variety of advantages and disadvantages, deciding which to use depends on the desired outcome, Figure 3 (J. W. (Hans) Niemantsverdriet, 2012) shows the above-stated gasifier types and fluid movement in each.

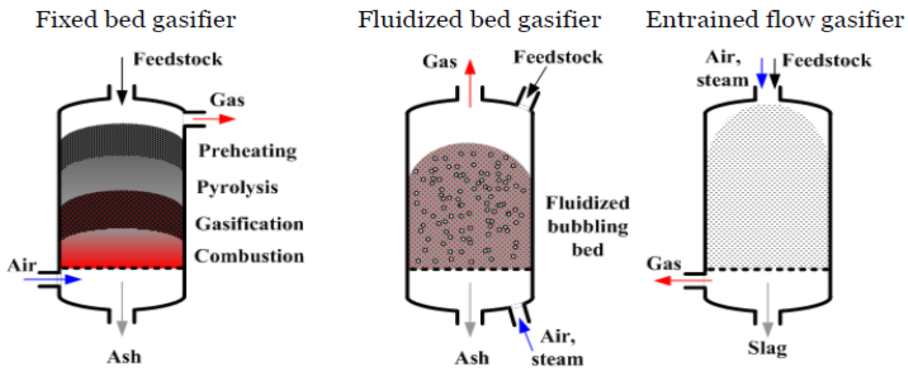

Figure 3 : Coal Gasifiers

The bubbling gasifier or fixed bed gasifier is the oldest technology in the gasification process, contrary to its name fixed, the fluid within the gasifier moves due to gravity flow. The gasifying agent is introduced at the bottom of the component at high temperatures, while the coal is added at the top of the gasifier, this configuration results in the maximum heat economy where the conditions of low temperatures and oxygen at the top results in gas with a high composition of methane, therefore, a higher heating value. However, the gasifier is limited to a specific feedstock as it is unable to process coal with a moisture content greater than 35% as these cracking coals tend to swell when heated and lead to maldistribution further causing process failure(Andersson, 2015).

A fluid bed as shown in figure 3, offers extreme mixing of the coal and gasifying agents as the gasifier maintains uniform values in temperature and coal mass. This allows the system to use a range of coals including cracking coals, however, the configuration of the gasifier affects the carbon conversion during gasification, till date the best existing fluid bed has a carbon conversion of 97% which is much lower than the other bed each at 99% carbon conversion. The advantage of the entrained bed is that it can handle any coal feedstock while producing a clean tar free gas(Andersson, 2015). However, this comes at a cost of more coal preparation work and very high oxygen consumption.

Although these gasifiers work differently the general working principle is the same and the main equations that govern the gasifier include energy, momentum, and species transport equations. The energy equation is solved for temperature for the fluids within the gasifier and that of fields of solid walls(Sharma and Agarwal, 2019):

$$\frac{\partial(\rho u)}{\partial t} + \nabla * (\rho v h) = \nabla * (k\nabla T + \tau v) - \nabla * \left(\sum_i h_i j_i\right) + S_h$$

Where:

$$j_i = -\rho D_i \nabla y_i, \qquad h = \left(\sum_i h_i j_i\right), \qquad u = h - \frac{p}{\rho} \; and \; h_i = \int_{T_{ref}}^{T} C_{p_i} dT$$

Where the terms are defined as below (Sharma and Agarwal, 2019)(Poraj *et al.*, 2016):

- ρ-density u-internal energy t-time h-specific enthalpy
- k-effective thermal conductivity
- v -velocity vector T-temperature τ-effective stress tensor J-diffusion mass flux
- S-source term in the transport equation of the scalar quantity D-mass diffusion coefficient
- y-mass fraction c_p-isobaric specific heat p-the pressure

The momentum equation is solved for the velocity vector together with the pressure of the fluids:

$$\frac{\partial(\rho v)}{\partial t} + \nabla * (\rho v v) = -\nabla p + \nabla * \tau + \rho g + S$$

Where g and S is the gravitational acceleration and source term respectively, while gases species transport is given by(Poraj *et al.*, 2016):

$$\frac{\partial(\rho y_i)}{\partial t} + \nabla * (\rho v y_i) = \nabla * \rho D_i \nabla y_i + S_{yi}$$

3. Power Generation

The advancement of the IGCC system was developed in the early 1980s, where experiments were conducted by various of research institutions around the world led by the electric power research institute to generate power in a way that consumed much less coal while increasing the efficiency of the system(Hitachi Mitsubishi Systems, 2012), this has seen the technology develop and advance over the decades. This section aims to give the fundamental presentation of an integrated gasification combined cycle and gives operational comparisons between gasification and combustion.

3.1 Integrated Gasification Combined Cycle

A basic schematic diagram of an integrated gasification combined cycle is given in Figure 4 (Chen *et al.*, 2012), the system is made up of subsystems that are interconnected to convert coal into energy, the most complex subsystem is the gasifier and has been described and depicted in Figure 1, where a coal feedstock goes through a gasifier to produce syngas, the clean gas is fed into a combustion turbine further turning the generator to produce electricity by converting gas kinetic energy into mechanical energy (Chen *et al.*, 2012).

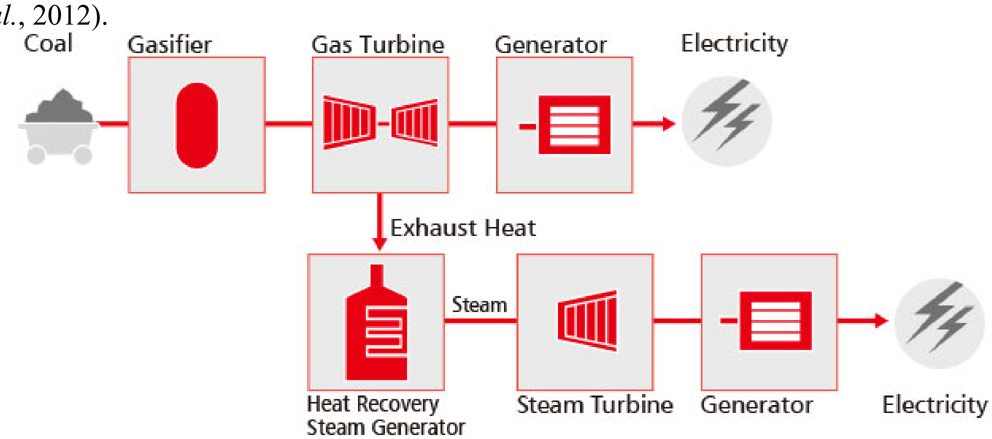

Figure 4 : IGCC Schematic

The product of the gas turbine goes into a heat recovery steam generator, into a steam turbine to further generate electricity. The system depicted above does not include a carbon capture section, IGCC systems with carbon capture follow the same principles, the small difference is that between the gasifier and gas turbine a shift reactor is added which converts the carbon monoxide in the syngas into hydrogen gas and carbon dioxide (Wang *et al.*, 2015), which later goes through an absorption tower where its captured and stored.

3.1 Combustion vs Gasification

The processes of combustion and gasification are considered as two justifications that lead to the same results, although these processes both lead to the generating of electricity, the fundamentals principles are different and so are the yield results. Table 1 below compares these two processes for similar characteristics (Pinto, 2020) (Wang *et al.*, 2015).

Table 1 : Difference between Combustion and Gasification

	Combustion	Gasification
Chemical Reaction	Full Oxidation (Excess Oxygen)	Partial Oxidation (Inadequate Oxygen)
Equation	$C + O_2 \rightarrow CO_2$	$C + \frac{1}{2}O_2 \rightarrow CO$
Enthalpy Change	-32 822 kJ/kg	-9 123 kJ/kg
Products	Electric Power	Electric power, Hydrogen Gas, Chemicals, and Liquid Fuel
Efficiency	35-37% HHV	39-42 HHV
Risk at Maturity	Low risk (Adequate Experience)	High risk (new technology)
Emissions	~1 NSP	~1/10 NSP
Cost Issue (USD)	~ 3.5-4.8 Billion	~ 7.5 billion

Coal gasification and combustion are different processes used for power generation, however, the table above concludes that gasification is more efficient, environmentally friendly, and has a competitive operative cost compared to combustion as the process has less compelled emissions tax while generating high profit due to more products. The capital cost issue shows that although gasification has many advantages it is costly to build at almost twice the estimated price of coal combustion plants (Eskom, 2016)(Abadie and Kutxa, 2009). Table 1 also shows that coal gasification is high risk at maturity as a result of less technological experience (Breeze, 2014); noting that South Africa has deep expertise from its Sasol coal to liquid fuel operations.

4. Related Work

The major challenge that most nations have in common is energy security, which is finding a reliable source of energy that meets the standards and requirements of clean energy rather than depending on a single fuel as an energy source. The gasification process offers a universal solution to the energy security challenge since the syngas produced can be used for power generation, production of chemicals, and transport fuels all from the same feedstock. Coal gasification is not a new process and has been used all around the world as an evolving technology to generate electricity in places such as Japan, China, India, the USA, and England successfully while reducing and managing coal emissions from power generation.

4.1 Osaki Coolgen Japan

The Osaki Coolgen is a recently completed power plant that generates 166 MW of power through clean coal technology, in the design stages the power plant was divided to two stages, stage 1 completed in 2018 included the system design, construction, and testing while stage 2 is the integration of carbon separation and storage technologies.

Testing commenced in 2018, with the main focus being the performance of the plant, the level of reliability as well as the environmental aspects of operating a power plant, Osaki successfully generates over 160 MW on a feedstock of 1180 tons/day coal, with an efficiency of 40.8% with great ease in the controllability of the facility, tests showed that the exhaust gas composition shows less than 8ppm of Sulfur oxides and less than 5ppm of Nitric oxides (Sakamoto and Yokohama, 2015). The power plant showed a high level of durability and reliability with the ability to operate continuously for 2168 hours, proportional to 90 days.

The successful erection of the Osaki Project opened many doors for the IGCC technology in Japan, one of the power plants currently underway is the Nakoso power plant expected to have 543 MW capacity using gas drives instead of steam turbines (Asano, 2017), the power plant is to operate on a 3400 tons/day coal feedstock with an efficiency of 48% and emissions at 19 and 6 ppm of sulfur oxides and nitric oxides respectively.

4.2 GreenGen China

The GreenGen project was started in 2004, divided into 3 phases with phase 1 the construction of a 250 MW power station already complete, phases 2 and 3 to focus on the adding of fuel separation technology, carbon storage, and introducing fuel cells to upgrade the capacity to 400 MW. All design, construction, and initial demonstrations were completed in 2008 and the full phase 1 facility can be seen in Figure 4 below (Xu, 2014).

Figure 5 GreenGen Phase 1

The plant was commercialized in 2012 after a series of standard tests, the power plant surpassed the standard 72 hours continuous operation minimum requirement and currently runs on a 2000 tons/day coal feedstock. Over the years the GreenGen project has achieved a steady 690 hours of continuous operation which is equivalent to 29 days, with a generation efficiency of 48% (Xu, 2014). Although the initial design was for 250 MW capacity, the plant has an output of 265 MW with fewer emissions compared to the Ningxia Lingwu coal-fired power plant.

4.3 Kowepo South Korea

Korean Western Power or commonly known as KOWEPO is an innovative power generating facility in South Korea that has set goals on combating emissions associated with power generation, the facility is the first that made use of IGCC technology in the country and has continued to successfully operate such plant since 2016 when the Taen IGCC power plant was commercialized. Initially, the plant was designed to have a net power of 305MW once operated it was measured to have an overall power of 380MW, at a coal consumption of 2 670 tons/day, and a net efficiency of 42%(Kim, 2015).

Project upgrades at the Kowepo Taen complex have seen the plant increasing its capacity from 305 MW to 6 446 MW in four years, operating 11 units using coal gasification technology, its currently the largest power plant in South Korea producing over 57% of the Kowepo capacity by making use of state of the art technology such as cyclone desulfurization and dust collection technology with results nearing zero emissions of sulfuric oxides.

4.4 Small Modular Nuclear Reactors

SMR powered by nuclear can supply heat at temperatures in the range of 1000°C for application in chemical processes such as the synthesis of liquid or gaseous energy carriers. Nuclear coal gasification could open a new door of opportunity for the South African coal sector. This approach could be extended to include the production of hydrogen for the emerging hydrogen economy of electric vehicles and stationary fuel cell powered micorgrids. In a study promoted by Stellenbosch University (Botha et al, May 2013), in an integrated nuclear assisted carbon to liquid process, the system was evaluated in terms of syngas production efficiency versus carbon utilization. Early results show if the hydrogen production plant is sized to deliver the required oxygen for the gasification plant, syngas efficiency of 63% is achieved while 71,5% of the carbon is utilized. The optimum outlet temperature of the high temperature reactor was 850 °C. The system potential could be extended and improved such that carbon utilization reaches 90%.

5. Conclusion

The application of coal gasification technology is mature and commercial. The literature review study draws the following conclusions:

i. The use of synthetic gas in power generation increases the efficiency of the system, is eco-friendly, and is a better substitute for coal combustion in thermal power stations.
ii. The thermal efficiency of an integrated gasification combined cycle plant is relatively higher than that of a coal combusting power plant
iii. Coal gasification technology is compatible with machinery and equipment currently used in coal combusting facilities in South Africa.
iv. Technical advancement and carbon capture technology enable coal gasification plants to produce much less carbon emissions.

Towards the future, The United Nations Framework Convention on Climate Change has aspiration that post 2050, coal will cease as a primary energy resource for mankind. South Africa has three decades to migrate away from carbon energy resources such as coal, oil and gas. To make the transition from carbon to non-carbon resources over three decades, an option is to consider syngas from coal. Syngas has the attributes of localization for energy independence and the capacity and capability for energy security. Adding in a small modular nuclear reactor as heat source, mitigates using coal combustion for heating and will start a new economy in industrialization, promoting both nuclear and hydrogen engineering and technology. When all is done and coal is removed as primary energy resource, South Africa will have accumulated strength in both nuclear and hydrogen energy resources. The South African Energy Transition Pathway could read : Coal combustion to coal gasification; Towards a nuclear and hydrogen energy economy which is complimented by solar and wind renewables with pumped hydroelectricity energy storage, having present day demand of 35 GW with a potential 70 to 80 GW demand in 2050.

The key research questions remain:

a. Can coal gasification using the heat from a small modular nuclear reactor be an economically viable strategy in moving from 100 % coal combustion to zero coal combustion by 2050, to leave behind a new economy in nuclear and hydrogen engineering, technology as sustainable non-carbon energy resources ?
b. Can nuclear and hydrogen energy resources compliment and associate with renewable energy resources, including using municipal solid and sanitation waste as primary hydrogen feedstock post coal?
c. Can the UNFCCC Global Climate Change Fund, finance a new coal gasification investment in Mpumalanga (similar to Sasol) that will have a 2 decade life span (2030 to 2050) in powering the existing South African Thermal Power Stations, a potential 40 GW stranded national asset?

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